EXPERT SYSTEM BASED SWITCHED MODE POWER SUPPLY DESIGN

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ABSTRACT

The design of power electronic systems requires wide ranging expertise in complex and often tedious tasks, such as the design of the power circuit, selection of power semiconductor devices, design of the feedback loop, design of wound components, and design for Electromagnetic Compatibility (EMC). Many of the tasks rely heavily on the experience of the designer, and cannot be solved analytically. This makes the design iterative, time consuming, and heavily dependent on the designer’s experience.

At present, circuit simulation packages such as SPICE or SABER are used to test a design in software. Even with these tools, it is still necessary to build a prototype to verify the design, usually followed by several test-modify-retest cycles before a final design is reached. This process involves considerable decision making, which requires substantial expertise in all aspects of power electronics.

This thesis investigates the use of expert system technology, one of many artificial intelligence techniques, to assist in the design of power electronic systems. Faster design times and a more efficient design are among the advantages that can be achieved using an expert system based design. In this study, Switched Mode Power Supplies have been chosen as a typical power electronic system. An expert system (developed using wxCLIPS) has been linked with a circuit simulator (SPICE), extensive databases and a graphical display system to provide a comprehensive design environment. The techniques used in the system covers all facets of the design: preliminary circuit design, component selection, circuit simulation, control loop design, and design for EMC. Extensive knowledge bases covering the various design rules are built into the expert system. The design methodology aims to give a near complete system design with an optimum configuration produced at minimum time and cost.

The investigated techniques could readily be adapted to other power electronic applications, such as Uninterruptible Power Supplies or motor drives.
DECLARATION

I hereby declare that this thesis is my own work,
unless otherwise stated

'Amarnath Reddy
ACKNOWLEDGEMENTS

I would say, without an iota of doubt, Dr. Ewen Macpherson is solely responsible for successful completion of this research. He supplied me abundant inspiration and moral support which will last for my entire life (I hope to live beyond 2100 AD!). Thank you so much Ewen.

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Many thanks to Mr. Richard Soh, Minebea Inc., Port Glasgow, for teaching and clarifying me so many power supply design issues. His feedback proved to be very invaluable, though it sometimes caused me headaches!

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GLOSSARY

δ  Effective skin-depth
η  Efficiency
ΔI_{step}  Peak-to-peak step load change
ΔT  rise in temperature
ΔV_{step}  Allowed peak-to-peak output voltage deviation.
A_c  Effective core area
A_{EIA}  Error amplifier gain
A_{f-cross}  The required gain of the error amplifier required at the cross-over frequency to obtain an overall gain of 0 dB at that frequency.

a_i  Wire-cross section area of the i^{th} winding
A_L  Core inductance factor
A_p  Area product of a core
A_s  Exposed surface area of core
A_w  Winding window area of a core
B_m  Maximum flux density
C  Filter inductance
CAD  Computer aided design
CENELEC  European Committee for Electrotechnical Standardisation
C_i  Junction capacitance of diode
CLIPS  Expert system development tool
COOL  CLIPS object oriented language
C_{sd}  Diode Snubber capacitance
C_{sn}  MOSFET Snubber capacitance
C_X  X-capacitance
C_Y  Y-capacitance
D  Duty ratio
D_{max}  Maximum duty ratio
D_{min}  Minimum duty ratio
EMC  Electromagnetic compatibility
EMI  Electromagnetic interference
ES  Expert system
FCC  Federal Communications Commission
f_{main}  Mains supply frequency
f_o  Output filter corner frequency
f_s  Switching frequency
GUI  Graphical user interface
<table>
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<th>Description</th>
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<tr>
<td>$I_{ac(peak)}$</td>
<td>Peak input current.</td>
</tr>
<tr>
<td>$I_{ac(rms)}$</td>
<td>Rms input current</td>
</tr>
<tr>
<td>$i_L$</td>
<td>Output filter inductor current</td>
</tr>
<tr>
<td>$I_{L_{max}}$</td>
<td>Maximum inductor current</td>
</tr>
<tr>
<td>KB</td>
<td>Knowledge base</td>
</tr>
<tr>
<td>$K_w$</td>
<td>Winding utilisation factor</td>
</tr>
<tr>
<td>$L$</td>
<td>Output filter inductance</td>
</tr>
<tr>
<td>$L_{max}$</td>
<td>Maximum output filter inductance</td>
</tr>
<tr>
<td>$L_{min}$</td>
<td>Minimum output filter inductance</td>
</tr>
<tr>
<td>$n$</td>
<td>Turns ratio of primary to secondary winding of a transformer</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of turns of a winding</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Number of turns of the $i^{th}$ winding</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed circuit board</td>
</tr>
<tr>
<td>$pf$</td>
<td>Power factor of the circuit.</td>
</tr>
<tr>
<td>$PM$</td>
<td>Phase margin</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Total power output of a power supply</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>SQL</td>
<td>Sequential query language</td>
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<tr>
<td>$T_{main}$</td>
<td>Mains supply period.</td>
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<tr>
<td>$T_c$</td>
<td>Charging period of each reservoir capacitor</td>
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<td>$t_f$</td>
<td>Maximum drain-source current fall time</td>
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<td>$t_{on}$</td>
<td>Turn-on period</td>
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<td>$T_{on_{-max}}$</td>
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<td>$t_r$</td>
<td>Maximum drain-source voltage rise time</td>
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<td>$T_s$</td>
<td>Switching time period</td>
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<td>$V_{ac(rms)}$</td>
<td>Rms input voltage</td>
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<tr>
<td>$V_c$</td>
<td>Control voltage</td>
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<tr>
<td>$V_{CM}$</td>
<td>Differential mode noise voltage</td>
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<td>$V_{DM}$</td>
<td>Common mode noise voltage</td>
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<tr>
<td>$V_{ds}$</td>
<td>Maximum drain-source voltage</td>
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<tr>
<td>$V_F$</td>
<td>Forward voltage drop</td>
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<tr>
<td>$V_o$</td>
<td>Output voltage</td>
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<tr>
<td>$V_{p_{-max}}$</td>
<td>Maximum primary voltage</td>
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<td>wxCLIPS</td>
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Chapter 1

INTRODUCTION

1.1 OVERVIEW

This thesis investigates the use of Artificial Intelligence in the design of power electronic systems. The basic design concepts and the present state-of-the-art of computer-aided design are introduced in this chapter. An ideal design environment for power electronic systems, the rationale and the objectives of the present research are then discussed.

1.2 POWER ELECTRONIC SYSTEMS

Power electronic systems process electrical energy using semiconductor switches. The evolution of power electronic systems has closely followed that of power semiconductor devices [1]. Power electronics became popular after the invention of the thyristor or silicon controlled rectifier by the Bell Telephone Laboratories in 1956, later commercialised by the General Electric Co. The subsequent development of high power semiconductor devices (MOSFET, GTO, IGBT etc.) with improved electrical characteristics has resulted in a huge growth in power electronics. A new entrant to this field is the power-integrated circuit incorporating both power switch and control circuitry on a single chip [2]. These power integrated circuits, also known as ‘smart
power’ devices, are expected to give cost reduction and improved reliability. However, providing adequate isolation between high- and low-voltage circuits and cooling are serious limitations.

The basic building block of a power electronic system is the converter which controls and shapes the voltage and current waveforms. Converters are generally classified on the basis of their function into:

- ac-dc converter (rectifier),
- dc-dc converter (chopper),
- dc-ac converter (inverter),
- ac-ac converter at one frequency (ac controller),
- ac-ac converter at different frequencies (cycloconverter).

Often a power electronic system combines more than one converter to meet the needs of a particular application.

Modern power device development has resulted in improved power converters in terms of size, cost, reliability, and performance. Thyristor forced commutated converters are now almost obsolete. Stringent national regulations in terms of permissible harmonic content and power factor have brought in new converter topologies. Resonant converter topologies are gaining in popularity due to their efficiencies being higher than that of PWM converters.

Technological advances have led to the development of Integrated Circuit (IC) power supply controllers, application specific integrated circuits (ASIC) using VLSI chips, and microcomputers. These advances in microelectronics make power electronics systems commercially more viable because of improved performance, reliability, and reduced size.

Power electronics is used in a wide variety of applications, such as

- switched mode power supplies,
- uninterruptible power supplies,
- electrical machine drives,
- heating and lighting control,
Advances in power electronics have led to improved productivity in industry. Power electronic systems offer higher efficiency and reduced size compared to their linear power processing counterparts. For example, by using a switching power supply, an efficiency up to 90% can be achieved, whereas with an equivalent linear-type power supply, the efficiency would be typically 30 to 40% [3].

Power electronics is a multi-disciplinary subject encompassing:
1. power semiconductor devices,
2. converter topologies,
3. wound components, and
4. control theory.

Figure 1.1 shows a switched-mode power supply, typical of power electronic systems.

1.2.1 Design of Power Electronic Systems

Power electronic systems are non-linear in nature, and are characterised by their mixed mode analogue and digital behaviour. Since the power processing functions of these systems necessitate keeping resistances as low as possible, the key passive circuit elements are inductors, capacitors and transformers, in contrast to most other analogue circuits that contain resistors and capacitors as the main passive elements. The strong non-linear characteristics of power electronic systems make them difficult...
to analyse accurately. This is made more difficult by the presence of device/system parasitic elements.

The design of power electronic systems requires a wide range of expertise in complex and often tedious tasks, such as:

- **Power electronic circuits.** This includes the selection and design of a suitable converter.
- **Control theory.** The system’s dynamic performance must be designed to guard against dynamic perturbations and overall instability.
- **Motor characteristics.** One of the largest markets for power electronics is electric motor drives, so motor characteristics must be known.
- **Design of wound components.** Most power electronic systems use magnetic components. These components can be complex, and careful design is essential. Considerable skill in the choice of core material, core design, core size, and winding design are required for a cost-effective system.
- **Power electronic devices.** Selection of components such as power MOSFETS, IGBTs can be very time consuming.
- **Analogue/ digital electronic circuits.**
- **Design for Electromagnetic Compatibility (EMC).** All power electronic systems inevitably generate electromagnetic noise which can interfere with other equipment if unsuppressed. This electromagnetic interference (EMI) is undesirable and is subject to restrictions imposed by international safety agencies. Since EMI is a random phenomenon and needs considerable heuristics to tackle it, design for EMC is a daunting task even for an experienced design engineer.
- **Design for safety.** The designer must include safety considerations such as the separation and creepage distances between primary and secondary circuits in systems including an isolation transformer.

The above issues result in the following:

- The design heavily depends on the designer’s experience. No two designers will arrive at the same solution to an identical task. This often leads to a non-optimum design.
The non-linear behaviour of power electronic circuits often makes it necessary to use a design-test-redesign (trial-and-error) approach.

The design process is lengthy and time consuming.

1.3 COMPUTER-AIDED DESIGN

To succeed in today's competitive world market, design engineers are under pressure to shorten the design cycle and to improve system quality and reliability. In the design process, designers often use computer-aided design (CAD) tools as CAD potentially holds the key to better design, manufacture and quality. CAD is not only cost effective for the initial design of products, but also for ensuring optimisation of the final design.

Extensive testing of laboratory prototypes is commonly used for circuit development as well as for performance evaluation. It has been estimated [4] that as many as 50% of the design faults in power electronic systems that are discovered during the product realisation process could have been detected at an earlier stage by an appropriately structured circuit validation tool. Early detection of circuit design flaws allows errors to be corrected before a prototype is constructed, with consequent savings in time and expense.

Computer-aided design tools can greatly aid the designers in both circuit design and circuit validation. An ideal computer-aided design environment is an integrated system of the necessary software tools to automate the design process, with two-way communication to allow the user to interact with the system at all stages of the design process as shown in figure 1.2. Currently, CAD tools for the design of power electronic systems include:

1. circuit simulation tools such as SPICE [5] and SABER [6] to assist in circuit performance verification, such that expensive and time consuming hardware testing is minimised. Simulation tools provide a software environment in which the designer can test the design prior to building a prototype.

2. printed circuit board (PCB) layout tools, such as PowerPCB [7], to produce production-level schematics which can be auto-routed to manufacture PCBs. The
layout tools use either simulation code or schematic code to produce the desired PCB layout.

Figure 1.2 A custom set-up of a computer-aided design

1.3.1 Limitations of Existing CAD Tools

At present, there is no proper integration of the various design tools available to power electronics designers to cover the different stages of the design comprehensively. The existing CAD tools do not:

- design the circuit, and
- assist in component choice.

For example, the simulation tools can only simulate a designed circuit, leaving the designer to:

1. generate the simulation specific code (netlist) of the circuit,
2. simulate the circuit successfully,
3. trouble-shoot for any simulation errors,
4. process the simulation results,
5. check for violation of the specification, and
6. redesign the circuit.
The design process thus requires considerable decision making, and substantial expertise in all aspects of power electronics.

Currently, there is a dearth of experienced power electronic designers abreast with the rapidly changing power semiconductor, converter and control technologies. Therefore, there is an identifiable demand for improved CAD aids.

1.4 DESIGNING POWER ELECTRONIC SYSTEMS USING AN EXPERT SYSTEM

Artificial Intelligence (AI) is a computer science discipline concerned with the development of computer systems with a semblance of human intelligence, and includes such operations as natural-language recognition, and uses heuristic problem solving, pattern recognition, generalisation based on experience, and analysis of novel situations [8]. AI deals with understanding the nature of intelligent action and constructing computer systems capable of such action. AI has developed over the years into several fields, including expert systems, fuzzy logic and neural networks. Of the above fields, expert systems are probably the most well used application of AI, and have made inroads into many fields of engineering.

An expert system is a computer program that solves a complex problem by emulating a human expert with specific knowledge and inferences [9-10]. It is intended to model or emulate human expertise and knowledge in a specialised problem-solving domain. If they are embodied with expertise from human experts (e.g., design engineers), expert systems are capable of decision-making. An expert system not only offers a solution to a problem, but can explain the decisions which it has taken. This ability of expert systems to educate the user about its decisions makes this technology both powerful and user-friendly.

Expert systems are likely to play an increasingly important role in future decision-making. As expertise is expensive, perishable, and scarce, an expert system is an attractive low cost alternative to assist in design. Expert system technology has matured over the past decade into a valuable tool for assisting decision making by human experts, with applications over a wide range of disciplines, including
computer-aided engineering and computer-aided manufacture. Expert systems (ES) are further discussed in chapter 2.

For the design of power electronic systems, expert systems are preferred to other software techniques such as spreadsheets, and conventional programming languages (C, C++, Pascal, FORTRAN etc.). Unlike the above two, there is no sequence of instructions to be followed in ES, and there is a greater ease of maintenance and flexibility [11]. With an ES, it is straightforward to alter or update the design process, and experiment with new technological advances.

An effective way of enhancing CAD tools is to embed decision support into them using an ES. ES technology can be applied to the design of power electronic systems in the following areas:

1. automated system design
2. modelling and simulation
3. optimisation

An expert system based design environment should include:

1. schematic generation
2. component selection
3. simulation (design verification)
4. graphical display
5. PCB layout

The design stages include decision support to advise the designer/user about the consequences of each design sequence. An expert system based design can offer advice and decision support in the following areas:

- **Selection and design of converters.** This is performed by programming characteristics of standard power converter circuits into the expert system.

- **Selection of circuit components.** For a fully integrated automated design package, databases of available components such as power semiconductor devices, capacitors and magnetic cores are necessary, as device selection is an extremely important area of the design, in which cost plays a key role. A design package with well supported databases can be a useful tool even for an experienced engineer, as
component selection can be very time consuming.

- **Computer-aided simulation assistance.** Verification of the circuit design may be realised by performing repeated simulations, each stressing different aspects of the circuit. This needs automatic generation of the simulation code and the schematic of a circuit. With ES technology simulation errors can be avoided, shortening the design validation process.

By linking different stages in the design process with computer-aided simulation and validation tools, an expert system based design offers a shortened design-test-redesign cycle. Additionally, automatic placement of components from simulation code to produce a production level PCB schematic makes total automation of the design possible.

### 1.5 REVIEW OF PREVIOUS WORK

Research into circuit design automation has been pursued actively in recent years. The author of this thesis has reviewed relevant literature covering the period from 1988 to the present.

Foutz [12] created an expert-system based circuit development aid that generates a cost estimate (labour hours, material cost, critical path schedule etc.) for power supplies using the work-plan method as an input. Though this work does not cover design of power supplies, it applies expert system techniques to assist in power supply circuit development. The author also highlights selection of an expert system shell and the importance of the user-interface for the design of power electronic systems.

Earlier research into expert system design automation [13] was reported for analogue circuit design, basically with operational amplifiers. The authors outlined how an expert system technology could be used to combine both formal design techniques and heuristic design techniques to create an analogue circuit design environment. In this work, the expert system is programmed to invoke the circuit simulator automatically to validate the design: this sound design concept allows the user to check the correctness of the design, and experiment with different alternatives.

Another paper [14] reported a successful development of an expert system for the
design of a variable speed constant frequency generator which is used in an aircraft power supply. After querying the specification, the expert system selects and designs a suitable synchronous generator, converter system and control circuitry. The positive aspect of this work is selection of components from databases. This paper also demonstrates the feasibility of expert system technology for the design of power electronic systems. Interaction with the user is given a top priority: the expert system provides explanations for its decisions in the form of “why” and “how” questions. However, there is no design validation implemented in the expert system.

Liang et. al. [15] proposed an artificial neural network based circuit design approach for thyristor snubber circuits. This paper concludes that the time consuming traditional design process may be speeded up by artificial intelligence design automation. The efficiency of this design approach is still to be proved. The paper advocates the use of fuzzy databases to automate electronic component selection. The authors remark that this type of database provides a quick method for finding suitable components from a choice of components with similar specifications.

Debebe et. al. [16] developed an expert system learning aid for power electronic principles. Though the expert system is not for design purposes, the authors implemented sound design concepts such as selection, design and simulation of a suitable power electronic converter with user interface features.

Cumbi et. al. [17] identified a knowledge-based approach for the design of power electronic circuits, mainly PWM inverters. This is one of the few papers that deals with the design of power electronic systems comprehensively. Salient features of this work include interactive design with extensive graphical user-interface, database interaction and circuit simulation (the expert system was linked with a circuit simulator). After querying the specification inputted by the user, the expert system designs a suitable inverter, selects required power semiconductor components from a database, and simulates the converter. The developed expert system falls short of forming a comprehensive design environment, in that there was no proper coordination between the expert system and the SPICE simulator. The user was merely allowed to simulate the design produced by the expert system. It was left to the user
to process the simulation results each time and check for any violation of specifications manually. Moreover, there is no methodology to design the magnetic components and solve the electromagnetic interference issues. The authors’ choice of the UNIX operating environment is questionable as it is not widely used in the power electronics industry.

Hsieh et. al. [18] developed an integrated knowledge- and algorithm- based method for power converter design. This paper proves that integration of the knowledge-based system with the circuit simulator is essential for a successful and reliable design. The authors used algorithm-based techniques for circuit simulation and design verification, which reduced the flexibility of the design methodology. For example, it is not possible for the user to experiment with different circuit component values or variations in existing converter topologies. It is also noticed that there is no user-interaction during the design due to the lack of user-interface. This paper also fails to address issues such as selection of components from databases, design of wound components and designing for EMC.

In [19], an expert system is developed that assists in the design of PWM voltage-fed inverters for induction motor drive systems. A noteworthy aspect of this work is its use of databases for automated selection of major semiconductor components. The authors developed innovative database development concepts to represent graphical data such as semiconductor device characteristics. This is done by subjecting the printed data (usually curves) to a number of conversion stages. The main drawback of this is lack of design validation: the expert system is not linked with simulation programmes so that the design can be checked for both specification violation and optimisation. Moreover, not all aspects, such as design of wound components and electromagnetic compatibility of the power electronic system design were tackled.

Another similar paper [20] used the above expert system principles for the design and selection of an industrial drive fed by voltage and current source inverters. The authors identify the importance of an efficient user-interface for a flexible and user-friendly design environment. In this work, a simple text-based interface is used to communicate with the user during the design. Databases of required power
semiconductor devices were developed using sound database concepts and interfaced with the expert system. Though this paper recognised the significance of design validation, it was not implemented. Design of wound components and measures for EMC are not included in this expert system.

In [21], a knowledge-based approach has been developed for the design automation of microprocessor-based systems such as electric drives. The design tasks include not only hardware design but also software modules which control different circuit variables. This work demonstrates the capability of an expert system approach to tackle complex and diversified tasks.

Fezzani et. al. [22] presented an elementary expert system approach to design basic static converters. This expert system is intended for use in the educational domain to understand the design of converters. The required voltage and current waveforms are entered, and by synthesising these waveforms, the expert system identifies device types and their ratings.

Expert systems have also been developed [23-25] for the design of high frequency power transformers and inductors. Both these works used heuristics integrated with formal techniques (electromagnetic field calculations) to produce optimised wound component design. Depending upon the power requirement, a suitable magnetic core is selected from a database containing magnetic characteristics. However, in both the approaches, the user interaction is very limited: most of the design choices are automatic, selected by the expert system.

In [26], a knowledge-based system was used for fault diagnosis in three-phase inverter circuits. Though the development of the expert system was not explained, the authors identified a fault location by monitoring circuit variables, and comparing these with simulated results.

There has been other research [27-29] published on computer aided design packages for power converters. These are not based on expert systems, but focus on elementary design and simulation tasks. Some works [30-33] applied expert system concepts to SPICE simulation assistance during netlist generation and simulation diagnostics.
CHAPTER 1: INTRODUCTION

After a thorough review of previous CAD research, the following observations are made:

- There is no work which covers all facets of power electronic design. The designer still has to select power devices and carry out the initial design. There is also no attempt to solve the electromagnetic compatibility problems associated with high frequency switching converters.
- There is no user-friendly design environment.
- There has been little attempt to exploit simulation tools.

It would thus appear that the true potential of ES techniques for the design of power electronic circuits has not been fully realised.

1.6 THE RESEARCH OBJECTIVES

This research examines whether expert system technology is suitable for designing power electronic systems. Objectives of this investigation are:

1. To embody decision support at all levels of the design. The successful transfer of expertise from design experts into a computer-aided design environment is the primary target.
2. To integrate into a single package all the design stages, from concept to production-level, including circuit design, component selection, circuit simulation, control loop design, and design for EMC.
3. To give a near complete system design with an optimum configuration at minimum time and cost.
4. To utilise computer-aided simulation extensively.
5. To develop a user-interactive design environment allowing the user ultimate choice.
6. To provide features of database technology.

1.7 THE RESEARCH FRAMEWORK

An expert system based package has been developed to assist in the design of power electronic systems. The developed expert system, named XpertPSD, addresses the
design issues raised in the sections 1.1 to 1.6.

It is not the aim to develop a package to design all types of power electronic systems. In this study, switched mode power supplies (SMPS) have been chosen as a typical power electronic system. The reasons for this are that:

- SMPS encompass most of the characteristics of a typical power electronic system,
- SMPS are widely used power electronic systems, and
- There is an acknowledged shortage of experienced SMPS design engineers.

The design methodology for SMPS is similar to that of other power electronic systems. This facilitates extension of the expert system to other applications with a minimum effort. The research has been carried out over three years, starting in October 1993.

1.8 THESIS LAYOUT

This thesis is organised into nine chapters. The concepts and principles of expert system technology are explained in chapter 2. Also described in this chapter is wxCLIPS, the expert system development tool used to build XpertPSD.

The design methodology and architecture of XpertPSD are covered in chapter 3. The SPICE simulation environment and development of different databases are also explained in this chapter.

Chapters from 4 to 7 describe how the different tasks in designing power supplies are implemented in XpertPSD. Chapter 4 explains implementation of the design concepts of power supplies: design of power circuitry including realistic analysis of specifications, selection and design of a suitable converter and component choice, and design validation using a simulation-approach.

Design of a suitable control system for the power supply is described in chapter 5. Issues such as selection of cross-over frequency, and estimation of phase angle and gain of the system are explained.

Chapter 6 explains how wound components are designed in XpertPSD.

Issues involved in designing the power electronic system to meet EMC regulations are
explained in chapter 7. Design of snubbers and an appropriate EMI filter within the expert system environment are discussed in this chapter.

Chapter 8 reviews the design and development of the expert system, including a study of the economics of using XpertPSD. The flexibility of the expert system to design other switched mode converters, and future development of expert system technology for the design of power electronic systems are then discussed.

Finally, chapter 9 gives the conclusions of the research.
2.1 OVERVIEW

The role of an expert system in research may be described as an 'investigative tool'. This chapter explains the basic concepts, architecture, and development of expert systems, and describes the expert system development tool, wxCLIPS, used in the present research.

2.2 COMPONENTS OF AN EXPERT SYSTEM

An ideal expert system contains a User Interface for problem-oriented communication with the user, a Knowledge-Base (KB) comprising facts and problem-solving rules, a Working Memory to act as a global database, an Inference Engine for processing of the rules and intermediate results, and an Explanation Facility for explaining reasoning processes to the user. Figure 2.1 shows the components of an expert system.

2.2.1 User Interface

The user interface is the mechanism by which the user and the expert system communicate for an exchange of information. In expert system development, the user-interface is extremely important as expert systems solve problems using the expert knowledge stored in the system [34]. The user-interface dissects, or parses, and
interprets user questions, commands, and volunteered information. Additionally, the interface formats information generated by the system, including answers to questions, explanations and justifications for its behaviour, and requests for data.

![Architecture of a typical Expert System](image)

Figure 2.1 Architecture of a typical Expert System

To manage any engineering or science application, a user interface should have:

1. **Ease of learning.** The complex subject matter requires built-in teaching aids to instruct new users of the system. To support ease of learning and enhance the usability of the expert system, the interface should provide simple point-and-select prompting techniques whenever possible. This allows the user to select from a list of alternatives instead of memorising numerous commands. Also it is desirable that documentation needed to understand any questions/process be provided by the expert system itself.

2. **Ease of use.** Since expert systems are interactive and depend on the data input, the interface should be comprehensible to the user, otherwise the system is likely to fail due to lack of user acceptance [35]. The interface must minimise keystrokes to reduce typographical errors and increase efficiency.

The computer display system determines the user interface; either a simple text-oriented display or a sophisticated high resolution bit-mapped display, called a graphical user interface (GUI), is used. The type of output has an impact on the user’s perception of the system.
2.2.2 Knowledge Base

The power of any expert system resides in the knowledge base (KB). The knowledge base is a computer-structured representation of a problem domain in which reasoning can be performed. A knowledge base is formed by analysis of the problem domain. The problem description may involve the observation of experts and/or the study of literature or training manuals.

Classification of knowledge

Knowledge can be classified [36] as follows:-

- Procedural knowledge describes how a problem is solved, and provides a methodology for carrying out a task. Rules and procedures are typical under this category.

- Declarative knowledge is what is known about a problem, and includes simple statements asserted to be true or false plus a list of statements that more fully describes some object or concept.

- Meta knowledge is knowledge about knowledge, and is used to select knowledge that best suits a problem.

- Heuristic knowledge describes a "rule-of-thumb" that guides a reasoning process, and is empirical in nature. It represents the knowledge compiled by an expert (or experts) of experiences in the problem solving domain.

- Structural knowledge describes an expert's overall mental model of the problem. Typically, it includes concepts, sub-concepts and objects of the mental model of the expert.

2.2.3 Knowledge Representation

Expert systems are built using symbolic programming techniques with a knowledge-based approach, in which there is a highly interactive environment making recommendations about the problem domain. In symbolic programming, problem solutions are based on the application of strategies and heuristics to manipulate symbols which, in AI jargon, are a string of characters representing real-world
concepts such as facts or rules for a domain knowledge [37]. In expert systems, there exists a symbolically structured KB, unlike a numerically addressed database used in conventional programming. The symbolic programming makes highly interactive processing possible, and the explanation facility easier to implement.

As shown in figure 2.2, there are numerous techniques for the representation of information in a knowledge base. There is no unique, or ideal, knowledge representation technique; a suitable knowledge representation technique must be selected for a given application. Frequently used ways of representing knowledge are explained below.

![Figure 2.2 Knowledge-representation in an expert system](image)

**Facts**

Facts, also known as object-attribute-value (O-A-V) triplet, are one of the basic forms of knowledge representation in an expert system. They are a form of declarative knowledge and provide some understanding of an event or problem. An O-A-V triplet divides a given statement into three distinct parts: objects, attributes, and attribute values. For example, the statement “converter output voltage is 5 volts” can be represented in O-A-V structure, figure 2.3, in which “converter” is the object, “output voltage” is the attribute, and “5 volts” is the value.

Facts can:

- **have single or multiple attribute values**;
- **be uncertain**. Facts represent a degree of belief in a statement, i.e., they cannot be
classified either true or false with complete certainty.

- **be fuzzy.** Facts may be used to represent ambiguous attribute-values with a degree of confidence.

![Figure 2.3 An object-attribute-value facet representation](image)

**Rules**

Rules are forms of procedural knowledge. These relate known information to other information which may be concluded or inferred. Rules best represent heuristics, which specify a set of actions to be performed in a given situation. Rules along with facts make a system work intelligently to solve a given problem.

A rule logically connects one or more antecedents (also known as “premises”), placed in its “IF” clause to one or more consequents (also known as “conclusions”), placed in its “THEN” clause. The consequents of the rule will be executed whenever its premises are satisfied, which is called *firing* or *activation* of the rule. Figure 2.4 shows the structure of a rule.

![Figure 2.4 Structure of a rule](image)
Rules provide a natural way of describing processes driven by a complex and rapidly changing environment. Rules are typically used to represent knowledge when the pre-existing knowledge can be naturally represented as rules; i.e., when the knowledge is:

- procedural,
- context-independent,
- heuristics, or "rules of thumb", and
- mostly categorical (yes-no type answers).

Rules may be thought of as IF-THEN statements as found in procedural programming languages such as C and Ada. However, the conditions of an IF-THEN statement in a procedural language are only evaluated when the program flow of control is directly at the IF-THEN statement. The most successful type of expert system is the rule-based / production system.

**Semantic network**

A semantic network is a method of knowledge representation consisting of a network of nodes, standing for concepts or objects, connected by links describing the relationship between the objects [38]. Links are commonly labelled with terms such as 'Is-A', 'Has-A' that clearly define the relationships between connected nodes, as shown in figure 2.5. Semantic networks are used to represent descriptive and declarative knowledge.

![Semantic network of DC-DC converters](image)

Figure 2.5 Semantic network of DC-DC converters
Each semantic network has the following properties:

1. **Flexibility.** A semantic network can be expanded by simply adding nodes and linking them to related nodes currently in the network. These new nodes represent additional objects or properties.

2. **Inheritance.** This is a powerful feature in a semantic network. Any new nodes added to a semantic network automatically inherit information from the network. The inheritance feature of a semantic network eases the task of coding knowledge.

**Frames**

Frames, also known as schema, represent typical knowledge about some concept or object, and include both declarative and procedural knowledge [39]. Frames are used to represent descriptive and declarative knowledge.

Generally, a frame is a data structure that organises knowledge as slots (attributes) and assigns values to each slot. Figure 2.6 shows the frame world of a forward converter (the same example as illustrated in figure 2.5).

<table>
<thead>
<tr>
<th>Frame Name</th>
<th>Forward converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class</td>
<td>DC-DC converter</td>
</tr>
<tr>
<td>Properties</td>
<td></td>
</tr>
<tr>
<td>Output</td>
<td>DC Voltage</td>
</tr>
<tr>
<td>Input</td>
<td>AC Voltage</td>
</tr>
<tr>
<td>EMI</td>
<td>Yes</td>
</tr>
<tr>
<td>Application</td>
<td>Power supplies</td>
</tr>
</tbody>
</table>

Figure 2.6 Frame structure of DC-DC converters

A frame-system organises its frames in a hierarchy, where frames in the upper level represent general concepts and those in the lower levels represent more specific instances of those concepts. Frame-systems support inheritance, which allows frames to inherit both slots and their values from frames above them in the hierarchy. Frame-based systems also offer a feature called facets that provide control over property
values.

**Logic**

Logic is perhaps the oldest form of knowledge representation in a computer. Two forms of logic representation are frequently used [36]:

- Propositional logic represents and reasons with statements that are either true or false. It assigns a symbolic variable to a proposition, and provides logical operators, such as AND, OR, NOT, that allow reasoning with rules.

- Predicate calculus is an extension of propositional logic that provides finer representation of knowledge by using functions and predicates to describe relations between individual entities.

### 2.2.4 Working Memory

All the intermediate hypotheses and decisions which the expert system manipulates are recorded in a global database, called the working memory or blackboard. Every expert system uses some type of intermediate decision representation, but only a few explicitly employ a blackboard for the three types of ideal expert system decisions:

1. **Plan elements** describe the overall or general attack the system will use to solve the current problem, including current plans, goals, problem states, and contexts.

2. **Agenda elements** record the potential actions awaiting execution, i.e., the next rule to be fired.

3. **Solution elements** represent the decisions the system has generated thus far along with the dependencies that relate conclusions to one another.

### 2.2.5 Inference Engine

The inference engine, the backbone to the whole system, makes inferences by deciding which rules are satisfied by facts, prioritises the satisfied rules, and executes the rule with the highest priority. It is essentially a computer program that provides a methodology for reasoning about knowledge in the knowledge base, and for making conclusions. The major elements of the inference engine are:

- **The Interpreter.** This executes the chosen agenda items by applying the
corresponding knowledge base rules (the agenda is the list of all rules which have their conditions satisfied and have not yet been executed).

- **The Scheduler.** In the inference system, the scheduler controls the agenda and determines which pending action should be executed next (this may utilise considerable knowledge such as "measure phase and gain margins"). When more than one rule is activated, the inference engine uses a conflict resolution strategy to select which rule should have its actions executed [40].

- **The Consistency Enforcer.** This adjusts previous conclusions when new facts are added to the knowledge base.

### 2.2.6 Explanation Facility

The explanation facility explains the reasoning of the system to the user. It allows the user to ask how the system came to a certain conclusion and why certain information is needed. In general, it answers questions about conclusions reached or why some alternative was rejected. Sophisticated explanation facilities allow the user to ask "what if" type questions to explore alternative reasoning through hypothetical paths.

### 2.2.7 Knowledge Reasoning Mechanisms

The inference engine combines facts, contained in the working memory, with knowledge, contained in the knowledge base, using inference or reasoning mechanisms (analogous to human reasoning) as the problem solving strategies of expert systems. Forward-chaining and backward-chaining are two general methods of reasoning commonly used. Depending on the design, an inference engine will employ either forward- or backward-chaining.

**Forward-chaining reasoning**

This inference process (also called data driven) starts at any given initial condition and works forward towards the goal. The inference engine tries to match the known facts with the antecedents of the rules. When the match is successful, the consequents of the rules are executed, and the results arising from this process become new facts. The pattern matching continues until no new facts can be generated. Since forward-chaining closely simulates heuristic and iterative problem solving, it is suitable for
applications such as the design of power electronic systems. For example, the selection of a suitable converter runs on forward-chaining reasoning as shown in figure 2.7.

Here, since inductor current mode is continuous, rule ‘A’ is activated to select buck-family converters. This resulting new fact, and the facts “Isolation required” and “output power = 200W” match rule ‘B’ which suggests the forward converter as suitable.

This reasoning mechanism is effective, is appropriate for user-interaction, and may be used to carry out database searches and decision making.

**Backward-chaining reasoning**

This starts at a pre-set goal. The goal, in general, is the same as a formulated hypothesis which has to be evaluated. The inference engine searches for the rules which contain the goal in their ‘then’ part. If the antecedents of the rules are known facts, then the goal stands proved, or else, if the antecedents still need to be proved, then these will become sub-goals. The reasoning process continues with the sub-goals until no further sub-goals are found.
Figure 2.8 shows implementation of finding a fault for low speed of induction motor at normal operating conditions. In this example, the reasoning starts with a hypothesis, “Internal Fault in the Motor”. This goal is a consequent of rule ‘A’, and if its antecedents, i.e., “Input voltage is normal”, “Input fuse is not blown”, and “There is no overload” are proved, then the rule will stand proved. Since the first two antecedents are known facts (which might have been proved by some other goals), the last one, “There is no overload” should be proved, and now this becomes a sub-goal of the reasoning process. This sub-goal is in turn a consequent of rule ‘B’ which in this example is proved by virtue of the known facts, “Rated motor torque = 5 N-m” and “Load torque = 4.5 N-m”, thus proving the main goal.

The backward-chaining reasoning tends to be more focused than forward-chaining. Backward-chaining is more appropriate for diagnostic applications, for instance trouble-shooting SPICE simulation errors, while design, monitoring and control applications are carried out better by forward-chaining.

Figure 2.8 Example of Backward-chaining reasoning

2.3 DEVELOPMENT OF EXPERT SYSTEMS

Development of an expert system differs from that of a conventional program primarily by the involvement of both a knowledge engineer and a domain expert. In the design of the expert system, the knowledge engineer collects expert knowledge by
interviewing domain experts, and representing the problem by symbolic programming techniques.

2.3.1 Development Stages

Developing an expert system is an exploratory process using incremental steps in an evolutionary manner. The major tasks involved in the development of expert systems are discussed below.

Problem specification

Problem specification is crucial to the success of any expert system. An early system analysis is essential. With expert system technology, if the problem domain is not carefully selected, then difficulties will ensue later in the development process [41]. The following factors require consideration while specifying the problem:

1. **Nature of the problem.** The problem should have a symbolic structure, and the necessary heuristics for its solution.
2. **Complexity of the task.** It should be neither too easy nor too difficult for a human expert.
3. **Feasibility of the problem.** The task should be of manageable size within a reasonable time schedule.

Knowledge acquisition

Knowledge acquisition is a process of acquiring, organising, and studying knowledge. It involves eliciting knowledge from an expert or multiple experts and also reading available documentation, manuals, and other written reports. However, the primary source of knowledge for most projects is the domain expert. The commonly used approaches for acquiring/eliciting knowledge include interviewing, questionnaires, observation, learning by example/analogy, and statistical methods.

Knowledge acquisition is a continuous process throughout the development of expert systems. As knowledge acquisition is an iterative process, and time consuming, sufficient time must be allowed [42].

Knowledge encoding

After acquiring knowledge, the next step is representing the knowledge in an
appropriate form. Different types of knowledge require different representation methods, as explained in section 2.2.2. An appropriate knowledge representation should select a scheme closely resembling the way the expert is thinking and expressing knowledge.

The next task is to encode the knowledge. At this juncture, it is appropriate to select a computer system, such as MS-Windows, or Unix, on which the expert system will be developed. There are two approaches normally followed in building expert systems:

1. Building expert systems from scratch, using languages such as Lisp, Prolog, C/C++.
2. Using readily available expert system development tools or shells to construct expert system prototypes. An expert system shell is a development tool (software) that consists of various utilities. This approach is followed in the present work, and is explained in section 2.3.2.

Design of user interface
As the user interface is an extremely important component, it must be designed in parallel with the development of the knowledge base. Normally the structure of the knowledge base is affected by the interface design.

Testing and evaluation
After encoding the knowledge, it must be tested and evaluated for consistency of the solutions reached and the quality/accuracy of advice given by the expert system. The approaches used for testing are:

- running the expert system against documented cases, and comparing the expert system-generated results with historical results, and
- having the domain expert and other experts test the system.

In evaluating the expert system, the users should assess the human factors in the design of the user interface. These factors include instructions, display and presentation styles, and utility of the system.

2.3.2 Expert System Development Tools
There are readily available expert system development tools called ‘shells’. Before the
advent of ES shells, programming languages such as LISP or PROLOG were used. These were obscure and not available on many computer systems.

An ES shell is a complete expert system that initially contains no specific knowledge. ES shells have greatly simplified the development of ES. Many tools are available, e.g., CLIPS [43], KappaPC [44], Crystal [45]. Most expert system shells are integrated with existing databases, spreadsheets, optimisation modules, or information systems.

Project scope, goals, and budget constraints are important factors in determining the type of shell to use. Many ES shells are tailored for specific expert domains, e.g., certain applications such as on-line diagnostics do not require extensive user-interface, but require a faster run-time. Broadly, the following factors should be considered while selecting an ES for power electronic applications.

1. The graphical user interface typically takes 40 to 60% of the total ES development effort. The tool should provide sufficient functionality for end-user interface development, and include an interactive developer-interface to build the interface and other modules such as rules, and debugging tools.

2. A sophisticated system interface is desirable to call external-program routines, such as graphical tools, or a SPICE simulator.

3. There should be an efficient numerical processing capability to handle the large quantities of data that may result from SPICE simulations.

4. A variety of ways (e.g., rules, semantic networks, and frames) of representing knowledge greatly increases the efficacy of the software development. It is always desirable to have a choice when choosing an inference mechanism. A rule-based expert system shell with both forward- and backward-chaining inferences is suitable for both design and real-time applications of power electronic systems.

5. A database interface is required to handle data storage and on-line or off-line retrieval. As sequential query language (SQL) [46] is being supported in all data sources including commercial and ASCII-format databases, the ES development tool should support this language.
6. Other considerations include vendor support, run-time licensing agreements, and portability to other computer systems.

The author examined several expert system development tools, including CLIPS, KappaPC, and Crystal. It was considered that KappaPC and Crystal had limited flexibility, inefficient numerical processing capabilities as well as licensing restrictions, so CLIPS was selected for this project. The positive factors of CLIPS are discussed in the following section.

2.4 CLIPS/wxCLIPS

CLIPS, an acronym for C Language Integrated Production System, is an expert system tool developed by NASA, USA. It overcomes a number of difficulties using LISP-based tools. CLIPS is a low cost expert system tool designed to facilitate the development of software to model human knowledge or expertise. The development history of CLIPS is explained in detail in reference [47].

On account of its portability, extensibility, flexibility, and low-cost, CLIPS has received widespread acceptance throughout industry and academia, and has over 4,000 users throughout the public and private community. The performance of CLIPS was compared favourably with other expert systems as explained in [48]. Since its first release in 1986, CLIPS has undergone continual refinement and improvement.

2.4.1 Features of wxCLIPS

WxCLIPS [49] is an extension of CLIPS with graphical user interface functionality to write a portable end-user interface. It is built using wxWindows [50], a C++ class library for different computing platforms including MS-Windows and Sun X-Windows. The salient features are explained below: for a detailed treatment, the reader should refer to CLIPS manuals.

GUI functionalities

wxCLIPS provides a complete environment for the construction of the end-user interface with good graphical user-interface functionality. wxCLIPS provides many forms of interface, including windows, dialogue-boxes, message-boxes and on-line
help in the form of hyper-text. There is also an interactive user-interface development facility which accelerates the otherwise notoriously slow development of the user-interface.

Knowledge representation
CLIPS supports different formats of knowledge representation, including rule-based, procedural, and object oriented. However, the primary representation of knowledge in CLIPS is rule-based.

1. **Rule-based Knowledge.** Rule-based programming allows knowledge to be represented using the forward-chain mechanism as its inference engine.

2. **Procedural Knowledge.** CLIPS also supports a procedural paradigm for representing knowledge similar to that of more conventional languages, such as Pascal and C. Its features include defining new executable elements to CLIPS that perform a useful side-effect, and partitioning of a knowledge base which can control the execution of rules.

3. **Object-Oriented Knowledge.** CLIPS supports Object-Oriented Language, COOL. In a pure object-oriented language, all programming elements are objects which can only be manipulated through messages. As with any object-oriented language, it speeds up the delivery mechanism due to the reusability of the code.

Inference mechanism
CLIPS inference is based on a Rete pattern-match forward-chaining control strategy. Conditions on the left-hand side of rules are matched with facts in the knowledge base. Rules with all conditions matched by facts are activated and executed. The Rete algorithm typically results in a significant decrease in the number of matching operations required. CLIPS does not support backward-chaining or frame-based inference mechanisms.

Development environment
The wxCLIPS development environment supports many computer hardware platforms, including the IBM PC, the Macintosh, and Sun workstations. The tool provides development interfaces that support pull-down menus, an integrated
MicroEmacs editor for a PC, and an interactive end-user interface builder. The debugging aids include commands that display how the facts are asserted in the knowledge base, and pattern-matching and an agenda of rules. CLIPS supports interfacing of external programs where interprocess communication can be used. It is also possible to embed CLIPS knowledge modules in any standard C-language application.

2.4.2 Choice of wxCLIPS

wxCLIPS, a version of CLIPS, was selected to develop the ES. The selection of this tool was prompted by many considerations, such as:

1. strong support for forward-chaining,
2. ease of integration with external systems,
3. portability over a number of hardware platforms,
4. fast execution,
5. easy user-interface development, and
6. no licensing restrictions, as it is available in the public-domain.
Chapter 3

DESIGN AND DEVELOPMENT OF 
\textit{XpertPSD}

3.1 OVERVIEW

This chapter discusses development of the expert system, \textit{XpertPSD}, for the design of power supplies. It introduces the concepts involved in the design methodology of power electronic systems, stressing the design of the various software components, such as the SPICE-simulator, the databases, and their linkage within \textit{XpertPSD}.

3.2 ES DESIGN METHODOLOGY

The design of a power electronic system involves distinct components: the power circuit (converter), the feed-back control system, magnetic components and design for EMC. An expert system based design has been evolved which carries out all of the above tasks, interacting with the user throughout the design process. Figure 3.1 shows the design sequence carried out by the expert system; the sequence is initiated by asking the user to input the specifications required. It is important to query each specification, as it is often written by a systems engineer who may not have an in-depth understanding of all the implications [51]. To probe these implications, the specifications are subjected to analysis to determine whether these are viable for a
power supply. Any modifications required are suggested to the user.

Figure 3.1 Design methodology flow-chart
A suitable converter topology is selected based on known constraints such as power throughput and type of load. After identification of the converter for a particular application, the design commences. To reduce complexity, the converter is split into sections such as input rectifier, basic converter (the dc-dc high frequency conversion stage), and control system, testing different design constraints at each section.

All components required are selected from databases, which contain libraries of components with their electrical characteristics. Device selection is extremely important: as well as electrical parameters, parameters that influence choice are cost, availability, and the reliability of the manufacturer. The user is prompted to select the necessary power semiconductors and filter capacitors from the databases.

Since any design must be validated, the expert system starts the simulation process by preparing a netlist (a circuit description code) for the SPICE-simulator. Different parts of the power supply are simulated separately to reduce the simulation complexity (and hence simulation time). A number of simulations are carried out, each emphasising different aspects of the circuit, such as steady-state voltage and current waveforms, transient response, stresses on power devices etc. The complexity is gradually increased by adding device/circuit parasitic characteristics.

After a successful simulation, the results are processed, and when performance is not satisfactory, the design values are altered and the simulation repeated. This trial and error process continues until all the specifications are met or the knowledge in the expert system is exhausted. When, at any stage, the simulation is not successful, a fault diagnosis is performed to identify and rectify errors.

After a satisfactory design of the converter, the design of the wound components is considered. Magnetic components are bulky devices that significantly affect the total size and cost of a SMPS. Careful selection of a suitable core material and size is thus required for a cost-effective design.

The design is not complete until compliance with Electromagnetic Compatibility conditions have been met. These are somewhat random phenomena and there are not clear-cut rules to follow; however, various suggestions and remedies such as the use of appropriate snubber circuits and input filters are offered.
After completion of the design, all results are written to a user file.

3.3 ARCHITECTURE OF XpertPSD

Figure 3.2 depicts the architecture of the developed expert system in which the above design methodology has been implemented. The user-interface, knowledge base and inference engine are developed using wxCLIPS. The inference engine, as explained in the previous chapter, is the CLIPS reasoning process and is the back-bone of the whole structure. It governs all the tasks including control of the user-interface, design validation, and searching of the databases. All the components of the ES are explained below.

![Architecture of XpertPSD](image)

Figure 3.2 Architecture of XpertPSD

3.3.1 User-interface

The user interface operates through nested menus to allow the user substantial control of the inference process. An interactive and friendly user-interface has been developed using different graphical user-interface forms. Frames/windows are used as front-ends
to specific design tasks such as database interaction, and simulation. Other forms extensively used are message-boxes to post messages from the inference mechanism and dialog-boxes for user feedback/response. Use of keystrokes has been minimised by GUI items such as check-boxes, choice-items, radio-boxes and sliders when requesting input data from the user.

Figure 3.3 shows a start-up window with a dialog-box asking the user to select a design application/project name. The user dialogue is in simple English. At almost all points in the process, the user can return to a menu for an orderly interruption of the process or for the resumption of the process at a different frame.

To provide technical information to the user, 'help' screens with illustrations have been developed to display hyper-text based text. This eliminates the need to ask the user many questions about design procedure including assumptions which appear meaningless to a novice user.

3.3.2 Knowledge Base

The KB has rules for design and program-flow tasks as outlined in figure 3.4. Since CLIPS is a rule-based production-level expert system, most of the knowledge in the knowledge base is represented in the form of rules: other forms include COOL objects
and facts as explained in section 2.4 of the previous chapter.

Figure 3.4 View of the different KB modules in the Expert System

The knowledge represented here falls broadly into two categories: meta-knowledge and design-knowledge. The meta-knowledge consists of program intricacies about different software-modules, as shown in figure 3.4. It deals mainly with general issues such as user-interface control and circuit simulation, which are applicable to any power electronic system design. These meta-knowledge issues are explained in sections 3.3.3 to 3.3.6. Design-knowledge belongs to a particular domain of application, and is focused here on the design tasks for switched-mode power supplies. Rules included here handle tasks such as selection and design for an appropriate converter topology, and design of magnetic components: these are explained in chapters 4 to 7.

### 3.3.3 Design Validation Sub-system

A simulation is carried out to validate the design of the converter stage, and the simulation results are processed to check for any violation of specifications. Figure
3.5 shows the overall design validation environment. *Design Validator*, a KB module in *XpertPSD*, checks for any violations of the specifications. When violations are detected, this sub-system will diagnose possible causes and suggest appropriate design modifications. As shown in the figure 3.5, *Task Controller*, a sub-component of the *Design Validator*, handles requests from different parts of the ES:

2. Processing of simulation data.
3. Displaying simulated circuit variables graphically.

The above tasks are explained in the following sections (3.3.4 - 3.3.6).

![Diagram](image)

*Figure 3.5 Elements of the design environment*

### 3.3.4 The Simulation Workbench

A SPICE circuit simulator is used to simulate the various circuits. SPICE performs non-linear dc, non-linear transient, and linear ac small signal analyses [52]. SPICE (an acronym for Simulation Program with Integrated Circuit Emphasis), is used in the present work as it has robust algorithms, it is supported for different computer platforms, and it is an industry-standard. In the simulation of power electronic systems, features such as transient and small-signal analyses are extensively used to study the effects of component parasitics on circuit performance, and small-signal loop gain characteristics.
**Simulation Workbench** is an assembly of several simulation routines (figure 3.6) which are co-ordinated by the **Task Controller**. These routines are programmed in CLIPS with the exception of **SPICE Simulator**, which is an external C program. These simulation tasks are placed in the KB module, **Simulation**, as shown in the figure 3.4.

![Simulation Workbench](image)

To validate the design of a circuit, its netlist must be prepared, checked for mistakes, and then simulated. A netlist is prepared automatically using the **Netlist Generator**, an **XpertPSD** rule-module, which contains the knowledge to generate SPICE netlists covering all design stages of a number of common converter topologies. Figure 3.7 shows the sequences in this knowledge-based simulation cycle.

To facilitate modifications by the user, a text-editor, **Netlist Editor**, is included. The editor first checks for mistakes in the netlist before it is displayed to the user. Features to edit the netlist are included such as copy, cut and paste, but editing is restricted to the circuit element values, and does not extend to node numbers or names of circuit elements. In case the user has committed errors in editing, the netlist is again verified for mistakes before the simulation is carried out. Figure 3.8 shows the editor displaying a netlist.
To enhance understanding of the design process, *Schematic Generator* displays a schematic in a separate window (figure 3.8). This schematic represents the netlist generated by the *Netlist Generator*. Currently, the *Schematic Generator* does not allow editing of the schematic.

The netlist contains references to SPICE sub-circuit models employed in the simulation: all power MOSFET models are referenced in this way in the netlist. The *Pre-processor* processes all sub-circuit calls in the netlist, and is invoked after the user
starts the simulation. The processed netlist is then supplied to the SPICE-simulator which is linked to the Design Validator.

When the simulation fails, the simulator will write all possible reasons (errors and warnings) responsible for the failure into an ASCII file, called the error file, and then exits. Most potential errors are related to the convergence of the simulator algorithms, since there should not be syntax errors after the double-checking of the netlist by the Netlist Generator. Frequently occurring errors are shown in table 3-1.

The Simulation Assistant identifies the above errors by reading the error file using a key-word searching strategy. For example, when there is an error ‘Time step too small’, the key-word in this is ‘Time step’ and ‘small’. After identifying the errors, possible remedies are suggested. Figure 3.9 shows the Simulation Assistant displaying errors with suggested remedies.

This simulation cycle continues until a successful simulation has been achieved. When the errors are not within the scope of the ES, control is passed back to the user. The simulation environment is fully interfaced with the ES, and can be used either as a stand-alone or as an integrated simulator.
Table 3-1 Frequent SPICE-simulation errors

<table>
<thead>
<tr>
<th>Simulation Error</th>
<th>Remedies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step time less than or equal to zero</td>
<td>Check the step-time on the transient analysis control statement</td>
</tr>
<tr>
<td>Time step too small</td>
<td>Increase the step-time or increase the ‘RELTOL’/ITL4 optional parameters</td>
</tr>
<tr>
<td>No definition of model</td>
<td>Verify all sub-circuit calls</td>
</tr>
<tr>
<td>Gmin stepping/Source stepping failed</td>
<td>Check all element connections and increase ‘ITL1’, an optional parameter</td>
</tr>
<tr>
<td>Singular matrix</td>
<td>‘Renet’ the netlist removing any duplicate node numbers</td>
</tr>
<tr>
<td>Singular matrix. Trying alternate initialisation</td>
<td>Check the initial conditions specified</td>
</tr>
</tbody>
</table>

Figure 3.9 Trouble-shooting a simulation failure

Use of macro simulation models

Since simulation of circuits by real models (sometimes called brute-force simulation) may take a long time, all the initial design stages are simulated with macro-models [53-55]. Average macro-models are used to predict overall system response, whereas switched macro-models are used to measure open-loop characteristics and device stresses. Appropriate average models have been developed for power MOSFETS,
power diodes and power supply controllers [56-78]. All the models are treated as sub-circuits and are placed in the netlist whenever referenced by the Pre-processor.

3.3.5 Data Processor

Various circuit characteristics require careful examination such as the open-loop performance, and the step-load response. Since CLIPS is not efficient at handling large quantities of simulation data, external software utilities are included in the Data-processor to process the data. The various data-processing utilities, as shown in figure 3.10, are explained below.

Figure 3.10 Interaction of Data Processor program modules with the Task Controller

1) Post-processor: After a successful simulation, the simulator writes all the results to an output file. The results are then formatted by the Post-processor, a C-language routine. The Post-processor removes all overhead information from the SPICE-simulation data, and writes data in columns into a data file. This data file is used by
several programs of the data processor to process the results.

2) **Open-loop Response Evaluator** (ORE):- This module estimates average, minimum, maximum, and ripple-content of all specified open-loop output variables, such as output voltage and inductor current.

3) **Bode Knowledge Evaluator** (BKE):- Since adequate gain and phase margins are required for stable operation, it is necessary to evaluate these by constructing the Bode plot of the system. The BKE constructs the Bode plot from small-signal frequency analysis and displays the gain and phase margins.

4) **Closed-loop Response Evaluator** (CRE):- This routine is executed after obtaining the converter closed-loop simulation results. It determines the overall closed-loop system response from the time-domain simulation data. Various closed-loop indicators are observed, such as the settling time, overshoot and undershoot of the output voltage for a step-load change.

5) **EMI Emission Evaluator** (EEE):- This module estimates the conducted common-mode and differential-mode emission levels at the input of the converter. It first constructs the emission spectrum, giving emission levels at different frequencies by applying a Discrete Fourier Transform (DFT) to the transient simulation data [79]. The DFT converts time-domain data into corresponding frequency-domain data. Different emission levels are then read off at the frequencies required.

Whenever there is a need to process simulation data, the **Design Validator** executes the data processing utility using the CLIPS external-program calling mechanism. All calculated results are written into the 'results-file'. The **Design Validator** reads this file and loads the results into memory for design verification.

### 3.3.6 Graphical Display System

Results (e.g. simulation results) are displayed graphically to the user using GNUPLOT [80]. GNUPLOT is a command-driven interactive function plotting program which can be used to plot functions and data in two- and three-dimensional plots in a variety of formats. This accommodates many of the needs for graphic data representation. As it is a "freeware" package, well supported for a large number of graphics file formats.
and operating systems (Unix, VAX/VMS, OS/2, Amiga, MS-Windows, Macintosh), it is used in the present work.

GNUPlot can display columns of data stored in a data file. All specification and coordinate axis information, (e.g. axes names and scaling) are mentioned in the plot-file, in the form of GNUPlot-specific syntax, at execution. The Pre-plotter, a CLIPS knowledge-module, contains rules to prepare the plot file for different types of analysis and data formats. Figure 3.11 shows the GNUPlot displaying waveforms.

![GNUPlot displaying waveforms](image)

**Figure 3.11 GNUPlot displaying waveforms**

### 3.3.7 Databases

The design of power supplies requires selection of suitable components, such as power semiconductor devices, filter capacitors, and magnetic cores. Manual search based on optimum ratings and prices from manufacturers’ databooks can be lengthy and tedious, as there are usually several similar devices from each manufacturer which may appear appropriate for a given application.

Device selection is aided by databases of component details, with automatic interactive searches. Since considerable decision making is required when choosing an appropriate device, an expert system search assists with the choice.
Development of databases
All databases have been developed with graphical front-ends. The databases contain electrical data (e.g. voltage, current and power ratings) required for the design, manufacturer and price. Table 3-2 represents a sample power MOSFET database.

Table 3-2 A sample record of power MOSFET database

<table>
<thead>
<tr>
<th>Part</th>
<th>Make</th>
<th>Cost ((£))</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRF730</td>
<td>IR</td>
<td>2.25</td>
<td>400</td>
<td>5.5</td>
<td>74</td>
</tr>
<tr>
<td>IRF740</td>
<td>IR</td>
<td>2.67</td>
<td>400</td>
<td>10</td>
<td>125</td>
</tr>
<tr>
<td>2SK962-10</td>
<td>TOSHIBA</td>
<td>6.8</td>
<td>1000</td>
<td>10</td>
<td>200</td>
</tr>
</tbody>
</table>

The databases are created in ASCII-format using a text-editor with each field separated by a space. This facilitates portability of the design package to other machines without the need for commercial database packages. The names of the various databases are shown in figure 3.12. Each database is explained as and when it is used.

![Figure 3.12 Profile of different databases in the ES](image)

Graphical data representation
Some component characteristics (e.g. magnetic core selection graphs) are presented graphically in the databases. These are produced by subjecting the graph to the
CHAPTER 3: DESIGN AND DEVELOPMENT OF XpertPSD

process explained below. As shown in figure 3.13, there are four conversion stages:

- Any graph to be represented in a database is first converted into a bitmap file by scanning the whole graph using a PC-based Hewlett-Packard scanner.

- The image-file is then digitised using a program called WinDIG [81]. WinDIG can recover numerical values from a graph by retracing. After loading an image-file into the program and defining the mapping of the co-ordinate system, the WinDIG digitises the graph into respective co-ordinate pairs, and saves all the points in an ASCII data file.

- GNUPLOT converts this data to a polynomial equation of a “best-fit” curve. This programme lists the degree of the equation along with its coefficients.

- These coefficients are stored in the database. Whenever this type of database is accessed, an equation of the form “y = f(x)” calculates any unknown co-ordinate point.

**The database interaction**

The database files are accessed using input/output interface functions in CLIPS called I/O routers. This system provides very flexible input/output access while remaining
portable. Each database file is an I/O device, and is assigned a logical name which is used in accessing, searching and closing the database. The I/O functions used here are 'open', 'close', 'read', and 'readline' [82]. Figure 3.14 shows the flow of information among the ES modules.

![Figure 3.14 Database interaction in the ES](image)

The data retrieved from the databases are stored in object oriented classes constructed in CLIPS. Each database has its own class and associated slots to hold information contained in the different fields of the database. In this representation, objects of the class represent different devices.

Whenever there is a need for data, the expert system searches databases as shown in figure 3.15. The knowledge base contains sufficient rules to identify the type of device and its associated database. The corresponding database is then opened and searched to find devices to satisfy the search criteria.

The data obtained is displayed to the user. For this, GUI front-ends have been developed for all databases. Dialog-boxes and message-boxes are extensively used to show the data flowing into and out of the databases. Figure 3.16 shows a front-end for a power MOSFET database.

The user can accept the data or search again using a different search criterion; for instance, increasing voltage rating limit when searching for power diodes. If the search fails at any time, control is passed back to the user.

As there will be a need to update databases, the database interface provides facilities for updating of existing databases, and also construction of new databases.
Figure 3.15 Steps in data retrieval from databases in the ES

Figure 3.16 A front-end for a power MOSFET database
4.1 OVERVIEW

Design of switched mode dc power supplies is supported in the current expert system as they are typical power electronic systems. As explained in the previous chapter, the design process is split into different modules, and each module is tackled separately before integrating the modules. The software currently designs buck and forward converters, but could readily be extended to cover other converter topologies. This chapter explains the design of the power circuitry, including analysis of the specifications, selection and design of a suitable converter, and component choice.

4.2 THE DESIGN METHODOLOGY

The power circuitry of a typical switched mode power supply system consists of input and output rectifiers, dc-dc conversion and output smoothing filter as shown in figure 4.1. The input ac voltage is rectified into an unregulated dc voltage by a diode bridge rectifier. A capacitor filter at the output of the rectifier filters the ripple in the dc voltage. The dc-dc converter then converts the unregulated input dc voltage to a regulated dc voltage at another level.

Figure 4.2 shows the design methodology adopted in the expert system. The design
starts with seeking the specifications from the user. After carrying out the design, the converter is simulated and verified for violations of the specifications as explained below.

![Diagram of a typical switched mode power supply](image)

Figure 4.1 Power circuitry of a typical switched mode power supply

![Flow-chart of the power converter design methodology](image)

Figure 4.2 Design methodology flow-chart of the power converter
4.3 POWER SUPPLY DESIGN SPECIFICATIONS

The ES obtains the power supply specifications in several stages as explained below.

4.3.1 Input Specifications

The ES requests the input specifications from the user in two stages. In the first stage, the user is asked to input (figure 4.3):

- type of input to the power supply (whether ac or dc) and
- the number of outputs (an optional specification).

![Figure 4.3 ES dialog-box seeking the input specifications](image)

The ES subsequently requests:

1. **Input voltage levels.** The levels required include nominal, maximum and minimum values.

2. **Supply frequency.** If the power supply is ac, its supply frequency, either 50 or 60 Hz, is also requested.

3. **Temperature range.** The working temperature range of the power supply needs to be specified as this affects the design of the power supply. The temperature inside the power supply is likely to be considerably higher than the ambient temperature.

4. **Efficiency.** Efficiency of a power supply typically varies from 60 to 80%. The user needs to specify the target efficiency. Too ambitious a specification may result in an uneconomical power supply. The efficiency, \( \eta \), of a power supply is:

\[
\eta = \frac{P_{out}}{V_{ac(rms)} \times I_{ac(rms)} \times pf}
\]

Equation 4-1
where:

\[ P_{out} = \text{total power output of the power supply} \]

\[ V_{ac(rms)} = \text{rms input voltage} \]

\[ I_{ac(rms)} = \text{rms input current} \]

\[ pf = \text{power factor of the circuit} \]

When estimating the input current, the ES suggests a suitable value for the power factor.

### 4.3.2 Isolation Requirements

It is usually necessary to isolate ac main voltages from the low voltage loads by using a transformer.

Although a transformer adds considerably to the size and weight, and also to the losses of the SMPS, the ES employs an isolation transformer when the input supply is ac.

### 4.3.3 Switching Frequency

There are no absolute rules for the selection of a particular switching frequency. High frequency operation is distinctly advantageous in that weight and volume of wound components and output filter capacitor are reduced, and transient response is improved. However, high frequency operation is limited by a reduced efficiency due to switching losses in the semiconductor switching devices, increased hysteresis and eddy current losses in the transformer core, and increased EMI. Consequently, a compromise must be made between the reduced efficiency at high frequencies and the reduced cost, size and weight of the magnetic components and filter capacitor. It is desirable to operate above 20 kHz to eliminate audio noise.

The ES suggests a switching frequency of 100 kHz which is typical for many applications. However, this can be adjusted by the user.

### 4.3.4 Output Specifications

The ES guides the user, as shown in figure 4.4, to enter the following specification for
each output:

1. **Voltage and current ratings.**

2. **Output ripple voltage.** This is expressed as a peak-to-peak voltage, at the fundamental switching frequency.

3. **Voltage regulation limits.** This is the steady state output voltage regulation.

4. **Step load change.**

5. **Transient response time.** This is the time required for the output voltage to settle to within the specified regulation limits, after a step change in load current.

![Figure 4.4 The ES dialog-box for entering output specifications](image)

**4.3.5 Realistic Analysis of the Specifications**

A cost-effective design needs a thorough understanding of the customer’s specifications. The customer may sometimes give a specification considerably more stringent than required, leading to an over-expensive design.

For instance, if a power supply with two outputs, one with specified output voltage of 5 volts with a minimum of 1 amp and a maximum current of 12 amps, and the other with a specified output voltage of 12 volts with a minimum current of 0 amp and maximum of 1 amp, is designed to meet all the extreme variations of the loads for the outputs, then a very expensive power supply will be the end result. But if the specification is queried, it is likely that some of the extreme combinations cannot in reality ever occur.
It is common to connect external resistors across a load, called pre-loading of a power supply, to avoid large values of filter inductance when the minimum load current is less than 5% of the maximum load current. For a chosen topology, actual load permutations are made to check whether the pre-load is unnecessarily large, and the designer is then advised to change the specification. This avoids add-on cost, and increases the efficiency of the power supply system. Similarly, other specification parameters must be clearly understood before proceeding with the design. The ES queries each specification, and suggests modifications to the user.

### 4.4 SELECTION OF CONVERTER

Converter selection is based on the power throughput and the requirement for transformer coupled circuits for isolation and/or multiple outputs. Power throughput is the total power output for all converter outputs. The knowledge base selects a suitable converter [83-85] for the application shown in figure 4.5.

![Figure 4.5 Knowledge-flow graph of converter selection criteria](image)

Figure 4.5 Knowledge-flow graph of converter selection criteria
The system lists possible converters and advises on the most suitable (figure 4.6). The ES also allows the user to overrule the choice and to select a different converter.

![Suitable Converter Window](image)

**Figure 4.6** The ES window asking the user to select a converter

### 4.5 INPUT RECTIFIER DESIGN

The input rectifier converts the ac mains voltage into unregulated dc voltage using a four diode bridge rectifier as shown in figure 4.7. The centre-tapped capacitor network along with the switch allows the power supply to operate either from a 220-240 voltage ac input (switch opened), or a 110 voltage ac input (switch closed). The capacitors are commonly known as bulk or reservoir capacitors.

![Four Diode Bridge Rectifier](image)

**Figure 4.7** Four diode bridge rectifier

When the switch is opened, the rectifier will operate as a standard diode bridge
rectifier, and when the switch is closed, the rectifier output voltage is twice the peak capacitor voltage. The following sections explain the rectifier design with voltage doubling (operation with voltage doubling is usually more demanding than full bridge operation).

4.5.1 The Rectification

Voltage drops occur between the mains supply and bulk capacitors due to the following parasitic resistances:

1. Inlet socket contact resistance
2. Fuse clip contact resistance
3. Thermistor residual resistance
4. PCB track resistance
5. Common- and differential- mode choke winding resistances in the input EMI filter

The above resistances typically total a fraction of 1 Ω [51], and cause a voltage drop, $V_r$. The resulting voltage drop must be taken into account when calculating the net rectifier output. The peak voltage drop due to the above resistances is:

$$V_r = R_{drop} \times I_{ac(\text{peak})}$$

where:

$R_{drop} = \text{total parasitic resistance}$

$I_{ac(\text{peak})} = \text{peak input current}$

$I_{ac(\text{peak})}$ is given by:

$$I_{ac(\text{peak})} = \frac{I_{ac(\text{rms})}}{\sqrt{T_c/T_{\text{main}}}}$$

where:

$T_c = \text{charging period of each capacitor}$

$T_{\text{main}} = \text{mains supply period}$

The $I_{ac(\text{peak})}$ is calculated by assuming that the input current flows for 25% (for operation with voltage doubling) of the total input cycle.

There is also a dynamic forward voltage drop $V_d$ across each diode which depends upon the diode current rating. Considering the worst case, this can add another 1V
dropped across each diode. The parasitic resistance voltage drop and the dynamic voltage drop reduces the net available ac voltage. The effective peak voltage across each bulk capacitor is thus:

\[ V_{p-cap} = V_{ac(peak)} - (V_r + V_d) \]  

Equation 4-4

where:

\( V_{ac(peak)} \) = peak input ac voltage

The maximum value, \( V_{dc(max)} \), and the minimum value, \( V_{dc(min)} \), of the total rectified output voltage are (for operation with voltage doubling):

\[ V_{dc(max)} = 2 \times V_{p-cap} - \Delta V/2 \]  

Equation 4-5

\[ V_{dc(min)} = 2 \times V_{p-cap} - (3/2)\times\Delta V \]  

Equation 4-6

where:

\( \Delta V \) = the peak ripple voltage. Under the worst case condition, this is assumed to be 40 volts: however, the user can adjust this figure.

The ES shows the assumptions made to the user for possible modification. The approximate average dc voltage is:

\[ V_{dc} = (V_{dc(max)} + V_{dc(min)})/2 \]  

Equation 4-7

There are power losses associated with the above voltage drops. Considering these losses, the net rectifier output power is:

\[ P_{dc} = P_{in} - (I_{ac(rms)}R_{drop} + I_{ac(rms)}V_{d-rms}) \]  

Equation 4-8

where:

\( V_{d-rms} \) = rms value of the diode voltage drop

4.5.2 Bulk Capacitor

The bulk capacitance influences the low-frequency input ripple voltage at the converter stage and also the hold-up time. Hold-up time (or hold-over time) is the length of time a power supply can maintain its rated output voltage during an interruption to the input. The total composite capacitance required is given by:

\[ C_{total} = (I_{dc} \times T_d)/\Delta V \]  

Equation 4-9

where:

1. \( I_{dc} \) = the average dc current. This dc current is calculated after taking into account
the various losses involved in the input EMI filter and the rectifier. The average dc
current is:

\[ I_{dc} = \frac{P_d}{V_{dc}} \]  

(Refer to figure 4.7)  

Equation 4-10

2. \( T_d \) = discharge time. This is the time during which each capacitor supplies energy in
a cycle of the mains supply. The ES assumes that the \( T_d \) is equal to 87% (with voltage
doubling) of the mains supply period as a judicious choice.

High-grade electrolytic capacitors with high ripple current capacity and low ESR are
used with a working voltage of 200 V dc minimum. A resistor across each capacitor is
connected to provide a discharge path when the supply is switched off.

The ES notifies the rectifier design results to the user giving an option to select a
suitable reservoir capacitance as shown in figure 4.8.

![Figure 4.8 The ES showing the design results of the input rectifier](image)

4.5.3 Selection of Rectifier Diodes

Either a diode bridge package or four discrete diodes can be used. If there is no space
problem on the printed circuit board, it is more cost-effective to use individual diodes
than a bridge package. Rectifier selection is based on the following electrical ratings:
1. Maximum forward current capability.
2. Peak-inverse voltage blocking capability.
3. Surge current rating.

The expert system searches for suitable diodes from the `diodes.dbk` database which contains electrical data of rectifier diodes from different manufacturers.

The system also offers advice on the PCB-assembly of the diodes:

- The polarities of the individual diodes and capacitors on the PCB should be aligned in the same orientation as a measure of designing for manufacturability.

- For improved reliability, the leads of individual diodes should be preformed at an appropriate distance from the body of the diode to reduce both thermal and mechanical stresses on the diodes.

4.5.4 Design Validation

The ES validates the design of the diode bridge, checking the output voltage level after rectification and allowing for losses. The system also tests the circuit for the specified hold-up time as explained in the following sections.

**Rectifier output voltage**

The ES simulates the rectifier, and processes the results for validation of the design. When the rectifier output voltage is too low, the embedded knowledge diagnoses possible reasons:

- inadequate input voltage, or,
- insufficient bulk capacitance.

The ES also suggests a remedy:

- When the input voltage is too low, the user will be prompted to modify it suitably.
- When the bulk capacitance is too small, the KB suggests a suitable value for consideration by the user. The design will be repeated in both cases.

**Hold-up time**

The ES calculates the hold-up time, $t_h$, using:

$$ t_h = \frac{C_{total} (V_{dc(max)}^2 - V_{dc(min)}^2)}{2 \times P_{in}} $$

where:
When the hold-up time is less than the specified value (typically 28msec), the expert system advises that a larger capacitance should be used.

4.6 OUTPUT FILTER DESIGN

The output filter converts the rectangular voltage waveform at the filter input to a dc output with a low ripple content. The main components of the filter are an inductor and a capacitor as shown in figure 4.1. After successful validation of the input rectifier design, the ES designs the filter as explained below.

4.6.1 Filter Inductor

The ES selects a suitable value of inductance based on:

- the output voltage,
- the duty ratio, and
- the allowed ripple current.

The inductance determines whether the power supply operates in a continuous or discontinuous current mode. For the buck family of converters, the minimum value for continuous mode operation is:

$$L_{\text{min}} \geq \frac{V_o (1 - D_{\text{min}})}{2 \times f_s \times I_{o-\text{min}}}$$

Equation 4-12

where:

- $V_o$ = output voltage
- $D_{\text{min}}$ = minimum duty-cycle
- $f_s$ = switching frequency
- $I_{o-\text{min}}$ = minimum output current

There is also an upper limit to the value of inductance. To prevent excessive transient recovery times after sudden load changes, the allowed maximum inductance [86] is:

$$L_{\text{max}} \leq \frac{V_o \times T_{tr} \times (D_{\text{max}} / D_{lc} - 1)}{I_{o-\text{max}}}$$

Equation 4-13

where:

- $T_{tr}$ = transition time
- $D_{\text{max}}$ = maximum duty-cycle
- $D_{lc}$ = load current
- $I_{o-\text{max}}$ = maximum output current
\( D_{lc} \) = duty ratio during the load change  
\( T_{tr} \) = transient response time desired during a sudden load change. Typically:

\[
T_{tr} = (5 \text{ to } 20)T_s
\]  
where:

\( T_s \) = switching period

**The inductor-current mode selection**

After calculation of the above boundary inductance, the system advises the user whether to operate the converter in the continuous or discontinuous mode. The ES takes account of the advantages and disadvantages of each as shown in Table 4-1.

**Table 4-1 Advantages and disadvantages of continuous and discontinuous modes of operation**

<table>
<thead>
<tr>
<th>Continuous mode</th>
<th>Discontinuous mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>• less output ripple current</td>
<td>• excellent closed-loop response</td>
</tr>
<tr>
<td>• good open loop load regulation</td>
<td>• high peak current</td>
</tr>
<tr>
<td>• poor small signal response</td>
<td>• poor open loop load regulation</td>
</tr>
</tbody>
</table>

Since not all converters can be operated in both modes, the knowledge-base suggests the following:

1. **The buck-family converters should be operated in the continuous current mode, not withstanding the poor closed-loop response (because of its second-order filter characteristic).** This mode results in a small output ripple current, easy filtering, substantially reduction in the output capacitor ESR and current rating requirements. The closed loop response is considerably improved by operating the converter with current mode control.

2. **The boost, buck-boost, and flyback converters are normally operated in discontinuous mode as this results in more stable operation due to the elimination of the RHP zero [87].**

**Pre-loading**

In applications where the minimum current is very small, the expert system suggests two alternatives:

1. **Pre-loading.** In this, the minimum current is raised by pre-loading the power
supply although this reduces its efficiency.

2. **Discontinuous-mode.** In this alternative, the converter is allowed to go into discontinuous mode when the minimum current becomes less than 5% of the maximum load current.

The ES checks the minimum output currents and suggests pre-loading the power supply if the output current falls below 5% of the maximum value. The designer can override the pre-loadings and allow the power supply to operate in the discontinuous mode. Figure 4.9 shows an interactive session during which outputs are checked.

![Checking Inductor Currents](image)

**Checking Inductor Currents**

Output

- 5.0V OUTPUT
- 3.3V OUTPUT
- 12.0V OUTPUT

You need to check the inductor currents (A) to set proper circuit options. Select any output.

- [ ] Checked
- [ ] Advice
- [ ] Help

![Checking 3.3V Output](image)

**Checking 3.3V Output**

Min Inductor current (A): 0.00

Max Inductor current (A): 16.00

The minimum inductor current is zero. You may have to use any of the following options.

- [ ] Pre-load the output
- [ ] Discontinuous mode at light load
- [ ] Use very large inductance

Select one of the options below:

- [ ] OK
- [ ] Advice
- [ ] Help

Figure 4.9 The ES dialog-box checking for any pre-loading requirements

When the user selects a pre-load for the power supply, a suitable pre-load resistor is calculated. The minimum inductance is modified by adjusting the minimum current requirement to 5% of the maximum load current. The calculated minimum and maximum inductances are then presented to the user for a final selection. The KB suggests selecting the final inductance value giving a margin of at least 10% over the calculated minimum inductance value.
4.6.2 Smoothing capacitor

The capacitor minimises the ripple content in the output voltage. The ac component of the inductor current flows through the capacitor. The ES selects a suitable value of capacitance to maintain the ripple voltage within the specified limits.

Based on charge storage considerations in the capacitor, the minimum capacitance for the buck-family of converters is:

\[ C = \frac{V_o}{\Delta V_o} \times \frac{(1 - D_{\text{min}})}{8 \times L \times f_s^2} \]

Equation 4-15

where:

\( \Delta V_o \) = allowed peak-to-peak ripple voltage

\( L \) = filter inductance selected

The capacitance given by the above equation is accurate only when the capacitor is ideal, i.e., without any effective series resistance (ESR) and effective series inductance (ESL). At high switching frequencies (greater than 300kHz) these conditions are closely met by polypropylene dielectric capacitors. Correction must be made to allow for parasitic series resistance and inductance when electrolytic capacitors are used. At medium frequencies (for instance 100 kHz), the ESR is the single most dominant factor in choosing a capacitor, with the effect of the ESL being negligible.

Capacitor ESR

Since the voltage drop across the ESR is the dominant component of the ripple voltage, the selection of the capacitor should be based on the ESR requirement. This requires using a capacitance much greater than the minimum value calculated based on the electrostatic consideration in equation 4-13. There are two possible methods to arrive at the allowed capacitor ESR:

1. Ripple voltage. For a specified ripple voltage and inductor ripple current, the allowed ESR of a capacitor is:

\[ ESR \leq \frac{\Delta V_o}{\Delta I} \]

Equation 4-16

where:

\( \Delta I \) = capacitor peak-to-peak ripple current
2. Surge load condition. Capacitor ESR is sometimes determined not by the ripple current but by the step load. A severe step load will cause an initial dip in the output voltage far in excess of the ripple voltage (in subsequent cycles this will be corrected by the feedback loop increasing the pulse width). In this case, the ESR of the capacitor must be selected to keep any output voltage deviations due to step load changes within the specified limit:

\[
ESR \leq \frac{\Delta V_{\text{step}}}{\Delta I_{\text{step}}}
\]

Equation 4-17

where:

\[\Delta V_{\text{step}} \] = allowed peak-to-peak output voltage deviation

\[\Delta I_{\text{step}} \] = peak-to-peak step load change in amperes

As it is necessary to test both the above cases, the software calculates the allowed ESR for each case and selects the one which has the most stringent requirement (i.e., produces the lowest value of ESR).

The capacitor should have a voltage rating in excess of the output voltage. The other rating required of a capacitor is its alternating current or ripple current rating. Since the ripple current is of a triangular waveform, the r.m.s. ac current rating of the capacitor in terms of its peak-to-peak ripple current is:

\[
I_{C-\text{rms}} = \frac{\Delta I}{2\sqrt{3}}
\]

Equation 4-18

4.6.3 Choosing the Filter Components

The ES submits the calculated filter details for final acceptance as shown in figure 4.10. The ES allows the user to change the inductor or capacitor values if required. To achieve a specific ripple content requires a specific LC product, independent of load current. Although this can be achieved with a variety of combinations of L and C, high inductance with low capacitance or low inductance with high capacitance, the ES advises small inductance and large capacitance for the following reasons:

1. With high frequencies and high power throughputs, it is more expensive to store energy in an inductor than in a capacitor. Also, an inductor will have considerably
greater weight and volume than a capacitor with an equal energy storage capacity (losses in a practical inductor are higher than in a capacitor with equal energy storage capacity, assuming low ESR).

2. Small L/C ratios results in a better transient behaviour for step changes in load current.

The above advantages outweigh the only disadvantage of using low L/C ratio: i.e., the large overshoot in input current on start-up, when the circuit is first energised [88]. This necessitates the use of current-limiting circuits to prevent this inrush current.

![FILTER DESIGN](image)

Figure 4.10 ES dialog-box showing selection of output filter components values

**Selection of the filter capacitor**

After accepting the design results, the system prompts the user to select a standard and available capacitor which should satisfy:

1. minimum capacitance,
2. voltage rating,
3. ESR requirement, and
4. ripple current rating.

In the present work, the database, `cap.dbk`, contains the ratings and manufacturer’s details of several electrolytic capacitors, and is linked with the expert system. The user can choose any readily available capacitor or ask the ES to search the database, as shown in figure 4.11.
CHAPTER 4: DESIGN OF SMPS

The output under consideration: 5.0V

Select a standard capacitor which meets the ESR requirement.

Specs. of the filter capacitor required:

- Min. Capacitor Value (uF):
- Required Voltage Rating (Volts):
- Required Ripple Current Rating (mA):
- Maximum ESR Allowed (ohm):

Search

Figure 4.11 The ES window displaying standard values for output filter capacitance

When there are no suitable capacitors available, the system advises the use of multiple capacitors in parallel, as this arrangement eases the ESR requirement of each capacitor. This is also advantageous in that a single capacitor of equivalent capacitance often has a considerable height, which may lead to construction difficulties. However, a compromise has to be made as this arrangement requires a larger mounting area. The ultimate choice rests with the cost: the system makes a cost comparison of the two arrangements, and the less expensive one is preferred.

4.7 MAIN SWITCHING DEVICE SELECTION

Fast switching power transistors and diodes are required for good efficiency in high frequency regulators. Conduction and switching losses in the transistors and diodes form the major component of total losses: careful selection of appropriate devices is therefore critical in producing an efficient power supply.

4.7.1 Power MOSFET

Power MOSFETs are generally used as the main power switching devices as these possess extremely fast switching characteristics, and require only a simple drive
circuit. A database, *powmos.dbk*, of power MOSFETS has been developed and integrated within the expert system. The database contains the electrical ratings and switching times of MOSFETS from different manufacturers. The user can interactively pursue the selection of a suitable MOSFET based on a search criterion of the following:

1. voltage blocking capability, and
2. current carrying capability (rms).

These parameters are determined by the type of converter in which the transistor will be used. For example, in a forward converter with a tertiary reset winding, the MOSFET has to block a voltage twice that of the maximum unregulated dc voltage, and the rms current carrying capability should be more than the maximum rms primary current of the transformer.

The ES displays the devices that satisfy these ratings. When there are several similar devices available, the embedded knowledge advises selection of the most suitable device based on cost. The ES allows the user either to modify the search criteria and search again or enter the data of a device not currently available in the database, as shown in figure 4.12.

<table>
<thead>
<tr>
<th>Suitable MOSFETs</th>
<th>Part Number</th>
<th>Voltage Rating (V)</th>
<th>Current Rating (A)</th>
<th>On-state Resistance (ohm)</th>
<th>Manufacturer of the Device</th>
<th>Price of the Device (UK Pound)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ20</td>
<td></td>
<td>50</td>
<td>15</td>
<td>0.08</td>
<td>IR</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Figure 4.12 The ES dialog-box showing suitable the power MOSFETs
4.7.2 Rectifier Diodes

The selection of the output rectifier diodes is as important as that of the power switching device, as the diode losses usually exceed the transistor losses. Optimum choice of the rectifying diode results in improved efficiency, reduced transistor stresses, EMI content, and cost.

The forward voltage drop of the diodes must be very low to optimise the efficiency, especially at low output voltages. As a part measure to reduce EMI, an ultra-fast device with a moderate recovery time is often the best choice.

Schottky diodes are widely used in SMPS due to their inherently lower forward voltage characteristics compared with pn junction diodes, and their fast reverse recovery time. Their limitations in peak inverse voltage, transient voltage capability and temperature make them unsuitable for high power applications.

In the ES, a database of Schottky and fast pn junction diodes from different manufacturers is included in the ES. The user can select interactively any suitable diode based on the following electrical ratings:

1. **Peak inverse voltage.** This is the maximum peak inverse voltage that can be applied across the diode, without exceeding the diode rated reverse leakage current. The rating of each diode should include a safety factor of 1.2 to 2.

2. **Maximum rated forward current.** This is the maximum average forward current that the diode may carry, with a specified current waveform (normally rectangular, with a 50% duty cycle), at a specified temperature [89].

3. **Reverse recovery time.** This must be less, preferably by a factor of at least 3, than the rise time of the transistor with which it will be used to minimise peak recovery current and switching loss.

As with the power switching devices, the above ratings depend upon the converter used. Table 4-2 shows the ratings for different converters [90-91]. The database interaction is similar to that for the power MOSFET, where the user can choose a suitable device suggested by the ES.
Table 4-2 Output rectifier voltage and current ratings

<table>
<thead>
<tr>
<th>Converter</th>
<th>Peak Inverse Voltage</th>
<th>Main diode max. average current</th>
<th>Freewheel diode max. average current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buck</td>
<td>$1.2V_{in\text{-}max}$</td>
<td></td>
<td>$(1-D_{min})I_{o\text{-}max}$</td>
</tr>
<tr>
<td>Forward</td>
<td>$1.2(V_0 + V_F)V_{dc\text{-}max}$ [\frac{V_{dc\text{-}min}}{D_{max}}]</td>
<td>$D_{max}I_{o\text{-}max}$</td>
<td>$(1-D_{min})I_{o\text{-}max}$</td>
</tr>
</tbody>
</table>

4.8 DESIGN VALIDATION

The embedded rules in the KB check that the choice of components does not result in a violation of the design specification.

After the design of the power stage and the selection of components, the expert system initiates the validation. As shown in figure 4.13, the system allows the user to skip the validation of any design stage.

![Design Validation](image)

The Output Under Consideration: 5.0V
To verify the design, the converter will be simulated without closing the feedback loop and the following specifications will be verified:
1. Output Voltage
2. Ripple Voltage
3. Inductor Current

Select next task:
- Validate the design of the converter
- Skip the validation of the design

Figure 4.13 The user can control design validation of any power circuit

The ES uses its knowledge of a particular converter design to select and adjust the component that would best eliminate violations of the design specifications. It suggests possible remedies, and examines their ramifications if carried out.

In the open loop configuration of the converter, the output performance parameters:
Output voltage, inductor current, and ripple voltage are verified, and if any violations are found the design is altered.

To minimise the complexity of the simulation and verification, the ES considers each output of the converter separately. Using the embedded simulation knowledge of the converter, the ES carries out a simulation of the converter stage to study the open-loop performance. After a successful simulation, the external open-loop results processor, Validate, processes the simulation results and supplies the processed results to the ES. Using its knowledge base, the system then starts comparing the simulation results against the desired specifications.

4.8.1 Output Voltage

Output voltage is checked first as it affects the remaining two specifications, i.e., inductor current and ripple voltage. The output voltage would normally be corrected under closed loop condition, as the feedback circuit adjusts the duty ratio. This module checks that the required output voltage can be achieved without:

1. exceeding the maximum possible duty ratio, and
2. operating with a very small duty ratio.

If the output voltage is either low or high, there could be possible errors, as shown in figure 4.14, in:

1. the simulation,
2. the input voltage, and
3. the turns ratio if there is an isolation transformer.

In all the cases, the ES re-estimates the necessary value and re-designs from that stage.

4.8.2 Inductor Current

The KB is equipped with rules to detect discontinuity in the inductor current and to suggest a suitable value for the inductor. If the inductor current is not continuous in a
continuous mode design, then the only option is an increase in inductance. After adjustment, the capacitor will be redesigned and checked. If the inductor current is continuous in a discontinuous mode design, the filter will be re-designed by reducing the inductance. Figure 4.15 shows the ES checking the inductor current.

![Diagram showing verification of inductor current mode](image)

**Figure 4.14** Possible reasons for poor open-loop performance

![Table showing open loop simulation results](image)

**Figure 4.15** The ES dialog-box showing verification of inductor current mode

### 4.8.3 Ripple Voltage

Ripple voltage amplitude is a critical design specification. There exist two major reasons for an excessively high value of ripple voltage:

1. **Turns ratio** high
2. **Inductance** small
1. **the value of capacitance is too low.** This is unlikely because the value of the capacitor is chosen based on the ESR consideration, and this value is normally higher than the one calculated based on the charge storage consideration (Equation 4-15). In case a low value was entered deliberately, XpertPSD would prompt the user to modify it.

2. **the value of capacitor ESR is too high.** This is generally found to be more likely reason.

If the specification is not met, the ES suggests the use of a new capacitor with a lower value of ESR as shown in figure 4.16. The suitable capacitors are displayed to the user. Upon reselection of a capacitor, the system will restart the design verification process.

<table>
<thead>
<tr>
<th>Open Loop Sim. Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Simulated Output Voltage Ripple (V)</td>
</tr>
<tr>
<td>The Expected Output Voltage Ripple (V)</td>
</tr>
</tbody>
</table>

The output ripple voltage is well above the specified limit. **Reasons?**

- ESR of the filter capacitor too high.

---

After a satisfactory design of the converter, the expert system proceeds to design the control circuitry with feed-back compensation, which is covered in the next chapter.
Chapter 5

CLOSING THE FEEDBACK LOOP

5.1 OVERVIEW

A power supply requires efficient negative feedback control to have good line and load regulation, and good dynamic response to system disturbances. In a feedback control system, the filtered output of the converter is normally regulated using pulse width modulated feedback control. The use of pulse width modulation rather than frequency modulation results in a narrow EMI spectrum which can be readily filtered.

Deficiencies in gain and phase margins must be compensated for using an appropriate pole-zero compensation network. This leads to a minimised steady-state error in the output, fast transient response to sudden load changes, and unconditional stability of the system.

This chapter explains the expert system based design of the control system for a switched mode power supply. Selection of cross-over frequency, and estimation of phase and gain characteristics of the power supply using SPICE are explained. Design using direct duty and current-mode control is implemented in this work. Finally, the design validation of the closed loop system is explained.
5.2 CLOSING THE FEEDBACK LOOP

Design of the compensation network is usually an iterative procedure. Figure 5.1 shows the flowchart for the design of the control system implemented in XpertPSD. The main design tasks are:

- Determine the open loop frequency response of the system (excluding the compensation network).
- Design the compensation network to give a total closed-loop response satisfying the design objectives.
- Validate the design process, and if necessary, modify the compensation network.

![Flowchart for the design of the control system](image)

Figure 5.1 Methodology flowchart of the control system design
5.2.1 Selection of a Control Strategy

The selection of a control method depends on the mode of inductor current (continuous or discontinuous), and the power supply topology used. XpertPSD asks the user to select any one of the three control methods:

1. **Direct duty ratio control.** This is a simple technique in which duty cycle is varied as and when there is a change in the output voltage. The PWM switching voltage is derived by comparing a sawtooth waveform with the control voltage which represents any deviations in output voltage (figure 5.2). This technique may be used either with continuous mode or discontinuous mode inductor current in all the topologies. However, it is not widely used now.

![Diagram](image)

Figure 5.2 Direct duty ratio control: (a) Functional block diagram; (b) Derivation of switching waveform
2. **Voltage feedforward control.** This technique is very similar to the direct duty ratio control, but the peak of the sawtooth waveform varies directly with input dc voltage as shown in figure 5.3. This control provides good open-loop line regulation in the continuous mode buck-family of converters and discontinuous mode buck-boost and flyback converters.

![Sawtooth waveform and control voltage](image)

**Figure 5.3 Voltage feedforward control**

3. **Current mode control.** In this control, an additional inner current control loop is used as shown in figure 5.4. The control voltage directly controls the output inductor current, and thus the output voltage. Though it introduces load current dependency which does require closed loop correction, current mode control is now the most widely used control method for all topologies because it:

- limits peak switch current,
- provides inherent good line regulation resulting in very good rejection of input line transients, and
- requires easier compensation due to the removal of one pole.

After selection of the control strategy, the ES prompts the user to select a power supply controller, as shown in figure 5.5. A database, *ps-ic.dbk*, which contains data of several power supply controllers, is linked with *XpertPSD* to assist the user in the
5.2.2 Design of Voltage Feedback

In all types of control, voltage feedback is used. A fraction of the filtered output voltage forms the voltage feedback signal. If the feedback signal is larger than the reference voltage, XpertPSD uses a voltage divider circuit to reduce the feedback signal.

If there are multiple outputs, the ES takes the feedback signal from the output with tightest regulation. The remaining outputs are corrected by the transformer turns ratio.
5.2.3 Design of Current Feedback

In addition to voltage feedback, current mode control has a current feedback loop. XpertPSD implements the current feedback using a peak current detection scheme which regulates the peak inductor current. Here, the peak current passing through the switch forms the feedback signal as shown in figure 5.6. The signal is converted into a corresponding voltage using a resistor [92-93], $R_{\text{sense}}$, as shown in the figure 5.6.

![Figure 5.6 Peak-current current-mode control with a PWM IC Controller](image)

The sense resistor is given by:

$$R_{\text{sense}} = \frac{V_{\text{sense}}}{I_{\text{peak}}}$$

Equation 5-1

where:

$V_{\text{sense}}$ = maximum sense voltage

$I_{\text{peak}}$ = maximum allowed switch current

XpertPSD suggests a sense voltage, typically 1.0 volt, depending upon the selected IC current-mode controller, and the user is given an option to modify this figure.

Components $R_f$ and $C_f$ suppress leading edge current spikes due to rectifier recovery and/or inter-winding capacitance in the power transformer. The components $R_T$ and $C_T$ are part of the oscillator circuit of the controller.
Slope compensation

Current mode control has the following drawbacks \[85][94-96] when operating buck-family converters in continuous inductor current mode:

1. If the input voltage is increased while maintaining the output feedback voltage constant, the peak inductor current will be maintained constant, but the average output current will decrease due to larger peak-to-peak ripple current. This poor intrinsic open-loop input ripple rejection becomes worse with increased input voltage.

2. Instability occurs for any fixed frequency switching operation above 50% of the duty cycle regardless of the voltage feedback loop. A small perturbation introduced in the inductor current waveform will become larger and larger, resulting in instability.

3. Inductor current exhibits a damped sinusoidal response at one half of the switching frequency leading to a ringing response to line and load transients.

4. At half the switching frequency, sub-harmonic oscillations occur in the voltage feedback loop due to peak current loop gain, and excessive phase shift in the pulse width modulator. This instability can be detected by observing duty cycle asymmetry between consecutive drive pulses.

These problems are arrested by including a slope compensation to the control signal as shown in figure 5.7.

In the ES, the user can choose the amount of the slope (if it is required). The system suggests an amount of compensation slope, \( m \), equal to or more than 50% of the negative inductor current slope [97] given by:

\[
m = M \frac{R_{\text{sense}}}{n} \frac{di}{dt} = M \frac{R_{\text{sense}}}{n} \frac{(V_F + V_o)}{L}
\]

Equation 5-2

where:

\( M \) = value of slope compensation (normally 50% or more)

\( n \) = turns ratio of primary to secondary (referenced output) of the isolation transformer

The above magnitude of slope compensation is significant in that it yields ideal current-mode control, where the average inductor current follows the control signal.
so that, in the small signal analysis, the inductor acts as a current source.

Figure 5.7 Illustration of slope compensation technique: (a) No compensation; (b) Compensation slope added to control voltage

*XPertPSD* estimates whether a higher value of slope is needed to prevent subharmonic oscillations at high duty cycles. With the slope \( m \) equal to \( m_2 \) (the slope of that portion of the inductor current waveform where the current is decreasing linearly), such oscillations will not occur if the error amplifier gain at half the switching frequency is kept below a threshold value given [98] by:

\[
AE/A < \frac{\pi^2 C_o}{4T_s} \quad \text{Equation 5-3}
\]

where:

\[
\begin{align*}
A_{E/A} &= \text{error amplifier gain} \\
C_o &= \text{sum of filter and load capacitances} \\
T_s &= \text{switching time period}
\end{align*}
\]

The ES implements the above slope compensation scheme with UC3844 series of current-mode controllers by connecting a resistor, \( R_{\text{slope}} \), as shown in the figure 5.4. Its value is given [97][99] by:
\[ R_{\text{slope}} = R_f \left( \frac{\Delta V_{\text{osc}}}{T_{\text{on-max}}} \times \frac{n \times L}{(V_F + V_o) \times M} \right) \]

where:
\[ \Delta V_{\text{osc}} = \text{peak to peak oscillator ramp amplitude} \]
\[ T_{\text{on-max}} = \text{maximum turn-on period} \]

### 5.3 ERROR AMPLIFIER COMPENSATION

The feedback system includes an error amplifier which measures any deviation in the output voltage from its referenced value. The generated error signal is then fed into the PWM controller. This signal needs to be compensated to cancel any excessive phase lag or lead of the power supply circuit, and hence compensation networks are necessary.

#### 5.3.1 Selection of Cross-over Frequency

The cross-over frequency is the frequency at which the open-loop gain falls to zero dB as shown in figure 5.8. The cross-over frequency is given \[100\] by:

\[ f_{\text{cross}} \leq \frac{k f_s}{2\pi D} \]

where:
\[ D = \text{duty ratio of the converter} \]
\[ k = \text{component tolerance factor} \]

![Figure 5.8 Phase and gain characteristics of current-mode controlled power supply](image-url)
XpertPSD advises the user, as shown in figure 5.9, to select a cross-over frequency limited to $f_s/10$ for the following reasons:

1. At the above limit, power supply response to transients caused by, for example a sudden change of load, is fast.
2. The system is likely to become unstable when $f_{\text{cross}}$ exceeds the above limit with a duty ratio more than 50%.

Now, Feedback control system will be designed.

The chosen control method: CURRENT MODE CONTROL

The Regulation Output: 5.0V

A cross-over frequency of 1/10 of switching frequency is normally enough to provide sufficient compensation.

Desired Cross-over Frequency (Hz) : 10000

Figure 5.9 ES asking the user to select a cross-over frequency

The component tolerance factor, $k$, should be used to avoid saturation of the error amplifier by the amplified output voltage ripple.

The user can overrule the above and choose any cross-over frequency below half the switching frequency.

5.3.2 Phase Margin

The phase margin determines the stability of the output during transient conditions, and should be positive for stable operation. The objective in the design of the compensation is an overall loop gain characteristic approaching that of a single pole, rolling off at -20dB/decade with a phase margin of $45^\circ$ to $65^\circ$ [3][84][101]. To avoid oscillations, ringing and instability at lower frequencies, the expert system sets a minimum phase margin of $45^\circ$ as the design target.

The dc gain of the power supply determines the steady-state error in the output, and should be as high as possible to minimise the error [102-103].
To be able to plot the gain and phase response of the system, the control to output (from point ‘A’ to $V_{out}$) transfer function characteristic must be found. For the system shown in figure 5.10, the transfer function is given by:

$$T_{OL}(s) = G_{PWM}(s) \times G_p(s) \times H_e(s)$$  \hspace{1cm} \text{Equation 5-6}

where:
- $G_{PWM}(s)$ = transfer function of the PWM modulator
- $G_p(s)$ = transfer function of the power circuit
- $H_e(s)$ = output filter transfer function

![Block diagram representation of a power supply](image)

Figure 5.10 Block diagram representation of a power supply

Though there are several methods of predicting the small signal response of a system, SPICE-simulation is implemented here due to its flexibility in allowing the user to modify/add components. In addition, it is more accurate than the conventional asymptotic approach, which results in errors of 3 dB and $5.7^\circ$ in the gain and phase angle respectively at poles and zeros.

*XpertPSD* builds a small-signal model of the closed-loop power supply available from the KB. The loop is broken for frequency-domain analysis at point ‘A’, as shown in the figure 5.10 [104].

After a successful simulation of the power circuitry, *XpertPSD* executes the program,
**GPEvaluator**, to construct the Bode plot and find the phase angle and gain at the desired cross-over frequency. The system then estimates the compensation required, and notifies the user (figure 5.11).

![Small Signal Frequency Response Table](image)

**Figure 5.11** The ES window displaying the uncompensated gain and phase angle at the desired cross-over frequency

### 5.3.3 Selection of a Compensation Network

A suitable compensation network should be selected [87] that provides adequate gain and phase characteristics, besides compensating for any zeros in the transfer function of the power circuit. The ES suggests such a network based on the type of compensation required:

- single-pole compensation, or
- double-pole compensation.

**Single-pole topology**

The single pole compensation circuit, as shown in figure 5.12, is used to compensate all power circuits which have single pole filter characteristics. This includes all topologies with discontinuous inductor current mode (irrespective of control method), and all continuous mode topologies used with current mode control. This network provides two compensation poles as listed in table 5-1.

With this topology, the feedback gain of the error amplifier is given by:

$$ A_{E/A} = 20 \log \left( \frac{R_f}{R_i} \right) \text{dB} $$

*Equation 5-7*
Table 5-1 Corner frequencies of two-pole compensation network (figure 5.12)

<table>
<thead>
<tr>
<th>Type</th>
<th>Purpose</th>
<th>Corner Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole</td>
<td>To compensate zero of the output filter capacitor ESR in the power circuit.</td>
<td>$\omega_{pe1} = \frac{1}{R_f C_f}$</td>
</tr>
<tr>
<td>Pole</td>
<td>To compensate for the right-half-plane zero that occurs with continuous mode boost and flyback topologies. It is omitted for topologies which have no such zero (e.g. buck-family of converters).</td>
<td>$\omega_{pe2} = \frac{1}{R_p C_p}$</td>
</tr>
</tbody>
</table>

**Two-pole topology**

The two-pole topology as shown in figure 5.13 is intended for power circuits which have a two-pole filter characteristic, i.e., all converters operating in continuous current mode and using either direct duty ratio or voltage feed-forward control. The circuit provides a zero and poles as shown in table 5-2.

The dc feedback gain of the error amplifier is given by:

$$A_{E/A} = 20 \log \left( \frac{R_{fp}}{R_{ip} + R_{iz}} \right) \text{dB}$$  \hspace{1cm} \text{Equation 5-8}

It should be noted that the large signal transient performance of this circuit may be impaired by the input capacitor charging, which causes a steady-state error in the...
output voltage and restricted transient recovery time.

![Two-pole compensation network](image)

**Figure 5.13 Two-pole compensation network**

<table>
<thead>
<tr>
<th>Type</th>
<th>Purpose</th>
<th>Corner frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole</td>
<td>To compensate for the filter capacitor ESR zero of the power circuit</td>
<td>( \omega_{pc1} = \frac{R_{ip} + R_{iz}}{R_{ip} R_{iz} C_i} )</td>
</tr>
<tr>
<td>Zero</td>
<td>To cancel one of the two filter poles</td>
<td>( \omega_{zc} = \frac{1}{R_{fz} C_f} )</td>
</tr>
<tr>
<td>Pole</td>
<td>To boost the low frequency gain, which is reduced by the above compensation zero, and to meet dc regulation requirements</td>
<td>( \omega_{pc2} = \frac{1}{(R_{fp} + R_{fz}) C_f} )</td>
</tr>
<tr>
<td>Pole</td>
<td>To compensate for any right-half-plane zero</td>
<td>( \omega_{zc} = \frac{1}{R_p C_p} )</td>
</tr>
</tbody>
</table>

Table 5-2 Corner frequencies of two-pole compensation network (figure 5.13)

The ES displays the suitable compensation network for the power supply as shown in figure 5.14. The user is given an opportunity to choose a different network if necessary.

### 5.3.4 Design of the Compensation Network

The design involves selection of corner frequencies corresponding to the poles and
zeros of the compensation circuit selected. As there are no clear-cut rules, the design is sometimes iterative to achieve a good transient response. **XpertPSD:**

- selects various corner frequencies depending upon the topology of the compensation network,
- determines the dc gain of the error amplifier required to achieve zero dB gain at the cross-over frequency, and
- calculates the component values required.

### Figure 5.14 The ES displaying the suitable compensation network

**Selection of corner frequencies**

The zeros and poles should be introduced in such a way that the low frequency gain may be increased without adding excessive phase shift as explained below.

1) **Two-pole compensation:** In this, a zero is placed to cancel one of the power circuit poles as shown in figure 5.15. The KB suggests that the zero is placed at approximately half the resonant corner frequency, $f_o$, of the output filter, so as not to add any additional phase shift at $f_o$ for a sudden second order transition. The corner frequency of the above zero is given by:
\[ f_{zc} = \frac{f_o}{2} \]

Equation 5-9

where:

\[ f_o = \frac{1}{2\pi\sqrt{LC}} \]

Equation 5-10

---

A pole is placed to cancel the ESR zero. This should be placed in such a way that it does not add excessive phase lag at the resonant frequency of the output filter. In the case of direct duty ratio control, the pole should be placed at frequency:

\[ f_{pc} = 5 \times f_o \]

Equation 5-11

2) Single-pole compensation: In current mode control, a pole is located at a low frequency to increase the low frequency gain as shown in figure 5.16. XpertPSD suggests this pole be located at a frequency equal to at least 5 times less than the
corner frequency of the ESR zero. The ES initially suggests a frequency given by:

\[ f_{pc} = \frac{f_z}{10} \quad \text{Equation 5-12} \]

where:

\[ f_z = \frac{1}{2\pi R_{ESR} C} \quad \text{Equation 5-13} \]

![Loop-gain characteristic of the power supply](image)

![Gain characteristic of the error-amplifier](image)

Figure 5.16 Compensation characteristics for current-mode control

Unlike the case of duty-ratio control, there is no restriction on the location of the pole with respect to the filter corner frequency because the power supply exhibits a single pole characteristic until \( f_z \).

**Gain of the error amplifier**

To provide an overall gain of 0 dB at the desired cross-over frequency, the gain of the error amplifier must equal the control to output gain without compensation as shown
in the figures 5.15 and 5.16.

For direct duty ratio control with single-pole compensation, the error amplifier gain, $A_{E/A}$, required at and below $f_{zc}$ (figure 5.15) is:

$$A_{E/A} = A_{f-cross} - 20 \log \left( \frac{f_{pc}}{f_{zc}} \right)$$

Equation 5-14

where:

$A_{f-cross}$ = the required gain of the error amplifier required at the cross-over frequency to obtain an overall gain of 0 dB at that frequency

Similarly, in the case of current-mode control with single-pole compensation, it is necessary to find the gain of the error amplifier required at the corner frequency of the zero, $f_{pc}$ (refer to the figure 5.16):

$$A_{E/A} = A_{f-cross} - 20 \log \left( \frac{f_{pc}}{f_{cross}} \right)$$

Equation 5-15

With the above embedded knowledge, XpertPSD estimates the error amplifier gain required. It then presents all the above compensation information to the user for any alterations as shown in figure 5.17.

<table>
<thead>
<tr>
<th>COMPENSATION DESIGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corner Frequency of the Filter Zero (Hz): 2584</td>
</tr>
<tr>
<td>Corner Frequency of the Filter Pole (Hz): 439</td>
</tr>
<tr>
<td>Required Freq. of a Pole to compensate the Zero (Hz): 258</td>
</tr>
<tr>
<td>Required Gain at the Corner Frequency (dB): 56</td>
</tr>
</tbody>
</table>

Figure 5.17 XpertPSD dialog-box displaying the compensation data

After acceptance by the user, the ES considers implementation of the network.

**Implementation**

XpertPSD supports the design of the 1524 and 3844 series of PWM controllers to provide direct duty ratio and current mode control respectively. Using the previously loaded design data of the controller from the database, the components of the compensation network are calculated.
For the converters with a RHP zero, the ES includes components $R_p$ and $C_p$ to compensate for this zero. For the buck-family converters, the components $R_p$ and $C_p$ are omitted as there is no RHP zero.

While designing the compensation circuit, XpertPSD reads any design constraints of the power supply controllers from the database (_ps-ic.dbk_). For example, the 1524 series controllers have a transconductance amplifier and require a minimum feedback resistance of 30 kΩ.

Using the above guidelines, tables 5-1 and 5-2, and the equations from 5-7 to 5-15, the remaining component values of the compensation network are calculated. XpertPSD then displays the compensation data (figure 5.18). The user can modify the component values.

![Compensation Circuit Components](image)

The Compensation circuit values:
- **Power Supply IC Controller:** UC3844
- **The Feedback Resistance $R_{fe}$ (kilo ohm):** 500.0
- **The Feedback Capacitance, $C_{fe}$ (pF):** 470
- **The Input Resistance, $R_i$ (kilo ohm):** 10

Next Task:
Verification of the design

Figure 5.18 ES window showing the designed compensation network

### 5.4 DESIGN VALIDATION

The design validation includes checking the compensation, and evaluating performance of the design. The KB contains rules to evaluate the above test conditions and redesign if necessary as explained below.
5.4.1 Checking the Compensation Sufficiency

Since it is necessary to check the gain and phase angle at the cross-over frequency, the ES simulates the closed-loop system with the compensation circuitry and calculates the gain and phase angle at the cross-over frequency. The ES prompts the user either to accept the results or to redesign the compensation circuit (figure 5.19).

If the gain is not zero dB at the cross-over frequency, then it is possible that the gain of the error amplifier is not enough, and the ES advises the user to modify it accordingly.

If the phase lag is greater than 135° for any frequency up to the cross-over frequency, \textit{XpertPSD} notifies the user and provides diagnostics. The possible reason for this could be wrong selection of the corner frequencies of the poles/zeros, and the ES redesigns the compensation circuitry.

5.4.2 Transient Response

A well designed optimum power supply should provide good dynamic voltage response with changing loads. To check this transient response, the ES validates the
overall design for the surge load condition mentioned in the specification.

The expert system simulates the complete closed loop power supply with a standard step-load change of 40%. After a successful simulation, the routine *CLValidate* is run to estimate the transient recovery time, overshoots and undershoots in the output voltage. The system finds any violations of the specification, and suggests possible reasons, e.g.:

1. When the transient response is poor, the cross-over frequency may be insufficient.
2. The filter capacitor ESR may be inadequate when the voltage deviation is high.

*XpertPSD* presents all the results to the user as shown in figure 5.20.

![Figure 5.20 ES dialog-box displaying the results of transient response](image)

After a successful design of the power supply feedback loop, the ES then tackles the design of the magnetic components, which is covered in the next chapter.
Chapter 6

DESIGN OF MAGNETICS

6.1 OVERVIEW

High frequency transformers and filter inductors are the two main wound components in switched mode power supplies. Design of the wound components has a significant effect on the overall efficiency and cost of a modern power supply, as they are bulky devices that contribute considerably to the total size of a SMPS. The critical elements in the design are the selection of core material, core geometry, windings, wire dimensions, and designing to reduce skin-effects. The design must meet specifications for maximum losses allowed and space limitations, and must also be cost effective.

XpertPSD considers the design of the wound components after a satisfactory design of the converter circuit has been completed. The knowledge base module, MAGNETICS, contains the design rules providing decision support. This module can be used either in association with the main power supply design or separately by inputting the required magnetics specifications. Design with RM-series cores and EE cores from the company MMG-NEOSD (formerly SEI) [105] are supported in the present ES. RM cores are used for low power applications and EE cores are used up to 5 or 10 kW of power handling capability depending upon flux density [3][106-107].
This chapter explains the various design issues in the design of wound components, including flux density considerations, selection and testing of the design. The various tasks involved in the implementation of the wound component design in the XpertPSD are also given a rigorous treatment.

6.2 DESIGN OF INDUCTORS

The expert system designs filter inductors in the power supply after the design validation of the high frequency converter circuit. Figure 6.1 shows the design methodology of the inductors implemented in the expert system. There are two distinct design stages:

- component design, and
- design validation.

After designing the inductor, the inductor design is subjected to a series of tests for validation. The design validation includes verifying available core winding area, and checking for dc winding resistance, core field strength and maximum allowable temperature rise. The expert system offers advice on different design possibilities and provides a friendly design environment, as explained in the following sections.

6.2.1 Core Material

The design starts with the selection of a suitable core material. The core material is selected on the basis of:

- optimal operating frequency range,
- weight,
- available core geometry,
- air-gap considerations,
- flux density, and
- energy storage capability.
CHAPTER 6: DESIGN OF WOUND COMPONENTS

Core material selection

Design assumption

Core size selection

Turns calculation

Use next larger core

Wire gauge selection

Resistance OK?

No

Yes

Skin effect OK?

No

Yes

Winding area OK?

No

Yes

Winding area OK?

No

Yes

Field strength OK?

No

Yes

Temp. rise OK?

No

Yes

All inductors designed?

No

Yes

To h.f. transformer design

Figure 6.1 Methodology flowchart for the design of a filter inductor
The core materials used in present-day high frequency switching wound components are ferrite, iron powder, and molypermalloy (also known as Genalex) cores. Ferrite material is the most popular material in modern converters, and is the only material considered in this present work. Ferrite is a ceramic ferromagnetic material with a crystalline structure consisting of mixtures of iron oxide with either manganese or zinc oxide [106][108]. Though they cannot be operated at high flux densities, ferrites offer:

1. low core losses at high frequencies up to 1MHz,
2. good winding coupling,
3. low cost, and
4. ease of assembly even if heavy-gauge wire is involved.

Cores made from ferrites come in many different geometric shapes and sizes. However, ferrites saturate at low flux densities and often require the use of an air-gap, with all the associated complications. Care is needed regarding temperature rise of the core, since ferrites are temperature sensitive.

Using the power supply specifications, XpertPSD searches the core material database for a suitable core material. This database contains the magnetic properties of different magnetic materials, including the name of the manufacturer, saturation flux densities and energy storage capabilities.

Figure 6.2 shows a dialog-box displaying the suitable core materials and prompting the designer to select one. A manufacturer/supplier of the magnetic material can be selected at this stage.

6.2.2 Design Assumptions

The next step in the design is to select suitable values for operating flux density, current density, and window utilisation factor.

Flux density

Selection of operating flux density is an important consideration in the design of wound components, and is constrained by increased core losses. Since core loss increases with maximum flux density, use of high flux density leads to an excessive
temperature rise of the core. On the other hand, if the core is operated at low peak flux density, more turns will be required which may lead to the use of a larger core size for the same power output. A typical choice is to start the design with a working flux density of 50% to 70% of maximum allowable saturation flux density of the core material at an ambient temperature. In general, the saturation flux density, assuming a linear variation with the core temperature [25], is:

$$B_{sat}(T) = B_{sat20} + (T-20)(B_{sat100} - B_{sat20})/80$$  \[\text{Equation 6-1}\]

where:

- $B_{sat}(T)$ = saturation flux density at any temperature
- $B_{sat20}$ = saturation flux density at 20 °C
- $B_{sat100}$ = saturation flux density at 100 °C

Since the filter inductor is normally designed to store maximum energy, any saturation of the core results in a drop of inductance which reduces stored energy. Normally the drop in inductance should not be more than 20% [109]. An optimal flux density equal to half of the saturation value is advised.

Figure 6.2 Interaction with the user on the selection of core material
Current density ($J$)
An important design consideration is the current density of a winding conductor. If the current density is very low, then for a given current, a very large conductor cross section is required, thereby demanding a large window area. However, it should be noted that a large conductor cross-section may not produce the expected low resistance, due to the skin effect.

An optimum current density between 2 and $5 \, A/mm^2$ is generally found to be a good compromise between conductor resistance and the window area of the core bobbin/former [110].

Winding utilisation factor ($K_u$)
This is the proportion of the total available window area filled by conducting material. The parameters which determine this utilisation factor are:
- **Bobbin.** If a bobbin is used for the winding, then the bobbin thickness reduces the available winding area.
- **Air-gap between conductors.** There is usually a gap between adjacent conductors.
- **Space factor.** The thickness of insulation used between layers of the winding reduces the available window area.
- **Insulation.** This is due the conductor insulation and depends upon the wire gauge used.

The above factors are considered when estimating the window utilisation factor. A factor of 0.6 is suggested as realistic assuming that there are no multiple windings in the inductor design.

All the expert system suggested values are presented to the user as shown in figure 6.3. The user can modify the suggested values, keeping within the maximum limits allowed.

6.2.3 Core Selection

A core is selected on the basis of maximum energy storage capability and winding window area. The energy storage capability depends on the topology of the converter
for which the inductor is designed. Normally, the above two constraints are expressed in the form of an Area-Product, $A_p$. The $A_p$ of any magnetic component (transformer or inductor) is:

$$A_p = A_c \times A_w$$

Equation 6-2

where:

$A_c = \text{effective core area}$

$A_w = \text{winding window area available}$

The area product of the filter inductor [111] is:

$$A_p = \frac{L \times I_{L_{-max}}^2}{K_w \times J \times B_m}$$

Equation 6-3

where:

$L = \text{filter inductance}$

$I_{L_{-max}} = \text{maximum inductor current}$

$K_w = \text{winding utilisation factor}$

$J = \text{current density}$

$B_m = \text{maximum flux density}$

For the core material chosen,

The Saturation flux density at 100 deg.C (T): 0.32
The Saturation flux density at 25 deg.C (T): 0.5
Operating Flux Density (T): 0.25
Current Density (A/sq-mm): 5.0
Window Utilization Factor: 0.4

Figure 6.3 Inductor design assumptions

A core is selected whose $A_p$ is greater than or equal to the above required value. The expert system calculates the area-product of the inductor required and searches the
suitable core.

The core database (cores.dbk) includes geometry of RM and ETD cores. The various fields in the database are core part number, core magnetic length, effective core area, effective volume, weight, window area available, mean turn length, surface (radiating) area of the core, bobbin width, bobbin height and bobbin area.

All cores satisfying the area-product requirement are considered and presented to the user as shown in figure 6.4. If more than one core is suitable, factors such as core cost, manufacturability (ease of winding/manufacture or mounting flexibility), quality and reliability of the manufacturer, robustness, physical size, and low losses are given due consideration.

<table>
<thead>
<tr>
<th>Suitable Core</th>
<th>Required Area Product (mm⁴): 2984</th>
<th>OK</th>
<th>Advice</th>
<th>Help</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETD29</td>
<td>Area Product of the core (mm⁴): 7372</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM10</td>
<td>Core Type: ETD29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RM14</td>
<td>Effective Path Length (mm): 70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETD34</td>
<td>Effective Core Area (sq-mm): 76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETD39</td>
<td>Effective Volume (mm³): 5376</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETD44</td>
<td>Core Winding Area (sq-mm): 97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ETD49</td>
<td>Surface Area (mm²): 1580</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.4 ES dialog-box showing details of suitable cores

**Core inductance factor**

The inductance factor of a core relates the inductance to the number of turns required, and is independent of core working conditions such as winding current and core flux density:

\[ A_L = \frac{L}{N^2} \text{ H/turns}^2 \]  

Equation 6-4

where:
where:

\[ A_L = \text{core inductance factor} \]

\[ N = \text{number of turns} \]

The inductance factor can be calculated from the energy storage capability of the core vs. its inductance factor curve [85][109]. The curves for various core geometries are converted into a set of polynomial equations and stored in the knowledge base of the expert system.

Whenever a ferrite core material is selected, the expert system automatically calculates the inductance factor \( A_L \) for the required maximum energy storage of the core, which is displayed to the user, as shown in figures 6.5. This can be modified if necessary.

The Required Energy Storage (mJ): 1.5

The Core Type Selected: ETD29

Following is the suitable core inductance factor for the above core. Alter the value if you want to.

The Suitable Core Inductance Factor, \( A_L \): 105.0

![Figure 6.5 ES window showing the calculated core inductance factor](image-url)

6.2.4 Turns Calculation

The design proceeds with the calculation of the number of turns required, using:

\[ N = \sqrt{L/A_L} \]  \hspace{1cm} \text{Equation 6-5} \]

After calculating the turns required, the user is given the option to adjust this, if desired, as shown in figure 6.6.

6.2.5 Winding Design

The design of the inductor winding includes selection of a standard wire gauge from databases, and layout of the winding on the core former or bobbin. The inductor
winding design is simpler than that of a transformer as there is only a single winding to be accommodated on the core, but this does not apply to a coupled inductor of multiple outputs (where all the output inductors are wound on a common core).

<table>
<thead>
<tr>
<th>Number of Turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Total Power Loss of the Device (mW): 1250.0</td>
</tr>
<tr>
<td>The Required Energy Storage (mJ): 1.5</td>
</tr>
<tr>
<td>The Core Type Selected: ETD29</td>
</tr>
<tr>
<td>The Core Inductance Factor: 105.0</td>
</tr>
<tr>
<td>Now, the Turns Calculated: 24</td>
</tr>
<tr>
<td>Set the Turns if you want to ..... 24</td>
</tr>
</tbody>
</table>

Figure 6.6 XpertPSD window showing the number of turns needed

**Wire gauge selection**

The required cross-section area, \( a \), of the winding-wire required is estimated using:

\[
a = \frac{I_{L,\text{max}}}{J}
\]

Equation 6-6

The wire diameter, \( D \), is given by:

\[
D = \sqrt{\frac{4 \times a}{\pi}}
\]

Equation 6-7

Using the previously selected current density, the ES calculates the cross-section area and then the required wire diameter. A standard wire size is then selected from the wire database, wires.dbk, which contains data of grade-2 enamelled copper-wires. XpertPSD reads from the database appropriate data, such as wire diameter, overall diameter, approximate resistance per metre, bare copper weight, and current rating at a given current density.

The wire-size selected is then optimised for:

- specified winding resistance, and
- skin effect.
a) **Winding Resistance**: The maximum dc resistance of the winding must be limited as dc resistance is directly related to the resistive voltage drop across the inductor. If this limit is violated, then either a larger core or a lower wire-gauge must be used (a larger core reduces the number of turns resulting in a lower dc winding resistance).

The ES calculates the total resistance using the following equation:

\[ R_{dc} = N \cdot l_M \cdot R_w \]  

Equation 6-8

where:

- \( R_{dc} \) = total dc resistance
- \( l_M \) = mean turn length
- \( R_w \) = wire resistance

The estimated resistance is then compared with the allowed resistance, and the test results submitted to the user as shown in figure 6.7. If the calculated resistance is greater than the specified limit, as shown in figure 6.8, the user is offered the following choices:

1. modify the wire diameter,
2. choose the next larger core, or
3. continue with the design.

![Resistance Check](image)

The Max. Specified Resistance (milli ohm): 50.0
The Resistance Calculated (milli ohm): 19.8

The Calculated resistance is within the limits.
The next task is to check the core saturation.

Figure 6.7 ES checking the allowed dc resistance of the inductor winding

If the first option is selected, the expert system calculates a new wire size and checks the winding resistance limit again. If the next larger core option is chosen, the design will restart, starting from the calculation of the number of turns. If the user ignores the skin effect, the software will proceed to the next task.
CHAPTER 6: DESIGN OF WOUND COMPONENTS

The Max. Specified Resistance (milli ohm): 1.0
The Resistance Calculated (milli ohm): 3.9
It is greater than the specified value.
You need to use either a larger core or modify wire size.

The Present Core: ETD49

There are no more larger cores available from the database.

Your choice?
☑ Modify wire size
☐ Continue with the design

Figure 6.8 Window showing different options to meet the resistance requirement

XpertPSD checks whether the wire size needs to be modified on account of the skin-effect and if necessary advises the user to redesign either by modifying the wire diameter or choosing the next larger core. The user can also overrule the choice, and proceed with the design. Note that proximity effect is not considered here.

Sufficiency of winding area
Before proceeding any further, it is necessary to check whether the winding area of the core is sufficient to house the windings, taking into account bobbin thickness, conductor insulation, air-gaps between conductors, and insulation used between various winding layers. These factors typically reduce the useful winding area to about 60% of the available winding area.

To meet the sufficiency, the following inequality must be satisfied:

\[ A_w \times K_w > a \times N \]  
Equation 6-9

The knowledge base is equipped with rules to check this inequality, and if the inequality is not satisfied XpertPSD notifies the user, giving an option to restart the design with the next larger core as shown in figure 6.9. In this case, a list of available larger cores is displayed, and the user is prompted to select the next larger core from

107
the list. Upon selection of the core, the number of turns is recalculated, and the design will be repeated as shown in figure 6.1. If no larger cores are available, the ES will halt the design, and pass control to the user.

<table>
<thead>
<tr>
<th>The Available Winding Area (sq-mm):</th>
<th>38.8</th>
<th>OK</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Required Winding Area (sq-mm):</td>
<td>26.2</td>
<td>Advice</td>
</tr>
<tr>
<td>The winding area is enough.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The next task is to design winding lay-out.</td>
<td></td>
<td>Help</td>
</tr>
</tbody>
</table>

Figure 6.9 The expert system checking the available winding area

**Winding lay-out**

The winding layout involves selection of a bobbin, and housing all the turns calculated within the available window area of the bobbin. For this, XpertPSD reads the dimensions of the bobbin from the core database.

Since the entire winding area cannot be used for winding due to practical limitations, the following reductions [3] are used:

- a 10% reduction in the available width because of slippage during winding;
- a 20% reduction in the available height because of insulation and bulge.

With these available dimensions, turns per layer, the number of layers required to fit the turns, and turns in the last layer are calculated. The expert system suggests a suitable insulation type to the user prescribed by the regulatory bodies. For inductors, winding insulation is chosen on the basis of providing mechanical strength for the building of the inductor since there are no high electrical fields. Polyester tape, a Type-B insulation material, is chosen as it can withstand high temperature. Finally, the winding layout information is then presented to the user as shown in figure 6.10.

6.2.6 Variation of Inductance with DC Current

Since there is a possibility of the core saturating under dc working conditions leading to a drop in inductance, it must be tested for saturation. There are several different
methods, depending upon available core characteristics, to check the drop in inductance. In the present work, two possible methods are implemented for RM and ETD cores.

---

**Winding Arrangement**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of the Winding Window (mm):</td>
<td>19.1</td>
<td>OK</td>
</tr>
<tr>
<td>Height of the Winding Window (mm):</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Total Number of Turns:</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Total Layers:</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Allowed Turns per Layer:</td>
<td>13</td>
<td>Help</td>
</tr>
<tr>
<td>Turns in the last Layer:</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Total Depth Occupied (mm):</td>
<td>2.99</td>
<td></td>
</tr>
<tr>
<td>Insulation Used:</td>
<td>Type B</td>
<td></td>
</tr>
</tbody>
</table>

The window area is enough. You can accept the design.

---

Figure 6.10 The expert system consulting the user on layering of the windings

---

**a) RM-cores:** The inductance versus field strength characteristic shown in figure 6.11 is normally given for RM cores. The working and saturation regions of all the cores are represented in the rule-base. The operating field strength is calculated using the following equation:

\[
H = \frac{N \times I_{L_{\text{max}}}}{l_e}
\]

Equation 6-10

where:

- \( H \) = field strength
- \( l_e \) = effective core magnetic path length

Using this field strength, the corresponding drop in inductance is read from the core’s characteristic.
b) ETD cores:- The drop in inductance is estimated using the $A_L$-$NI$ characteristic, which gives a variation of core inductance factor with the ampere-turns of the core as shown in figure 6.12. All such core characteristics are represented in the database, *alni.dbk*.
For a given ampere-turns, the corresponding core inductance factor is calculated from the graph. The drop in inductance is then estimated using the following relationship:

$$\%\text{drop in } L = 100 \times \frac{L - (A_L \times N^2)}{L}$$

Equation 6-11

For ferrite cores, the reduction in the inductance should not normally be more than 10%. The ES submits, as shown in figure 6.13, all the above information to the user for consideration.

![Checking Core Saturation](image)

The drop in the inductance is less than 10%.
The design is OK. Choice is yours.

Figure 6.13 The ES interacting with the user about the drop in inductance allowed

If the drop in inductance is more than the allowed limit, the designer is offered the option to redesign with a larger core, whereupon *XpertPSD* will present a list of available larger cores and will restart the design.

### 6.2.7 Estimation of Temperature Rise

Increase in core working temperature increases the winding resistance, and hence, leads to an increase in losses. This results in reduction of flux density and degradation of the insulating material. The need to limit the temperature rise to an acceptable value under real working conditions defines the required surface area and hence the size of the wound component. Broadly, the temperature rise is a function of:

- total power loss,
• the surface area and emissivity, and
• air-flow.

Power loss
The expert system estimates the total power loss, \( P_L \), comprising of core and copper losses:

\[
P_L = P_{\text{core}} + P_{\text{cu}} \tag{6-12}
\]

where:
\( P_{\text{core}} \) = core loss
\( P_{\text{cu}} \) = copper loss

a) Core loss: The core loss depends upon peak flux density, switching frequency, and temperature. It can be estimated approximately using [111-112]:

\[
P_{\text{core}} = K \cdot f_s^{m-k} \cdot B_{\text{max}}^{n-k} \tag{6-13}
\]

where:
\( K \) = material factor depending on the ambient temperature
\( m-k \) = constant within the range: 1.3 < m < 1.6
\( n-k \) = constant in range: 2 < n < 2.6

Core loss can also be calculated from loss curves, which give core losses at different temperatures, frequencies and flux densities.

b) Copper loss: The copper loss is given by:

\[
P_{\text{cu}} = I^2 \cdot R_{\text{ac}} \tag{6-14}
\]

where:
\( I \) = rms winding current (this should include the ripple current)
\( R_{\text{ac}} \) = effective winding resistance

The effective winding resistance includes the increased resistance caused by the skin-effect. The effective winding resistance is given [111] by:

\[
R_{\text{ac}} = R_{dc} \times \frac{(d / 2\delta)^2}{[(d / 2\delta)^2 - (d / 2\delta - 1)^2]} \tag{6-15}
\]
where:
\[ \delta = \text{effective skin-depth} \]
\[ d = \text{diameter of the wire} \]

Since the resistivity of copper increases approximately 0.43% per degree centigrade rise from its value at 20°C, this effect must also be considered.

**Temperature rise**

The temperature rise of a wound component can be estimated [112][24] assuming free air cooling of the inductor and an ambient temperature of 25 °C, using:

\[ \Delta T = 80 \times A_r^{-0.7} \times P_L^{0.85} \]

Equation 6-16

where:

\[ A_r = \text{exposed surface area of the core in cm}^2 \]

The estimated temperature rise is checked with the permitted value. If the calculated temperature rise is too high, the ES will advise the user to use a larger core which results in:

- a larger wire size,
- lower dc resistance,
- a lower copper loss, and
- larger surface area.

Since there is no change in the flux density, the core loss will be the same. The overall effect is a reduction in power loss leading to a lower temperature rise.

Figure 6.14 shows the dialog-box displaying the temperature rises and options for the user to control the design.

### 6.2.8 Air-gap Considerations

Output filter inductors require an air gap to prevent the core saturating (otherwise a very large core would be required). For a high permeability core, the air-gap, \( l_g \), is given by:

\[ l_g = \frac{\mu_0 \times N^2 \times A_c}{L} \]

Equation 6-17
where:
\[ \mu_0 = \text{permeability of free air} \]

<table>
<thead>
<tr>
<th>Temperature Rise Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Calculated Temperature Rise (deg C): 11</td>
</tr>
<tr>
<td>The Allowed Temperature Rise (deg C): 40</td>
</tr>
<tr>
<td>The temperature rise is within the limits.</td>
</tr>
</tbody>
</table>

Figure 6.14 Checking the temperature rise of the device

The expert system calculates the required air-gap and checks the inductance. If the flux density was assumed while calculating the number of turns, the air-gap calculated may not be exact, and this requires trimming of the inductance value by slightly adjusting the air-gap.

6.3 DESIGN OF TRANSFORMERS

Though inductors and transformers are both magnetic components, there is a difference in their operation and design process:

- In a transformer, the core flux depends on the magnetising current, and is not affected by the load current.
- In an inductor, the flux depends on the load current, and an excessive current may lead to core saturation.

This makes the core selection process for transformers simpler, although the winding design is more complex. Nevertheless, the design methodology of transformers and inductors run on similar lines with the same user-interface features, with a few differences as highlighted in the following sections. As with the inductor design, the scope of the design is limited to RM and ETD cores.

Figure 6.15 shows the design methodology flow-chart for a transformer. There are five stages in the design:
1. Core material selection,
2. Design assumptions,
3. Core selection,
4. Winding design, and
5. Design evaluation.

![Methodology flow-chart for transformer design](image)

Figure 6.15 Methodology flow-chart for transformer design

The first four stages are similar to those for the inductor design, and share identical user interface features. The following sections explain the main features of the design implemented in the expert system.

### 6.3.1 Core Selection Process

As with the inductor design, the design starts with selection of a suitable core material based on the power supply specifications. The selection criteria are the same as for the inductor.
CHAPTER 6: DESIGN OF WOUND COMPONENTS

Following the selection of the core material, the expert system suggests a suitable value for the operating flux density using equation 6-1, taking into account the temperature rise of the power supply, and saturation flux density of the core material.

An initial current density of 5A/mm² is suggested. Unlike in the inductor design, a smaller window utilisation factor, 0.4, should be used as:

- there are multiple layers of windings with thick layers of insulation, which are needed to meet breakdown voltage requirements;
- creepage distance is needed between the windings and the bobbin for isolation purposes.

The core selection is similar to that for the inductor. A core is selected whose area product is more than the calculated area product of the converter transformer. For example, the area product for a forward converter [110] is:

\[
A_p = \frac{\sqrt{D \times P_{out}} \times (1 + 1/\eta)}{K_w \times J \times B_m \times f_s}
\]

Equation 6-18

where:

\( P_{out} \) = total output power of all outputs
\( \eta \) = efficiency desired
\( D \) = duty ratio

The area product approach results in more consistent values than other techniques, as it considers factors such as the power handling capability of the core, and the winding space available on the core.

6.3.2 Turns Calculation

The method for calculating the number of turns of a transformer depends upon the converter selected. For low voltage multiple output transformers, it is best to start the design from the secondary side, with the secondary having the lowest output voltage, as the number of turns for the secondary windings will be small, and errors in estimating secondary turns from the primary side considerations will be significant. The secondary winding turns is given by [113]:

116
\[
N_{\text{sec}} = \frac{V_{\text{sec}} \times D_{\text{max}}}{A_c \times B_{\text{max}} \times f_s}
\]

Equation 6-19

where \(V_{\text{sec}}\) is the total voltage across the secondary winding under consideration, taking into account all voltage drops, including
1. diode drop,
2. secondary winding resistance,
3. output inductor resistance,
4. PCB track resistance, and
5. output connector resistance.

The number of turns calculated is then rounded up to the nearest integer value. The number of turns for other secondary windings is calculated using:

\[
\frac{V_{\text{sec}-x}}{N_{\text{sec}-x}} = \frac{V_{\text{sec}}}{N_{\text{sec}}}
\]

Equation 6-20

where \(N_{\text{sec}-x}\) and \(V_{\text{sec}-x}\) are the number of turns and the total winding voltage required for the other secondary windings respectively.

The number of primary turns required is then estimated using:

\[
\frac{N_p}{V_p} = \frac{N_{\text{sec}}}{V_{\text{sec}}}
\]

Equation 6-21

where \(V_p\) is the minimum voltage across the primary winding, allowing for resistance drops.

In the case of the forward transformer, as the demagnetising winding is usually wound bifilar with the primary winding to reduce leakage inductance, its number of turns is invariably chosen equal to the number of turns on the primary.

In all the above calculations, if any of the number of turns is not a whole number, then it will be rounded up to the nearest integer (though design with half-turns is possible with RM cores, it is not implemented in the present work). All the turns calculated are then presented to the user for acceptance as shown in figure 6.16.
CHAPTER 6: DESIGN OF WOUND COMPONENTS

Calculated Primary turns: 115
Calculated 5.0V Secondary Turns: 8
Calculated 12.0V Secondary Turns: 19
Calculated 3.3V Secondary Turns: 5
Calculated Tertiary Turns: 115

Figure 6.16 ES showing the calculated number of turns

The user is given an opportunity to change the number of turns while maintaining the same turns ratios.

6.3.3 Winding Design

Unlike the inductor design, the winding design is complex as there are multiple windings to be accommodated on the core. The winding should ensure [3] minimum leakage inductance and capacitance.

Wire gauge selection

As in the case of the inductor design, the required wire gauges for the different windings are calculated using RMS current and the selected current density with equations 6-6 and 6-7. Standard wire gauges are then selected using the wire database.

As shown in figure 6.17, the expert system presents the standard wire gauges available for all the transformer windings. The user can change the standard values by interacting with the wire database.

Sufficiency of winding area

Even though the area-product approach takes into account different design parameters, the design needs to be checked to see whether the turns fit into the window area of the core for the following reasons:

- As standard wire gauges are available in discrete sizes, it is sometimes necessary to
select a wire gauge whose area is greater than the calculated value. This may require a larger window area;

- When several windings are used, the window utilisation may reduce as there are more insulation layers.

<table>
<thead>
<tr>
<th>Winding Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Select a Winding</strong></td>
</tr>
<tr>
<td>PRIMARY</td>
</tr>
<tr>
<td>Calculated Wire Diameter (mm):</td>
</tr>
<tr>
<td>Current Density (A/sq-mm):</td>
</tr>
<tr>
<td>The standard values:</td>
</tr>
<tr>
<td>Overall Wire Diameter (mm):</td>
</tr>
<tr>
<td>Wire Resistance (ohm/m):</td>
</tr>
<tr>
<td>Bare Copper Weight (gm/m):</td>
</tr>
<tr>
<td>Current Rating (A):</td>
</tr>
</tbody>
</table>

You can change the above values.

Figure 6.17 Standard wire gauge selection for all the windings of the transformer

The window sufficiency is checked by verifying the inequality:

\[ A_w \times K_w \geq \sum_{i}^{m} a_i \times N_i \]  

Equation 6-22

where:

- \( a_i \) = wire-cross section area of the \( i^{th} \) winding
- \( N_i \) = number of turns of the \( i^{th} \) winding
- \( m \) = the total number of windings

The user is presented with the state of the sufficiency test as discussed in section 6.1.6. Figure 6.18 shows a non-satisfactory design of a transformer where the user is advised to restart the design by choosing any of the displayed larger cores.

**Winding layout**

Suitable insulation needs to be provided between the windings to meet the breakdown voltage requirements specified by regulations (e.g. CENELEC, FCC). The insulation
requirements depend upon the application and the specifications of the power supply. Polyester tape, a Type-B insulation material, is suggested as it can withstand high voltages and temperatures.

The software designs the layering of the turns on a given winding space of the coil former, whose dimensions are read from the database, giving suitable allowance for creepage distance. Figure 6.19 shows the expert system displaying the layering information to the user.

### 6.3.4 Optimisation for Maximum Efficiency

The transformer design is then optimised for maximum efficiency. Efficiency of a transformer is given by:

\[
\eta = 100 \times \frac{P_o}{P_o + P_L}
\]

where:

- \(P_o\) = total power of all outputs
To obtain maximum efficiency, an optimum balance between core loss and copper loss must be maintained, which occurs when both the losses are equal. The efficiency can be improved depending upon the amount of core and copper losses as discussed below (figure 6.20).

**Dominant copper loss**

When the copper loss is more than the core loss, the efficiency can be improved by:

- **increasing wire gauges keeping the same core size.** This measure reduces the winding resistance, leading to a reduced copper loss; however, to accommodate all the windings in the winding window, the number of turns in each winding has to be reduced. As a result, the core loss will be more due to a corresponding increase in the flux density to maintain the same secondary induced voltage (equation 6-19). The net effect is an overall reduction in the total losses.

- **using a larger core size.** With a larger core size, the flux density can be reduced which brings down the core loss. Since there is more winding area, larger wire sizes can be used which reduces the copper loss also.
Dominant core loss

When the core is more than the copper loss, the efficiency can be improved by:

1. increasing the number of turns keeping the same core size. With this option, the flux density can be reduced for the same secondary induced voltage, leading to a reduction in core loss. Although the copper loss is more now due to reduced wire sizes to accommodate the windings, the total loss will be less.

2. using a larger core size.

*XpertPSD* aims to utilise the winding area effectively during the entire optimisation
process. The expert system calculates the efficiency and suggests the above options to the user to improve the efficiency as shown in figure 6.21.

<table>
<thead>
<tr>
<th>Checking Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Estimated Copper Loss (W): 5.2</td>
</tr>
<tr>
<td>The Estimated Core Loss (W): 0.9</td>
</tr>
<tr>
<td>The Estimated Efficiency: 98</td>
</tr>
<tr>
<td>The Specified Efficiency: 98</td>
</tr>
</tbody>
</table>

For max. efficiency, the Core Loss should equal Copper Loss.

To improve the efficiency, the design is to be reconsidered with one of the following options. Your choice?

- Increase the wire sizes
- Increase the core size.
- Continue with the design

Figure 6.21 Optimising the transformer design for maximum efficiency

6.3.5 Testing for Temperature Rise

The temperature rise of the transformer must be maintained within acceptable limits. As the surface area affects heat dissipation, this can affect the transformer size. It is argued that secondary effects, such as losses, skin and proximity effects, cooling efficiency, and insulation, play a significant role in determining the overall size of a transformer. The expert system tests the design of the transformer for maximum temperature rise using equation 6-22. If the design fails, the user is given an opportunity to re-design with the next larger core available as explained in section 6.2.6 of the inductor design.

After a successful design of the transformer, the expert system calculates all the resistances and leakage inductances of the windings, and then advises the user to test the power supply design for electromagnetic compatibility.
Chapter 7

ELECTROMAGNETIC COMPATIBILITY

7.1 OVERVIEW

Switched mode power supplies generate high frequency (kHz and MHz) broadband noise which propagates either by radiation or through line conduction. This generated noise may cause malfunctioning of nearby equipment, or other parts of the SMPS such as the PWM control circuit. In most countries, government agencies place legal requirements on emission (noise) levels.

This chapter deals with satisfying the limits imposed on noise signals conducted into the commercial mains power system. The ES based design methodology for EMC includes design of snubbers for power semiconductor devices, analysis of the power supply for emission measurement, and the design of an appropriate filter to reduce the emission levels.

7.2 SOURCES OF EMI

Broadly, the electromagnetic interference coming out from a power supply is of two types:

1. **Conducted emission.** This type of emission is conducted through the input and
output leads of the power supply.

2. **Radiated emission.** This emission propagates through electric and magnetic fields into the surroundings.

The conducted emission may cause radiated emission due to conductors acting as antennas. The conducted noise is separated into two components:

1. **Common-mode (CM) noise.** This type of noise flows out through the phase and neutral conductors and the earth wire (safety ground). In a two-wire system where the earth is not connected to the power supply, CM noise also exists due to parasitic capacitance between the phase/neutral wires and the power supply frame, which acts as a return path.

2. **Differential-mode (DM) noise.** This noise is between the phase and neutral conductors.

Figure 7.1 shows paths of the common-mode noise, $I_{CM}$, and differential mode noise currents, $I_{DM}$.

![Diagram](image)

Figure 7.1 Conducted emissions: (a) common mode current paths; (b) and differential mode current paths

The main sources of EMI in a power supply are explained below.
7.2.1 Power MOSFET Switching Waveforms

Sharp voltage and current edges are produced during fast switching of the power MOSFET. As rise and fall times of a power MOSFET are very small, usually a few tens of nano seconds, the switching waveforms contain high frequency components over a wide bandwidth [114-116].

**MOSFET switch current**

The principal source of differential mode emissions is the high frequency drain current of the MOSFET (figure 7.2). The ac component of this current contains significant harmonics up to several mega-hertz, and flows through the bulk energy storage capacitor, as shown in figure 7.3, creating an effective differential mode voltage source. The magnitude of this voltage depends on the ESL and ESR of the bulk capacitor.

![Figure 7.2 Typical voltage and current waveforms across power MOSFET in a forward converter](image)

The switch current may also induce common mode currents due to radiated magnetic fields if a current path defined by the PCB layout encircles a large physical area [117].
MOSFET drain-source voltage
Common mode conducted emissions are mainly due to parasitic coupling to ground. In a switched mode power supply, the principal source is the high rate of change of MOSFET voltage (figure 7.2). This voltage charges and discharges parasitic capacitances, mainly the capacitance between the MOSFET heatsink to the ground [118-119], thereby transferring high frequency harmonics to the heatsink which will in turn act as a source of radiation. In order to reduce the effect, the heatsink is normally connected to the ground. This arrangement diverts high frequency energy of the drain-source voltage to ground such that it appears as common-mode noise [120-123].

Figure 7.4 shows paths of the common-mode currents produced. The phase-wire common mode current flows through the bulk capacitor due to very high impedance across the primary of the transformer. This results in unequal phase and neutral CM currents, generating differential mode emission also [119].

Transient oscillations
The sudden transitions of the switching waveforms produce high rate of change of voltage (dv/dt) and current (di/dt) values which also result in overvoltage transient ringing or oscillations in resonant circuits formed by the power supply parasitic
capacitances and inductances due to PCB tracks, the isolation transformer [3][124] etc. These very high frequency oscillations also cause emission, mainly radiated.

Figure 7.4 Common mode current paths in a power supply

7.2.2 Diode Reverse Recovery

As explained in section 4.7.2, the output rectifier diodes are normally fast switching and low on-state voltage type. Figure 7.5 shows typical voltage and current waveforms of the rectifier diode in a forward converter. The diode voltage (similar to the MOSFET drain-source voltage), will generate common mode currents in the presence of stray capacitances between the output leads and the ground.

**Transient oscillations**

During the turn-off process, the diode exhibits an abrupt reverse recovery characteristic: the diode current decreases to zero and becomes negative before becoming zero again. As the amplitude of the reverse current can be quite large with a typical fall time less than 1 μs, high voltage transients with wide frequency spectra can appear in a resonant circuit [125] formed by the leakage inductance of the isolation transformer and the junction capacitance of the diode. The diode will be damaged if the peak of this ringing voltage causes the diode blocking capability to be exceeded.

Because the switching frequency is very high, interference due to the diode reverse
recovery can easily couple into other parts of the power supply circuit. This will also cause malfunctioning of the control circuit, leading to instability of the power supply [124].

![Diode current and voltage waveforms](image)

**Figure 7.5** Typical current and voltage waveforms across the rectifier diode in a forward converter

### 7.3 ES BASED EMC DESIGN

Figure 7.6 shows the ES design methodology to meet EMC regulations. There are government regulations covering both the types of emission, which have to be met. *XpertPSD* suggests several measures to control the conducted emission, as shown in the figure 7.6:

1. **Snubber circuits.** These are low pass RC filters which attenuate high frequency harmonics produced in the switching action of semiconductor devices.

2. **EMI filter.** As a last resort to block conducted emission reaching the mains power supply, a suitably designed filter is placed near the mains input to the power supply.

The filter design involves adding suppression elements or changing existing elements
XpertPSD analyses the power supply under design for conducted emission using the SPICE-simulator, and an appropriate input filter is designed. The rules for the design of the input filter are built into the KB: however, due to the nature of the problem a trial-and-error approach is required.

After completion of the design of the EMI filter, the ES prepares a detailed design report, and stores it in a file 'project-name'.esd. The user may view/print the file.

The following sections explain the implementation of the above design methodology in the ES.

7.4 EMC REGULATORY BODIES

XpertPSD asks the user to select governmental agency/agencies EMC requirements. The ES aims to meet conducted emission requirements under the Information Technology category of the following agencies:

1. European Committee for Electrotechnical Standardisation (CENELEC). This committee formulates and approves safety and electromagnetic standards.
CENELEC members are national electrotechnical committees of United Kingdom, Germany, France, and other European countries, and are bound by its regulations. The CENELEC directive EN 55022 specifies limits and methods of measurement of radio disturbance characteristics of information technology equipment [126].


All the above standards classify power supplies into two types:

- **Class A.** Products that are used in a commercial, industrial or business environment come under this class.

- **Class B.** The products that are used in a residential environment are branded Class-B products.

The allowed emission limits and frequency ranges for the above agencies are shown in figure 7.7. The Class B emission limits are more stringent than the Class A limits, under the assumption that interference in an industrial environment can more readily be corrected than that in a residential environment, where the interference source and susceptible device are likely to be in close proximity.

After selecting the agency and the Class, the ES interprets the respective agency conducted emission curves of figure 7.7, and calculates the allowed conducted emission limit. Emission levels are measured, in this work, in dBμV [128]:

\[
dB\mu V = 20 \times \log \left( \frac{V_{\text{noise}}}{10^{-6}} \right)
\]

Equation 7-1

where:

\(V_{\text{noise}}\) = noise voltage

The ES notifies the allowed emission levels to the user whereupon any modification can be made (Figure 7.8).
Figure 7.7 Conducted emission limits of government agencies. (a) EN 55022 (b) FCC

Table 7.1 Emission Limits

<table>
<thead>
<tr>
<th>Switching Frequency (Hz):</th>
<th>100000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic Emission Standard:</td>
<td>EN55022</td>
</tr>
<tr>
<td>The Allowed Conducted Emission (dBuV):</td>
<td>79.0</td>
</tr>
</tbody>
</table>

Enter Your Choice:

New Conducted Emission Allowed (dBuV): 79.0

Figure 7.8 ES window displaying allowed emission level
7.5 SNUBBER CIRCUITS

As the most effective way of dealing with the EMI is to prevent the EMI from being generated at the source [3], XpertPSD suggests using snubbers across the power MOSFETS and the output diodes. This approach reduces the radiated and conducted interference, thus reducing the need for EMI filters and other protective measures.

Snubbers are small electric networks whose primary function is to control the effects of circuit reactances by absorbing energy from these elements. Snubbers:

- reduce device stress by dissipating an excess turn-off energy which otherwise would be dissipated by the transistor. This transfer of losses to the snubber circuit increases reliability of the devices.

- smooth sharp edges in the switching waveforms, thereby reducing EMI [3][129].

- dampen resonant or ringing current formed by the parasitic LC circuits.

In this work, design of passive RC snubbers, as shown in figure 7.9, is implemented.

![Figure 7.9 Snubber Circuit for MOSFET/Diode](image)

7.5.1 Snubbers for Power MOSFETs

XpertPSD designs the component values of the snubber circuit using [90][130-131]:

\[ C_{sm} = \frac{I_{ds}(t_r + t_f)}{V_{ds}} \]

Equation 7-2
\[ R_{sm} = \frac{t_{on}}{3 \times C_{sm}} \]  

Equation 7-3

where:

- \( C_{sm} \) = MOSFET snubber capacitance
- \( I_{ds} \) = maximum drain-source current
- \( V_{ds} \) = maximum drain-source voltage
- \( t_r \) = maximum drain-source voltage rise time
- \( t_f \) = maximum drain-source current fall time
- \( R_{sm} \) = MOSFET snubber resistance
- \( t_{on} \) = turn-on period of the MOSFET

If the above calculated resistance is too low to satisfy the condition that the capacitor discharge current through the switch at turn-on should be less than 25\% of the maximum switch current, the ES increases the resistance value with a lower limit at:

\[ R_{sm} > \frac{V_{ds}}{0.25 \times I_{ds}} \]  

Equation 7-4

The maximum power rating, \( P_R \), of the above resistor is given by:

\[ P_R = \frac{1}{2} \times C_{sm} \times V_{ds}^2 \times f_s \]  

Equation 7-5

The designed snubber values are then shown to the user with options to modify them (figure 7.10).

### 7.5.2 Snubbers for Output Rectifier Diodes

Similar to the power MOSFET snubber design, the ES calculates the values of the diode snubber components using [90-91]:

\[ R_{sd} = \frac{\sqrt{L_T/C_J}}{n} \]  

Equation 7-6

where:

- \( R_{sd} \) = snubber resistance of the diode
$L_r = \text{leakage inductance of the transformer}$

$C_j = \text{junction capacitance of diode}$

$n = \text{primary-to-secondary turns ratio of the transformer}$

The designed snubber component values:

<table>
<thead>
<tr>
<th>Suitable Snubber Capacitance (pF):</th>
<th>62</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Nearest Standard Capacitor Value (pF):</td>
<td>68.0</td>
</tr>
<tr>
<td>The Snubber Resistance (ohm):</td>
<td>19607</td>
</tr>
<tr>
<td>Power Dissipation (mW):</td>
<td>451</td>
</tr>
</tbody>
</table>

Figure 7.10 ES dialog-box displaying designed snubber component values

The snubber capacitance may be chosen anywhere from 0.01 to 0.1 \( \mu \text{F} \), and is normally set at:

$$C_{sd} = 10 \times C_j$$  \hspace{1cm} \text{Equation 7-7}

The power dissipation rating of the resistor is given by:

$$P_R = \frac{1}{2} \times C_{sd} \times \left( \frac{V_{p_{\text{max}}}}{n} \right)^2 \times f_s$$  \hspace{1cm} \text{Equation 7-8}

where:

$V_{p_{\text{max}}} = \text{maximum primary voltage}$

As in the case of the power MOSFET snubber design, the ES notifies the design results to the user.
7.6 MEASUREMENT OF EMISSION

Though there are methods such as transmission-line modelling for the calculation of anticipated emission levels, the SPICE-simulation approach is used in the expert system as it offers more flexibility at the design level. However, accurate SPICE-models for both active and passive components [118][132-133] are required.

The simulation method is similar to the practical method used to measure EMI experimentally [134] as shown in figure 7.11. The various circuit modules, as explained below, are simulated to obtain transient analysis data, and this data is processed to obtain emission levels at frequencies of interest.

![Figure 7.11 A set-up to measure EMI of a power supply](image)

7.6.1 Line Impedance Stabilisation Network

Emissions from a SMPS under test are measured using a Line Impedance Stabilisation Network (LISN) inserted between the mains power supply and the SMPS ac cable. Each government agency prescribes its own topology for the LISN. The objectives of a LISN are:

- to present a constant impedance (50Ω) at the power supply’s outlet (between the phase conductor and the ground wire and between the neutral conductor and the ground wire) over the frequency range of the conducted emission test;
- to block conducted emissions that are not produced by the power supply being tested so that only the conducted emissions of the power supply are measured.
At the power line frequency, the LISN provides a low impedance path for mains current to flow from the mains supply to the power supply under test, and a high impedance path to ground.

The LISNs of different EMC regulatory bodies [116][126-127] are shown in figure 7.12. In both the LISN networks, the circuit elements have the following roles:

- Capacitor $C_1$ diverts "external noise" on the commercial power mains and prevents that noise from flowing through the measurement device and contaminating the test data;
- Inductor $L_1$ blocks the above mentioned noise;
- Capacitor $C_2$ prevents any dc from overloading the input of the test receiver, and resistor $R_d$ allows discharging of the capacitor $C_2$ if the test equipment is removed.

Figure 7.12 LISN for use in the conducted emission measurement: (a) EN 55022; (b) FCC
7.6.2 Modelling Power Supply for Emission Measurement

The power supply model shown in figure 7.13 is used in the expert system to estimate the emission. Since EMI occurs at frequencies substantially in excess of the input frequency, simulation is limited to a small portion of the mains supply. Additionally, over the period of interest, the input voltage may be assumed as constant in value, for example, equal to peak mains voltage. While simulating the circuit, actual switch models of the power semiconductor devices are required.

![Figure 7.13 A power supply model for measurement of emission](image)

**Bulk capacitor**

As explained in section 7.2.1, the principal source of differential mode emissions is the impedance of the input rectifier filter capacitor. A high value of capacitance is normal for smoothing and for the power supply to have an adequate hold-up time. The larger the capacitor value, the smoother the line voltage, but the higher the DM currents and hence increased EMI [135]. The model of the bulk capacitor takes into account both ESL and ESR which along with the bulk capacitance determine the differential mode noise current.

**Heatsink Capacitance**

Common mode conducted emissions are mainly due to the heatsink to ground
CHAPTER 7: ELECTROMAGNETIC COMPATIBILITY

capacitance [118][120]. This capacitance is formed by, typically, a TO-3 can and the heatsink separated by an insulator.

The capacitance is given [119] by:

\[ C_{sink} = \frac{0.0885 \times \varepsilon_r \times A_{drain}}{t_{insul}} \text{ pF} \]

where:
\[ \varepsilon_r = \text{relative dielectric constant} \]
\[ A_{drain} = \text{collector area, cm}^2 \text{ (typically 5 cm}^2 \text{ for a TO-3 package)} \]
\[ t_{insul} = \text{thickness of the insulator, mm} \]

Typically, \( C_{sink} \) varies between 142pF to 156pF (with mica insulation).

**Parasitic capacitance, \( C_{load} \)**

This capacitance represents major parasitic leakage paths to ground on the output side. A typical value of 100pF (between 5pF and 100 pF) is used in the simulation [118][135]. This capacitance also helps the simulation to converge.

**Transformer**

The model used for the transformer takes into account leakage inductance, which together with stray capacitances across different windings forms a resonant circuit with high frequency oscillations during switch current changes [136].

### 7.6.3 Separation of CM and DM Emissions

To reduce conducted emission noise at a particular frequency, the power supply filter element which affects this noise must be changed. This necessitates separation of the total noise into two components.

A noise separator network has been developed in references [137-139]. A SPICE model is developed for this network as shown in figure 7.14. The measured phase voltage, \( V_P \), and neutral voltage, \( V_N \), of the LISNs are:

\[ V_P = V_{CM} + V_{DM} \]  \hspace{1cm} \text{Equation 7-10}

\[ V_N = V_{CM} - V_{DM} \]  \hspace{1cm} \text{Equation 7-11}
The model uses a combination of adder, subtractor and divider networks to separate the two voltages $V_{CM}$ and $V_{DM}$.

![Figure 7.14 SPICE-based emission separation model](image)

After a successful time-domain simulation of the power supply model along with the LISN and noise separator network to calculate the common-mode and differential-mode voltages, the ES executes the program module, *FftEvaluate*, to calculate emission levels in $\text{dB}_{\mu}\text{V}$ at specified frequencies. Figure 7.15 shows *XpertPSD* displaying the different emission levels.

<table>
<thead>
<tr>
<th>Electromagnetic Emission Standard:</th>
<th>EN55022</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Switching Frequency (Hz):</td>
<td>100000.0</td>
</tr>
<tr>
<td>The different emissions found by simulation are:</td>
<td></td>
</tr>
<tr>
<td>The max. emission occurred at the frequency (Hz):</td>
<td>100000.0</td>
</tr>
<tr>
<td>The Common-mode Emission (dBuV):</td>
<td>130.70</td>
</tr>
<tr>
<td>The Differential-mode Emission (dBuV):</td>
<td>77.69</td>
</tr>
<tr>
<td>The Total Conducted Emission (dBuV):</td>
<td>130.72</td>
</tr>
<tr>
<td>The Allowed Conducted Emission (dBuV):</td>
<td>79.00</td>
</tr>
</tbody>
</table>

The Conducted Emission exceeds the limit and there is a need to use/redesign input emi-filter.

![Your choice](image)

Figure 7.15 ES window showing the measured CM and DM emissions
7.7 DESIGN OF EMI FILTER

The ES tests the maximum emission at each frequency within the specified band of the frequency range. If it is not within the stipulated limit, then the system suggests the use of an EMI filter at the input of the power supply to ensure that the conducted emission is below stipulated emission levels at all frequencies.

7.7.1 Generic EMI filter

Figure 7.16 shows a generic line filter which suppresses both common mode and differential mode emissions [3][128][140]. The different components and their purposes are:

- **"Y"-Capacitors, \( C_y \).** These line-to-ground capacitors divert common-mode currents to the ground. Their insulation properties should be approved by safety agencies.

- **"X"-Capacitors, \( C_x \).** These line-to-line capacitors divert differential-mode currents. These capacitors too should have their insulation properties approved by safety agencies for use as line-to-line capacitors.

- **Common-mode choke.** The common-mode choke is represented by coupled inductors. Typically, this element consists of two identical windings on a common ferrite core with suitable characteristics over the conducted emission range. The self-inductance, \( L_c \), blocks the common-mode currents whereas the leakage

![Figure 7.16 Generic input EMI filter](image-url)
inductance, $L_D$, inhibits the differential-mode currents. Care should be taken to ensure that the ac input current does not saturate the core.

### 7.7.2 Design of the EMI Filter

For a typical power supply, DM emissions dominate at lower frequencies (< 800 kHz), whereas CM emissions dominate at higher frequencies [141-144] as shown in figure 7.17. The total emission is:

$$V_T = \sqrt{V_{CM}^2 + V_{DM}^2}$$  \hspace{1cm} \text{Equation 7-12}

Since the total emission current is the 'complex sum' of CM and DM voltages, the total emission is determined by the dominant component. In order to reduce the level of the dominant component and hence the total emission, the expert system adjusts the EMI filter elements which affect that component.

![Figure 7.17 Frequency spectrum of CM, DM and total emissions](image)

From the CM and DM equivalent circuits of the EMI filter of figure 7.18:

- the CM emission is affected by the values of $C_Y$, the self-inductance $L_C$ and leakage
inductance \( L_D \) of the common-mode choke;

- the DM emission is affected by all the filter components, but predominantly by the values of \( C_X \) and \( L_D \).

\[
\begin{align*}
\text{(a)} & \quad \text{Phase} \quad \frac{L_c}{2} \quad \text{Phase} \\
& \quad 2C_Y \quad \text{Neutral} \quad \text{Neutral} \\
\text{(b)} & \quad \text{Phase} / \text{Neutral} \quad L_c \quad 2L_0 \quad \text{Phase} / \text{Neutral} \\
& \quad C_X \quad C_X \quad CV/2 \quad \text{Earth} \quad \text{Earth}
\end{align*}
\]

Figure 7.18 Equivalent circuits of the generic filter for: (a) CM emission current; (b) DM emission currents

A hierarchical design approach in which filter components are added one after another as required is implemented in the ES, as shown in figure 7.19. After the addition/change of a filter component, the ES calculates emission levels and checks whether it is CM or DM to find out which filter component should be added or modified.

**Y-capacitors**

The first blocking measure starts with Y-capacitors. Generally, the higher \( C_Y \), the greater will be the blocking. However, there is an upper limit governed by the maximum allowed leakage current set by safety agencies. This maximum value is given by:

\[
C_{Y_{\text{max}}} < \frac{I_{\text{leak}}}{2\pi f_{\text{main}}} V_{ac(rms)}
\]

where:

\[I_{\text{leak}} = \text{maximum leakage current}\]
\[ f_{\text{main}} = \text{mains supply frequency} \]
\[ V_{ac(RMS)} = \text{mains normal supply voltage} \]

The knowledge base contains ground leakage current limits for different agencies [85] as shown in Table 7-1.

Table 7-1. Allowed leakage currents and Y-capacitor values

<table>
<thead>
<tr>
<th>Regulation</th>
<th>Leakage current limit (mA)</th>
<th>Max. Y-capacitor value (\mu F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 55022</td>
<td>0.25 to 5.0 at 250V, 50Hz</td>
<td>0.0032 to 0.064</td>
</tr>
<tr>
<td>FCC UL 1283</td>
<td>0.5 to 3.5 at 120V, 60Hz</td>
<td>0.011 - 0.077</td>
</tr>
</tbody>
</table>

Capacitance \( C_Y \) added to either phase or line forms a parallel circuit with the
equivalent LISN resistor, $R_{LISN}$, which is equal to 50Ω. Each will reduce both CM and DM above the break frequency, $f_{by}$:

$$f_{by} = \frac{1}{2\pi R_{LISN} C_Y}$$

Equation 7-14

Since the maximum allowable value for $C_Y$ is preferred, the minimum break frequency, $f_{by-min}$ that could be obtained is:

$$f_{by-min} = \frac{1}{2\pi R_{LISN} C_{Y_{max}}}$$

Equation 7-15

The ES calculates the maximum value of $C_Y$ that fits within the above constraints and asks the user to accept/modify it, as shown in figure 7.20.

![Design of Input Filter](image)

**Figure 7.20 The ES designing the EMI filter: addition of Y-capacitor**

**X-capacitor**

The line-to-line X-capacitor, when added to the previous filter component Y-capacitor as shown in figure 7.21, will also form a parallel circuit with the LISN output resistor. This X-capacitor will only reduce DM above a break frequency, where the equivalent impedance of the X- and Y-capacitors to DM components equals the LISN output resistance:
\[
f_{byx} = \frac{I}{2\pi R_{LISN} C_{YX}}
\]

Equation 7-16

where:

\[
C_{YX} = 2C_x + C_y
\]

Figure 7.21 EMI filter with Y- and X- capacitors

The choice of \(C_x\) is determined by the lower limit of the frequency range over which the emission should be reduced. The ES calculates the required X-capacitor, and notifies the user of the design. A typical value of X-capacitor is 0.047 \(\mu\)F [128].

**CM inductance**

After the inclusion of Y-capacitors, if the emission level is still too high the ES suggests adding common-mode inductance. As expected from the figure 7.18, this element blocks CM emission, and its value is given [135][145-149] by:

\[
L_c = \frac{2A_{cm}}{10} \frac{40}{(2\pi f_{emission})^2 2C_y}
\]

Equation 7-17

where:

\[A_{cm}\] = required attenuation of CM emission, dB

\[f_{emission}\] = frequency at which the emission level is to be reduced

The ES calculates the inductance required to reduce the CM emission to a level well below the allowed limit. Typical values for the inductance are of the order of 10mH.
DM inductance

After inclusion of both X-capacitors and Y-capacitors, if the DM emission level is still too high, the ES proposes adding differential-mode inductance. The differential mode inductance, as seen from the figure 7.18, attenuates DM emission, and its value $L_D$ is given [135][145-149] by:

$$L_D = \frac{2A_{dm}}{10^{\frac{40}{(2\pi f_{emission})^22C_X}}}$$

Equation 7-18

where:

$A_{dm} = \text{required attenuation of DM emission, dB}$

The ES calculates the above inductance required to reduce the DM emission to a level well below the allowed limit. Typical values for the inductance are of the order of a few micro henries.

Figure 7.22 shows the ES notifying the user about the complete filter design. When the emission levels are still not met, the user may adjust the values of filter components until the requirements are satisfied.

![Design of Input Filter](Image)

Figure 7.22 The ES window showing design results of the EMI filter
8.1 OVERVIEW

Previous chapters describe the expert system based philosophy for designing power electronic systems. In this chapter, the difficulties associated with the design of power electronic systems are highlighted and the developmental and design phases of the expert system, \textit{XpertPSD}, are discussed.

This chapter describes the design issues tackled and implemented in the expert system, critically examining each aspect. It ends with a discussion of future research into other design aspects such as optimisation, and schematic generation.

8.2 PROGRAMMING ASPECTS

\textit{XpertPSD} has been built using wxCLIPS, an expert system development tool available in the public domain. Considerable time was devoted to the choice of the most appropriate operating system and expert system development tool. Due to its wide usage in industry, the MS-Windows operating system was selected. The choice of suitable expert systems was limited as there were few expert systems with the necessary functions and flexibility.

The code of the expert system in wxCLIPS syntax (including the user-interface, facts-
base and knowledge base) requires approximately 2 mega bytes of memory. Whenever the expert system is run, wxCLIPS compiles the code, and then executes it. Though it slows down the execution time (e.g. selection of a suitable core size for an output inductor takes approximately 5 to 10 seconds on 80486/66MHz PC), this approach was followed as it is easy to modify the code and thereby speeds up the development of the expert system. An alternative to the above approach is to programme the code using the advanced programming techniques of CLIPS [150].

In XpertPSD, the expert system runs other software components, as shown in the figure 3.2, including the SPICE simulator, the databases and the data processor. To keep the architecture of the expert system as simple as possible, these external software modules are not embedded into the ES. The data transfer between the expert system and other components is through i/o device operations, i.e., by file operations. This approach is followed as there is no other suitable functionality within wxCLIPS, but the approach is not efficient and consumes considerable computer resources. A more robust data transfer approach in MS-Windows would be the alternative technique of dynamic data transfer (DDE) protocol.

8.2.1 Design Validation

SPICE is the standard software for electrical circuit simulation, with built in powerful algorithms that make the results widely acceptable. In XpertPSD, SPICE is used to validate circuit design; however, a number of problems were encountered.

To simulate a power supply, accurate models of the various circuit elements are required. The simulator has in-built models for basic circuit elements and default models for semiconductor switches. However, SPICE models of power semiconductor devices and power supply IC controllers were not readily available, and consequently considerable time was required to develop the models necessary for the simulations, prolonging the development of the expert system.

No accurate models for power supply controllers could be developed, as the manufacturers of these ICs are reluctant to release their electrical characteristics. This forced the use of macro-models and hence the simulation results have a limited
accuracy. However, the use of macro models greatly reduces the simulation time.

The major disadvantage of a SPICE based simulator is the long simulation time (this author observed that simulation of a single-output forward converter with actual device models took approximately 30 minutes on 80486/66MHz PC) required to simulate steady state behaviour with real device models. This can be alleviated by using advanced computer systems such as Intel Pentium processors.

8.2.2 Database Representation

The databases used in XpertPSD are simple representation of data in ASCII-files, with each field of the database separated either by a space or a non-alphabetic character. Simple i/o file operations are used to retrieve data.

Commercial database packages such as Access [151], Dbase [152] use different formats of data representation, with a provision for portability of the databases across different computing platforms.

There is a trade-off between using a commercial database system and an ASCII-format database system:

**Overheads**

As ASCII-format databases are developed, maintained, and operated upon without commercial database packages, these may be called 'stand-alone databases'. This independent data representation reduces overheads by eliminating the need for commercial database software.

**Portability**

Portability of the databases is one of the requisites for easy and effective implementation of the expert system in industry. For commercial reasons, many companies, such as Cortech Systems Ltd. [153] and Minebea Ltd. [154], carry out their design and development at a different location to their production (in the above two companies, the locations are in different countries). Under the above circumstances, a simple and portable database accelerates the transfer of design information between design and production units. It is one of the reasons for employing ASCII-format databases.
Computing resources
ASCII-format is not suitable for large databases, as it is not an efficient form of data storage and data retrieval takes longer. Gary Riley, one of the architects of CLIPS, is of the opinion:

“When database operations work satisfactorily, then it really doesn't matter whether a text file or a real database is used. Offhand, I don't see why using a text file vs. a database would necessarily require lots more/less memory. The real question is probably speed. If the text file is fast enough and easily implemented, then go with it.”

In the design of power electronic systems, there are no huge databases required and hence ASCII-format may be used. When data search time is a concern, it can be improved by using sequential query language which supports ASCII-format of databases.

As explained in section 3.3.7, the user can update the databases with new components. When new semiconductor devices are included, the user should also enter their SPICE models in the device library folder of the expert system.

8.3 LIMITATIONS OF DESIGN MODULES

8.3.1 Power Circuitry
This module deals with preliminary circuit design including design of input and output rectifiers, design of output LC filter, selection of different components selection etc.

Selection of a converter is based on power output and isolation requirements. This may be inadequate in some situations, and more stringent consideration should be used based on cost implications coupled with an optimised design. The ES should allow the user to specify cost constraints, and possibly examine different designs.

8.3.2 Control System
In this module, XpertPSD implements direct duty and current-mode control with standard power supply controllers. The ES also designs a suitable compensation circuit to provide a phase margin of 45-60 degrees at a desired cross-over frequency.

While evaluating the compensation circuit, the control system has been validated to
ensure a satisfactory transient response to sudden load change only. Other aspects such as line regulation, surge load conditions, and turn-on and turn-off overshoots are not verified.

8.3.3 Magnetics Design

The selection of the magnetic core is one of the principal aspects in the design of wound components. Two possible approaches were studied:

1. **Area-product approach.** This is a mathematical approach where selection of the core is based on energy storage and winding area.

2. **Graphical approach.** In this approach, the core energy and copper loss characteristics supplied by the manufacturer are used to select an appropriate core.

Though the graphical approach offers core selection based on closer circuit working conditions of the core, this was not used due to the non-availability of uniform core characteristics from several manufacturers. Since the area-product approach offers more uniform core selection with different cores, this technique was implemented in the expert system. Accuracy was improved to that of the graphical approach by examining in detail aspects such as core saturation, temperature rise and maximum efficiency.

When designing the filter inductor, the expert system suggests a suitable length of air-gap needed in order not to saturate the core, but currently it does not check whether introduction of the air-gap alters the operating conditions of the core, such as flux density and temperature rise (due to a change in losses).

8.3.4 Electromagnetic Compatibility

It was hoped that the expert system methodology would be effective in tackling EMC issues in the power supply. It was demonstrated that the design of the EMI filter to reduce conducted emission noise can be implemented successfully with heuristic knowledge. However, the estimation of the conducted emission using SPICE simulation is very sensitive to circuit parasitics and device models as explained below.

- **Power semiconductor switches.** Repeated simulations of a power supply were carried out changing the SPICE semiconductor device models starting from ideal
to exact models. It was observed that accurate measurement of electromagnetic conducted emission depends critically on the SPICE models of the power supply. A major handicap was the non-availability of exact models from the manufacturers. Device models may be evolved using manufacturer datasheets, but it is tedious and often inaccurate as the manufacturers do not normally disclose all device characteristics.

- **Parasitic capacitances.** These greatly affect the EMI as discussed in section 7.2. It is very difficult to estimate the capacitances accurately, though there are mathematical formulae to calculate them: however, the formulae become inaccurate as soon as the PCB is populated with components since the parasitics are heavily dependent on layout.

The above limitations make the simulation of emissions unreliable, and is likely to lead to inaccurate design of the power supply EMI filter. Though it was not accurate in evaluating the EMI, it was still possible to evolve a satisfactory approach to reduce conducted emission.

### 8.4 EVALUATION OF THE ES

Being computational systems, ES are generally more consistent and accurate in their reasoning than are human designers. The complexity of the reasoning process increases with the size of the knowledge base, particularly the number of rules. Should the rules be coded erroneously into the knowledge base, then false conclusions could be reached.

As with any other software system, expert systems need thorough evaluation with wide ranging tests. In this project, *XpertPSD* was evaluated with three power supply designs:

1. **Buck converter with direct duty ratio control.** This design, taken from a publication by Bunlaksananusorn et. al. [155] at the University of Edinburgh, evaluates the design methodology of buck-family converters with direct duty ratio control.

2. **Cortech Systems' power supply.** This power supply, based on the forward
converter topology, is designed for desktop computer applications. It has three outputs, and is current-mode controlled.

3. Minebea's power supply. This is a forward converter with a similar specification to the above power supply. The rationale behind evaluating another similar design is to check the flexibility and consistency of the ES with different designs.

Both XpertPSD and actual design results along with their specifications are given in Appendix A. Full specifications and design information is not given due to restricted access and proprietary rights of the companies.

The design results were compared module by module. Not all the ES generated design results could be compared. This was particularly noticeable in the choice of components and control circuit. Selection of various components depends upon the designer's choice, and is influenced by economic and manufacturing considerations. Also, there is a limited choice of components in XpertPSD, especially power semiconductors and magnetic cores.

The topology selection methodology could not be tested fully as only buck and forward converters are supported, hence the selection appeared simple in all the design examples.

In input rectifier design, the most important aspect is the design and selection of the reservoir capacitor. XpertPSD selects this capacitor by consideration of the allowed ripple voltage and required hold-up time. The ES suggested capacitors are very similar to those used in the commercial power supplies.

The ES designed values for the output filter inductances closely matched the commercial designed values, but the designs could not be fully compared as coupled inductors and second-stage LC filters were used in the commercial designs which are not supported in XpertPSD. Consequently, the expert system predicted higher filter capacitor ESR requirements. In the buck converter design example, the ES suggested filter values are very similar to those in [155].

Comparing the control system, the same control methods as advocated by the ES are used in the commercial power supplies, but their implementation was different. In
both the commercial power supplies, isolation in the feedback loop was provided using an opto-coupler, but in XpertPSD the implementation was kept simpler: opto-isolation was not included. Another noticeable difference is the closed loop regulation of the outputs: in both the Minebea and Cortech Systems power supplies, all the main outputs except the auxiliary outputs are regulated, whereas in the ES design, regulation was only provided for the output with the largest load current. These variations made the ES suggested feedback circuit components different from those of the commercial power supply values.

**XpertPSD** produced a complete magnetics design which include core type, winding and bobbin details etc. However, the magnetic designs could not be compared as the magnetic cores used in the commercial power supplies were different from the ES choices.

Designing for EMC in the ES mainly involved measurement of conducted emission using simulation methods. Not much correlation between the ES and commercial designs could be obtained. In one of the designs, the ES suggested that no EMI filter was necessary, whereas, an EMI filter was actually used in the original design. This under-estimation was due to the macro SPICE simulation models used.

The evaluation was limited to the above set of examples since it was not feasible to test the ES with a wide range of specifications. This makes the response of the expert system to all the possible combinations of input specifications uncertain.

### 8.5 ECONOMICS OF XpertPSD

The research, which was initiated in late 1993, involved active programming for about two years. **XpertPSD** has been aimed at the power supply design industry, to increase productivity by providing efficient and faster designs.

**Efficient design**

Since the design is carried out using a pool of design expertise, expert system based design should yield an efficient power supply design.

Most switched mode power supply companies employ a CAD engineer to develop a
production-level PCB design using CAD tools such as AutoCAD, PowerPCB etc. Associated tasks may also include maintenance of up-to-date lists of available components, creation of necessary component drawings to be used in a PCB layout, and generation of a bill of materials. As these tasks involve frequent consultation with design engineers, there is scope for improvement in the existing design approach.

With expert system design methods, it would be possible to co-ordinate the above tasks more effectively by integrating the CAD tasks within the expert system.

**Faster design cycles**

It is noteworthy how much time can be saved by using an ES to assist with a design. Mr Richard Soh, the chief engineer at Minebea Electronics (UK) Ltd, in Port Glasgow, states that a typical overall product development cycle for a complete power supply takes 4 to 6 man-weeks from initiation, with the first 3 man-weeks spent on initial design and verification as shown in Figure 8.1.

![Figure 8.1 Comparison of expert and non-expert system design approaches](image)

The expert system assisted design approach could reduce the initial design phase to less than week (depending upon the complexity of the design), most of which will be spent on design verification. Even with the simulation tools, it is still necessary:

1. to construct the netlist/schematic,
2. to simulate the netlist,
3. to trouble shoot simulation errors, and
4. to process the results.
With the embedded support for design and verification, the expert system should accelerate the design validation phase considerably.

8.5.1 Maintenance of the Software

A considerable overhead is the requirement to maintain the software, including both programming and non-programming tasks. Non-programming tasks are mainly concerned with maintenance of the databases.

Programming tasks include the addition of new converter designs, and enlargement of the knowledge base. These tasks need skills in:

- programming wxCLIPS, the expert system development tool,
- programming in C-language, and
- using GNUPLLOT and WinDig.

Engineers with these skills are not readily available, so maintenance of the expert system needs a considerable investment from the power supply manufacturer. It may not be viable to employ a full-time engineer to maintain the expert system. The economic viability of enlarging the expert system to include other switched mode converter designs is thus reduced, and depends on the likely frequency of usage of any such design.

Expert system assisted power supply designs are robust, critically examined and optimised, so maintenance of the software should be advantageous even for small-scale industries. A CAD engineer could be entrusted with maintenance of the non-programming issues of the expert system.

8.6 FLEXIBILITY OF THE ES

The ES currently designs buck and forward converters: however, the knowledge base can be enlarged to design other converter topologies such as flyback, boost or resonant converters. Though the design methodology of the switched mode converters remains the same (figure 3.1), the knowledge base must be equipped with rules governing the design of each converter topology.
8.6.1 Converter Design Knowledge

The KB of the ES should be updated with selection and design knowledge for the proposed converters. The ES is already programmed with the rules to select an appropriate converter from a list of common converters topologies (figure 4.5) based on required output power. The design has a modular approach, as shown in figure 8.2, so the addition of knowledge of new converters does not affect the existing designs.

![Diagram](image)

Figure 8.2 Converter design: a modular approach

New facts and rules must be programmed into the knowledge base. There are three different families of converter which should be considered.

**Buck-Family**
Knowledge of half-bridge and full-bridge converter design can be added with ease as these share most of the properties of the forward converter.

Designs of wound components depend upon the same magnetic principles, and hence the design rules will be similar to those used for the forward converter. Normally the
power handling capability of the wound component is considerably larger, so a different set of magnetic cores and construction methods are likely to be required.

**Buck-Boost Family**

The ES already supports selection of the buck-boost family of converters (boost, buck-boost, or flyback). However, new rules are needed to design the magnetic components and the control system. Since the goals (gain and phase) of feedback loop design are similar to those of buck converters, the design of the control system is similar, but new rules are required to study the small-signal characteristics of these converters. These converters are normally operated in the discontinuous current mode, so the compensation topology will be different. Existing power supply IC controllers can still be used.

As the power handling capability of the wound components is likely to be different, a different set of magnetic cores may have to be used.

**Resonant converters**

Resonant converters operate on different principles from buck or buck-boost family converters. The design methodology may be similar, but a new breed of knowledge base module has to be created in the ES as currently there is no support available currently for resonant converters.

There is a wide range of resonant topologies, such as load-resonant converters, resonant-switch converters etc. [102]. A different feedback control is normally required because most operate using frequency modulation. As more sophisticated control ICs are required, modifications to the existing power supply control ICs database needs to be carried out. Different feedback compensation topologies will also be required. The wound component designs would be similar, but with new design equations.

**8.6.2 Non-Standard Converters**

The advantages of *XpertPSD* are most apparent where a user is regularly producing variations of standard designs, such as forward converters for computer power supplies. These variations may include the number of outputs, different output
voltages, power throughput etc. XpertPSD is not so easily able to cope in cases where the user needs to make changes to the standard topologies to meet the design specification, such as including synchronous rectifiers in the output circuit to reduce losses, or employing soft-switching techniques to reduce switching losses. Changes such as these require substantial effort in updating the design knowledge in the expert system. Moreover, it will not be productive to update the KB to design a converter if this converter is not likely to be designed regularly.

The author expects that design changes could readily be incorporated into an already initiated design if there was a schematic generation capability in the ES. With this feature, design modifications could be made in a schematic which would update the converter and design validation knowledge in the ES. Lack of schematic capture capability is a major limitation of the XpertPSD: this is further discussed in section 8.8.2.

8.6.3 Design Environment

From the above discussion, it can be seen that there are no major modifications required in the structure of the expert system to adapt it to new converter topologies.

User-interface

Since the type of application is the same (i.e., switched mode power supplies), the existing user interface will not require modification when designing buck or buck-boost converters, but new dialog boxes will be required to design resonant converters. These modifications will be particularly demanding for the design of the feedback loop as different compensation topologies and compensation criteria are required. Apart from this, no major redesign of the user interface is anticipated.

Design validation

During design validation, a circuit is simulated to produce a set of circuit voltages and currents, which is compared with the original design specification. This validation process remains the same for all converters, but for new converter topologies:

1. new macro-models need to be developed, and
2. the circuit variables of interest may change.
Necessary rules to generate SPICE netlists for the converters should be incorporated into the KB. This knowledge of converters should emphasise the performance variables to be verified in the simulation, and link with the appropriate macro-models. In addition, the user interface must be updated to include more GUI forms (such as dialog-boxes).

It is currently not possible to edit the netlist as changes require to be mapped into the design knowledge, mainly due to the lack of schematic generation in XpertPSD. This prevents the user from altering interactively the circuit schematic, and hence its netlist, as can be done in commercial simulation packages such as PSpice or Intusoft Spice. As a result, there is no practical work-bench in XpertPSD where the user can experiment with addition or deletion of components such as, say, including synchronous rectifiers to improve efficiency, or including a second output LC filter stage to reduce output ripple voltage.

Databases

The ease of creating new databases depends upon the complexity of represented data. New databases alter the programming flow of data search. Consequently, new rules are necessary to implement processing of new data, requiring good skills in programming wxCLIPS and C++.

As explained in section 3.3.7, there are two types of databases used in the ES. One is a simple alpha-numeric representation of data which can be accessed and used directly in the design of different stages of the power supply. These types of databases are easier and less time consuming to develop than graphical databases, which involves a multi-conversion process, as described in section 3.3.7, which is time consuming and tedious. More-over, depending upon the degree of non-linearity of the graph, new algorithms may be needed to 'decode' the graphical databases.

Design of high power converters such as half-bridge or full-bridge converters requires high voltage and/or high current semiconductor devices. This requires an increase in the power semiconductor device database to include high power devices.

Currently, XpertPSD supports control system design using the UC1524 (direct duty ratio control), and the UC3844 (current-mode control). If new power supply
controllers are to be used, the databases would require updating. Design of a new control system with new controllers may require a different set of parameters than that available in the existing database: in this case, a new database may have to be created.

Magnetics databases, such as cores and their characteristics, would also need to be enlarged for high power applications. As many of the magnetic databases represent graphical data, expansion of these to include new magnetic cores involves considerable manual tasks. For instance, a man-day was required to scan, digitise, and link five EE-core datasheets.

Another major task with new databases is the development of the user interface to link them with the ES. As each new database requires a new graphical interface, this poses a daunting task. For example, a different dialog-box would be needed to present data of iron powder cores compared to that for ferrite cores.

8.7 ADAPTABILITY OF THE METHODOLOGY

One of the aims of the research is to evolve an expert system methodology that can be enlarged to design other power electronic systems such as electric motor drives and uninterruptible power supplies.

8.7.1 Uninterruptible Power Supplies (UPS)

UPS are used for supplying critical loads such as medical equipment, computers etc. Figure 8.3 shows a block-diagram representation of a typical UPS system.

UPS are similar to SMPS in many respects, although the circuit topologies are different. It is anticipated that the same expert system based design techniques could be used, but the similarity ends there as explained below.

Input rectifier system

As shown in the figure 8.3, the input rectifier converts the ac input into dc which is then fed to an inverter. The design of this dc system is similar to that for SMPS, but it is often designed for high power handling. Choice of single- or three-phase rectifiers depends on the output power of the UPS. The ES should able to design different
topologies:

- **Phase-controlled rectifiers.** These rectifiers are normally used for high power applications. The design approach of the input rectifier of switched mode power supplies could be extended to design the charging rectifier, but with thyristors instead of diodes.

- **Diode bridge rectifiers in cascade with dc-dc converters.** A diode bridge rectifier in cascade with a step-down dc-dc converter or a resonant converter is often used, especially when electrical isolation from the input mains is required. A number of new configurations are being developed to meet the requirements for unity input power factor. This type of rectifier system could be implemented in XpertPSD with minimal effort as these converters are well supported in the ES.

![Figure 8.3 A typical UPS system](image)

**Inverter system**

The principal component in an UPS is the inverter, which may be single-phase or three-phase type. There is a wide range of inverter topologies, such as PWM inverters, resonant inverters etc. The design of these inverters is not supported in XpertPSD, as these are not usual in switched mode power supplies. This requires a new design methodology, which should consider several design constraints such as minimisation of total harmonic distortion in the inverter output.

**Battery system**

A battery bank supplies power to the inverter during line outages. Although there are
many different types of battery, lead-acid and nickel-cadmium batteries are most commonly used for UPS applications. The expert system should support selection of a suitable battery depending on [156-157]:

- the power rating of the UPS,
- the back-up (stand-by) time required, and
- the operating conditions.

Another important design consideration is choice of battery voltage, as this determines the number of battery cells required, and hence size and cost of the UPS. The expert system should suggest a suitable battery voltage by considering the following design constraints:

1. Greater battery cost for higher dc voltages.
2. Severity of safety considerations with higher dc voltages.
3. Increased current rating of inverter system with lower dc voltage.
4. Poorer efficiencies with lower battery voltage systems.

**Battery charging system**

The battery charging system comprises a rectifier circuit to generate the charging voltage, and a control circuit to control the charging rate.

The charging voltage can be derived from the input rectifier system or from a separate phase-controlled rectifier. To reduce ripple content in the battery charging current, the ES must support measures such as use of:

1. an LC filter at the output of the rectifier, and
2. a three-phase bridge rectifier (as this reduces the size of the above LC filter), depending on the availability of three-phase supply.

The charging control circuit must charge the battery to its full capacity without over-charging it. The charging control circuit should constantly monitor the battery voltage, charging current, and include protection features such as shutting down the UPS whenever the battery voltage falls below its final discharge voltage.

Design of the charging control circuits is a new topic in XpertPSD. Moreover, different types of battery chargers rectifiers require different control methods, such as phase-angle control in thyristor bridge rectifiers. The ES should also support design of
the control circuits with IC battery charging controllers [158], as these minimise the size as well as complexity of the charging circuitry. As with all feedback circuits, the control system should prevent instabilities by using suitable loop compensation. Similar compensation topologies, and hence a similar design approach, as used in SMPS may be employed. However, there are differences, e.g. loop response is not a critical aspect in battery charging, so a conservative compensation with plenty of phase margin is normally employed.

**Inverter control system**

Unlike the SMPS control system which is primarily designed to keep the output voltage constant under all conditions, the inverter control system in an UPS not only modulates the inverter pulse widths to keep the output voltage constant, but also controls the inverter output frequency and output waveshape.

Selection of the inverter control method is straightforward as PWM switching is almost always used, since it reduces the inverter output filter size and improves the transient response of the UPS. As the objective of a control system is to provide a stable system against circuit perturbations and good dynamic response for sudden load changes, the same design approach to that implemented in *XpertPSD* could be extended to UPS inverter control system design, but with a difference: the control circuit is usually designed using discrete components, as IC controllers for UPS are not in widespread use.

**Wound component design.**

As in SMPS, the major wound components are transformers and filter inductors. The existing design methodology for wound components in the expert system can be adapted to the UPS design, but there is a major difference: the power handling capability of the wound component is usually considerably larger in UPS and different magnetic cores and construction methods are required. Iron powder cores, not ferrites, are used, and as they have different characteristics new magnetic databases should be developed and interfaced with the expert system. This is time consuming, as explained in sections 3.3.7 and 8.6.2.
Design for EMC

The EMC design module in XpertPSD is very general in its application and is portable to different power electronic systems with few changes in the methodology. In SMPS, the tasks include measurement of the emission levels and design of a suitable EMI filter. For an accurate design, exact SPICE models of the semiconductor devices used are necessary.

Meta knowledge

As discussed in section 3.3.2, the meta knowledge in the expert system deals with the design issues of the expert system architecture. Though the general structure of the expert system can be adapted, modifications in the user interface and design validation module, and alteration or construction of new databases, are required if the system is to be used for an UPS design:

1. **User-interface.** Feedback from the user and information presented to the user are specific to the particular application. In the user interface, the dialog box structures are used to obtain user feedback, and new dialog boxes would be required whenever new design knowledge is added to the knowledge base. Normally design of the user interface takes a major part of the total development time, and redesign of the user interface is one of the major impediments in adapting the expert system based methodology to other power electronic systems such as UPS.

2. **Design validation.** During validation, the circuit is simulated to produce circuit voltages and currents which may be compared with the original design specification. This validation process remains the same in all power electronic systems, but the circuit variables of interest may change. For example, total harmonic distortion in the inverter output waveform will be a critical variable in UPS. As a result, the data processor is the most seriously affected module, requiring new processing software utilities or extensive modifications to the existing utilities. Also, the KB should be enlarged with the rules necessary to generate SPICE netlists, emphasising the performance variables to be verified.

3. **Databases.** The existing semiconductor databases would need to be updated with high voltage and/or high current semiconductor devices. If new types of devices (for instance IGBTs) are to be used, a new database has to be created and linked
with the expert system using a proper user interface. The magnetics databases, such as cores and their characteristics, would also need to be updated. As each new database requires a new graphical interface, creation of databases poses a daunting task.

Summary
Reference [159] corroborates the views expressed in this thesis about the application of expert system technology for the design of power electronic systems. Though the above work did not consider commercial feasibility of the above technology for the design of UPS, this author stands by the following observations.

UPS are not normally purchased in large quantities, and customers normally select a model from the manufacturers' standard range. Consequently, the manufacturers are not continually designing power supplies with only minor changes in ratings. Design effort is concentrated on developing the standard range of UPS, by including new components and novel techniques. The expert system approach is not as well suited to this type of application as it is for SMPS.

Some of the SMPS design methodologies, such as input rectifier design, wound components and designing for EMC, could be extended to UPS design without difficulty. However, new design approaches would be necessary for the battery charging and inverter control systems. Development of the new databases would be a major task, although it could be based on XpertPSD's database framework. The same user-interface forms could be used, but with different design information. New facts and rules covering the above design changes must be programmed into the knowledge base.

In effect, most of the ES would need to be re-written, which would be a major task and would require considerable effort, but the same basic structure could still be used.

8.7.2 Electric Drives
Motor drives are used in a variety of applications ranging from very precise and high performance position controlled drives in robotics to variable speed drives for electric traction. Basic motor drives include:
• DC motor drives
• Induction motor drives
• Synchronous motor drives
• Stepper motor drives

Figure 8.4 shows a typical block-diagram of a power electronic based ac motor drive system [160-161]. A suitable power electronic converter system is selected depending on the motor and load characteristics.

Design of motor drives has very few tasks in common with that of SMPS. It was hoped that the XpertPSD could be extended to design electric drives, but this is unlikely to be feasible as explained below.

**Motor selection**

Design of an electric drive system starts with the selection of a suitable motor. There is a wide range of variable speed drive systems available, each having particular advantages and disadvantages. Selection of a drive type is dependent on a number of factors including economics, power rating, efficiency requirement, speed range, operating environment, maintenance considerations and general performance considerations [19-20].

Motor selection would be a completely new task for XpertPSD, and would need an exclusive knowledge base module to deal with the motor selection process.
**Converter system**

Selection of a suitable converter system to control a motor is more involved than the motor selection. There is a wide range of converters available. For dc drives, frequently used converters [102][162] are:

- Phase controlled rectifiers
- Switched mode dc-dc converters

For ac drives, the available choice is typically [163]:

- PWM voltage or current source inverters
- Square-wave voltage or current source inverters
- Cycloconverters
- Load-commutated inverters

Machine data such as power, voltage, current, speed, poles, and service factor forms the basis for converter selection. Since the design methodology of power electronic converters is similar in nature, the design framework including the basic converter design, component selection and design validation used in the XpertPSD could be adapted.

Because a new family of converters is used, the knowledge base would need to be programmed afresh.

**Control system design**

In SMPS, control methods are well defined such that the design of the control system mainly comprises selection of a control technique and a PWM IC controller.

In electric drives, the control system is more complicated as it contains multiple loops to control parameters such as speed, current, torque etc. Depending upon the type of application, variables such as speed, temperature, flux, current etc. are sensed and used to form a control strategy. The control system should also implement features such as power factor correction, low THD etc.

It is clear from the above discussion that different control schemes are used depending upon the converter and the type of speed-control. For example, implementation of a slip-power recovery scheme, used to control the speed of a three-phase induction
motor, differs from that of voltage-fed speed control system. Moreover, a single IC does not exist that can control the whole drive system.

As the design and implementation of the drive control system are radically different from those of SMPS, a total redesign of the control system module in XpertPSD would need to be carried.

**Design for EMC**

The EMC design module developed in XpertPSD is relevant to most of the power electronic systems since the objective in all of them is EMC. In XpertPSD, SPICE simulation is used to determine CM and DM noise. This approach demands accurate SPICE models for semiconductor devices and electric motors. Modelling of the electric motors for EMI simulation was not attempted in this work, and would form one of the major tasks in developing an expert system for the design of electric drives.

**Meta knowledge**

In XpertPSD, the user-interface, design validation and databases form the meta knowledge. For electric drives, these modules would require to be totally rewritten.

1. **User-interface.** The user-interface depends upon the design information exchanged between the user and the ES. Since the design of electric drives is different from that of SMPS, the user-interface forms (GUI forms) must be altered. As discussed in section 2.3.2, the user-interface development typically constitutes 40% of the ES development time. The author expects that this would be an enormous task.

2. **Design validation.** The design validation of drives involves verification of a different set of circuit variables such as speed, torque, armature current, total harmonic distortion etc. The software modules which were developed for SMPS design in the data processor of XpertPSD are no longer useful. This necessitates programming new data processing software utilities, and hence a new design validation hierarchy. Moreover, to validate any drive system, simulation models need to be made available to the expert system. Though suitable models for semiconductor devices exist, models need to be developed for the motors.

3. **Databases.** There are several new databases to be created, including databases for
electric motors, and a wide range of power semiconductor devices such as MOSFETS, BJTS, Thyristors, IGBTs.

Summary

XpertPSD was developed for the design of SMPS where different converter topologies and feedback systems are used. Consequently, there would be differences in the design approach. XpertPSD could not readily be adapted to drives, but it would still be possible to use the same basic techniques.

8.8 FUTURE SCOPE OF THE RESEARCH

XpertPSD currently designs buck and forward converters interactively, and can be expanded to cover other power supply topologies such as flyback converters, bridge converters and resonant converters by adding further design rules.

For a precise voltage regulation, post-regulators are normally employed in multi-output power supplies with low output voltages and high currents (e.g. 5.0V, 3.3V and 12.0V). The post-regulators also correct for any imbalances in voltage and turns ratios between the outputs. The ES can be extended to design a variety of post-regulators by embedding new design rules with a proper user-interface.

Apart from the expansion of the knowledge base to design new converters, there still exists a wide range of issues to be researched as outlined below.

8.8.1 Design Optimisation

The expert system produces a design in which each component or section is optimised: for example, the transformer is designed for maximum efficiency, and the design of the feedback compensation circuit to meet the desired transient response. The whole design has not been optimised for efficiency, size, and cost of the power supply. For instance, optimisation of the design for cost requires estimation of the cost of each circuit component and its effect on the overall design. However, minimisation of cost can result in a bulkier design, and an optimum break-even point must be established which needs considerable heuristics of the design. The overall size of the power supply can only be estimated accurately if there exists robust and
knowledgeable schematic generation and PCB layout tools.

8.8.2 Interactive Schematic Generator

Schematics are one of the principal means of conveying design information to the user. As a schematic makes design of power electronic systems more user-friendly and comprehensible, it was aimed to develop a schematic capture feature in XpertPSD. This eliminates manual construction of a schematic which demands special skills in perceiving and manipulating the schematic drawing. Moreover, this manual construction is time consuming and error prone.

Currently, the schematic capture feature in XpertPSD is very limited in its scope: the expert system only displays a schematic of the circuit under its consideration, and does not allow modifications to it. This seriously reduces the flexibility of XpertPSD as it is not possible to experiment with variations to a standard converter.

Figure 8.5 shows an ideal schematic generator that will enhance flexibility of the design process in the expert system. In this design environment, the designer could experiment by adding/subtracting components. After selection and design of a converter, the expert system would generate a relevant schematic of the converter, and allow the user to edit it. The expert system would then update the design rules. If a modification violates specifications, then the user would be informed.

![Figure 8.5 Design environment with Schematic Generator](image-url)
The schematic generator should produce a SPICE netlist for the SPICE simulator. If the results are not satisfactory, the user would be able to edit either the netlist or the schematic. After editing the netlist, the changes would be reflected back in the schematic, and vice versa.

**Design automation**

Another more distant objective of the interactive schematic generator is to estimate an optimum size for the power supply, and produce a PCB layout for the power supply from its generated schematic using routing algorithms. To produce a PCB layout using CAD tools such as PADS, a schematic is drawn manually, and is then transported into a PCB layout.

If the schematic generator could talk to a PCB layout tool, then it would be possible to automate the design and optimise the size of the PCB. As mentioned in chapter 1, placement of components on a PCB requires trial-and-error strategy and heuristics. For example, the timing components of the PWM chip should be as close as possible to the chip in order to reduce noise pick-up.

**Schematic generation techniques**

The SPICE netlist of a circuit contains description of circuit elements with their nodal connections. Since the knowledge base of the design validation module contains rules to generate a netlist of a circuit, this netlist can be used as a starting point to generate a schematic. However, to generate a circuit schematic from its netlist requires special component placement techniques which need to be investigated.

After a few attempts at developing such a schematic generator, it was realised that it would require more than an expert system approach, and this itself could form a full research project. This lack of schematic capture in the expert system reduces its design flexibility considerably.
9.1 OBJECTIVE

This thesis investigates the use of expert system technology to assist in the design of power electronic systems. The research was initiated after observing that the state-of-art of power electronic system design using software packages, such as SPICE and SABER, has been restricted to validation of the design, with the basic design still having to be carried out by the design engineer.

9.2 DESIGN METHODOLOGY

The expert system based techniques investigated the major aspects of designing a power electronic system, and integrate into a single computer-aided design environment. The techniques used in the system cover all facets of the design, including preliminary circuit design, component selection, circuit simulation and validation, control loop design, and design for EMC. The system provides a comprehensive and flexible computer-aided environment that can be used in a variety of different applications.

The design methodology, rather than actual design details, is emphasised in this project, since the principal aim of the research was not just to develop a software
package, but to investigate the methodology and suitability of an expert system based design. Design of switched mode power supplies was demonstrated as a typical case.

The ES based design methodology reduces the design complexity by dividing it into different levels (e.g. system-level, device-level). This approach allows the user to study a particular aspect of the specification (checking whether the specification is violated or not) before proceeding to the next stage of the design.

Component databases which contain both electrical and mechanical data are an important aspect of the design methodology. Stand-alone databases without the need for commercial software are considered appropriate: XpertPSD uses an ASCII-format of databases which is simpler and easier to develop and maintain. Though data search time is not long in XpertPSD, it could be improved with advanced database search techniques such as SQL.

9.3 DEVELOPMENT OF XpertPSD

The selection of a suitable expert system development tool is critical. Factors such as development time, speed of execution, user-interface functionality, technical support etc. must be considered when making the choice. WxCLIPS was chosen after a careful and lengthy study of several expert system development tools.

9.4 EVALUATION OF THE ES

XpertPSD produces a preliminary system design sufficient for an initial prototype model. This typically includes:

- **Design of the input rectifier and selection of the reservoir capacitor.**
- **Selection of the switching power MOSFET and output rectifier diodes.**
- **Design of the control system.** Feedback control using an appropriate PWM IC controller is designed.
- **Design of the output LC filter.** This involves calculating the filter inductance and selection of a suitable filter capacitor.
- **Design of the magnetic components.** This includes the high frequency isolation
transformer and the output filter inductor. This design gives a suitable magnetic core, number of turns, wire dimensions, winding layout etc.

- **Designing for EMC.** The input filter and various snubber circuits are designed.

**XpertPSD** has been evaluated with existing designs from two power supply manufacturers. Not all the ES generated design results, such as the control system, components selection, could be compared; however, in most of the design examples a good degree of accuracy in the design results generated by the ES was achieved.

A limiting factor was the dependency on SPICE simulation results, where more accurate and robust device models are necessary for improved accuracy. This can be overcome if device manufacturers release either full electrical data or accurate SPICE models of their semiconductor components.

Though the methodology evolved for ensuring electromagnetic compatibility of the system was considered to be adequate, the input EMI filter was sometimes over- or under-designed mainly due to inaccurate simulation models. Design to reduce radiated emissions was not attempted in this research.

The research also suggests that the design cycle of a power supply (a basic prototype model) can be brought down to just under a man-day by using the ES based design environment (this can not always be assured as there is a possibility of simulation failure due to non-convergence, or extraneous reasons such as the non-availability of simulation models of new devices).

However, a full production-level design is still not within the reach of the ES. To achieve such a design, further work is required to expand the ES to test all specifications such as transient response to input variations and temperature influence, which were not studied in the current work.

### 9.5 FLEXIBILITY

**XpertPSD** currently designs the more common topologies used in switched mode power supplies. Adapting it to other power supply topologies would be relatively straightforward, but it would only be economic if the topology is to be used
frequently.

The lack of schematic capture reduces the flexibility of the design environment; experimentation with variations in standard designs is not possible.

9.6 ADAPTABILITY

It was hoped that XpertPSD could readily be adapted to other power electronic applications, such as uninterruptible power supplies or electric motor drives. However, this would involve considerable effort in developing the user-interface, and constructing new knowledge bases.

This research demonstrates that expert system technology can be used to design power electronic systems. However, although it provides flexible and knowledge based design, it is still necessary that the user should have an understanding of power electronics and a basic understanding of SPICE simulation concepts.

9.7 FUTURE SCOPE FOR RESEARCH

New design concepts are required to optimise a power supply design for its efficiency, size, and cost. Future research should look into optimisation algorithms, and heuristics of the design.

It is anticipated that further automation of a power electronic system design could be achieved by generating an automatic placement of components using design and simulation data. Once a schematic is generated, it could be used to produce a production level PCB layout. In the present work, this design automation could not be achieved due to the lack of appropriately structured software tools such as schematic generation and PCB layout.

Schematic capture can be developed using the SPICE netlist of a circuit as a starting point. However, to generate a circuit schematic from its netlist requires special component placement techniques.

Further investigation into these issues would definitely enhance design automation in XpertPSD.
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A.1 BUCK CONVERTER

Specification Summary

1. Output power: 75 Watts
2. Input voltage: 29.7 to 36.3 V dc
3. Output voltage: 15 V dc
4. Min. output current: 0.75 A
5. Max. output current: 5.0 A
6. Output ripple voltage: 150 mV p-p
7. Max. step load change: 4A

Comparison of the Design: (overleaf)
<table>
<thead>
<tr>
<th>Point of Comparison</th>
<th>Bunlaksanonusorn Design</th>
<th>XpertPSD Design</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Converter</td>
<td>Buck converter</td>
<td>Buck converter</td>
<td></td>
</tr>
<tr>
<td>2. Switching frequency</td>
<td>100 kHz</td>
<td>100 kHz.</td>
<td>The same switching frequency was chosen in order to compare the results.</td>
</tr>
<tr>
<td>3. Filter details:</td>
<td>L = 50 uH</td>
<td>L = 74 uH</td>
<td>The expert system suggested filter inductance is more than the actual value used. This could be due to the different design assumptions such as voltage drops, safety factor etc. in XpertPSD.</td>
</tr>
<tr>
<td></td>
<td>C = 470 uF</td>
<td>C = 470 uF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ESR = 33mΩ max.</td>
<td>ESR = 33mΩ</td>
<td></td>
</tr>
<tr>
<td>4. Devices Selection:</td>
<td>IRF741 (400V, 10A)</td>
<td>IRF530 (100V, 14A)</td>
<td>The choice of IRF741 seems to be an overkill considering that the maximum input operating voltage is less than 40V.</td>
</tr>
<tr>
<td>a. Power MOSFET</td>
<td>MBR1045 (45V, 10A)</td>
<td>MBR1045 (45V, 10A)</td>
<td></td>
</tr>
<tr>
<td>b. Output Rectifiers:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Control System:</td>
<td>A customised direct duty ratio control with predetermined error feedback control implemented with UC1524.</td>
<td>Direct duty ratio control.</td>
<td>It is a typical case which demonstrates that the expert system approach is not well suited for a very custom design.</td>
</tr>
<tr>
<td></td>
<td>to improve dynamic response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Magnetics:</td>
<td>Core = ETD29 (AP = 0.684 cm$^4$)</td>
<td>Core = ETD29 (AP = 0.684 cm$^4$)</td>
<td>In both the designs, the selected core is the same, but the number of turns are different due to the different filter inductances.</td>
</tr>
<tr>
<td>Filter inductor</td>
<td>N = 16</td>
<td>N = 27</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D = Not Available (NA)</td>
<td>D = 1.1 mm</td>
<td></td>
</tr>
</tbody>
</table>
A.2 CORTECH SYSTEMS POWER SUPPLY

Specification Summary

- Output power: 233 watts
- Input voltage: 85-264 V rms
- Number of main outputs: 3
- Output requirements:

<table>
<thead>
<tr>
<th>Output 1</th>
<th>Output 2</th>
<th>Output 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage = 5.0 V</td>
<td>Output voltage = 3.3 V</td>
<td>Output voltage = 12.0 V</td>
</tr>
<tr>
<td>Min. current   = 0.0A</td>
<td>Min. Current = 0.0A</td>
<td>Min. Current = 0.0 A</td>
</tr>
<tr>
<td>Max. current   = 22.0A</td>
<td>Max. Current = 12.0A</td>
<td>Max. Current = 8.0 A</td>
</tr>
<tr>
<td>Ripple         = 50mV</td>
<td>Ripple = 50mV</td>
<td>Ripple = 120mV</td>
</tr>
</tbody>
</table>

Comparison of the Design: (overleaf)
<table>
<thead>
<tr>
<th>Point of Comparison</th>
<th>Cortech Systems Design</th>
<th>XpertPSD Design</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Converter</td>
<td>Forward converter</td>
<td>Forward converter</td>
<td></td>
</tr>
<tr>
<td>2. Switching frequency</td>
<td>25 kHz</td>
<td>25 kHz</td>
<td>Although the switching frequency in the Cortech Systems power supply is very low, the same value was chosen to keep the designs comparable.</td>
</tr>
<tr>
<td>3. Input rectifier: Bulk capacitor</td>
<td>680 uF</td>
<td>560 uF</td>
<td></td>
</tr>
<tr>
<td>4. Filter details: L = Inductance C = Capacitance</td>
<td>5V output: L = 39 uH C = 3300 uF ESR = NA</td>
<td>5V output: L = 52 uH C = 2200 uF ESR = 0.055Ω</td>
<td>In both the designs, the filter inductances are within reasonable accuracy, but there are considerable differences in the filter capacitors selected. One reason could be due to choice of capacitors available in the ES filter capacitor database. This database could not be augmented with the same capacitors used in the Cortech Systems design due to non-availability of the capacitors’ data such as ESR, ripple current etc.; Had the database contained these capacitors, the selected capacitors should have been identical.</td>
</tr>
<tr>
<td></td>
<td>3.3 V output: L = 25.5 uH C = 3300 uF ESR = NA</td>
<td>3.3 V output: L = 43 uH C = 2200 uF ESR = 0.028 Ω</td>
<td></td>
</tr>
<tr>
<td></td>
<td>12 V output: L = 221 uH C = 470 uF ESR = NA</td>
<td>12 V output: L = 196 uH C = 470 uF ESR = 0.033Ω</td>
<td></td>
</tr>
</tbody>
</table>
4. Devices Selection:
   a. Power MOSFET
   b. Output Rectifiers:
      - 5V output
      - 3.3V output
      - 12V output

<table>
<thead>
<tr>
<th>Device</th>
<th>5V Output</th>
<th>3.3V Output</th>
<th>12V Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>2SK956-5001 (800V, 9A)</td>
<td>MBR4045CT (45V, 40A)</td>
<td>BYV32E-150 (150V, 18A)</td>
<td></td>
</tr>
<tr>
<td>MBR2045CT (45V, 20A)</td>
<td>IN5829 (20V, 25A)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2SK956-5001 (800V, 9A)</td>
<td>MBR4045CT (45V, 40A)</td>
<td>BYV32E-150 (150V, 18A)</td>
<td></td>
</tr>
</tbody>
</table>

Component selection is very much a user choice, and may vary from one user to other. For example, XpertIPSD suggested both BYV32E-150 and IN5829 for the 3.3V output rectification, but the latter diode is chosen to show subjectiveness in the selection process.

5. Control System:
   - Current-mode control.
     - Both 5V and 12V outputs have been regulated.
     - Feedback control has been implemented with an output voltage error amplifier (TL431) and UC3844.
     - Opto-coupler was used to isolate the output stage of the feedback system.
     - A single-pole compensation topology was used.
     - Post regulator was employed on 3.3V output.
   - Only one output (5V) is regulated.
   - Simple feedback control with UC3844 is designed.
   - A single-pole compensation topology is designed in order to achieve a gain margin of 45 degrees.
   - Opto-coupler was used to isolate degrees.
   - A single-pole compensation topology was used.
   - Post regulator was employed on 3.3V output.
   - Although the control methods are the same in both the designs, but their implementations are different: there is no feedback isolation in the expert system generated design. Also, the design of post-regulators is beyond the scope of this work.

6. Magnetics
   Transformer: Core: EER39 (Area product = 2.2125 cm²) Core: ETD44 (Area product = 3.7022 cm²)
   In XpertIPSD, a larger core is selected due to optimisation of the transformer design for maximum

---

A-5
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N = No. of turns</td>
<td>N = 60</td>
<td>N = 115</td>
<td>N = 60</td>
<td>N = 115</td>
<td></td>
<td>Coupled inductors were used.</td>
</tr>
<tr>
<td>D = Diameter of wire</td>
<td>D = 0.71 mm</td>
<td>D = 0.56 mm</td>
<td>D = 0.29 mm</td>
<td>D = 0.063 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tertiary:</td>
<td></td>
<td></td>
<td>N = 60</td>
<td>N = 115</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = 0.71 mm</td>
<td>D = 0.56 mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5V output:</td>
<td>N = 5</td>
<td>N = 8</td>
<td>N = 5</td>
<td>N = 5</td>
<td>5V output:</td>
<td>Coupled inductors were used.</td>
</tr>
<tr>
<td></td>
<td>D = 0.29 mm</td>
<td>D = 1.9 mm</td>
<td>D = 0.37 mm</td>
<td>D = 1.4 mm</td>
<td>5V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.3V output:</td>
<td>3.3V output:</td>
<td>5V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N = 4</td>
<td>N = 5</td>
<td>N = 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = 0.29 mm</td>
<td>D = 0.37 mm</td>
<td>D = 0.063 mm</td>
<td>The inductor designs could not be compared as coupled inductors were used in the Cortech Systems design, whereas this type of design is not currently supported in the expert system.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.3V output:</td>
<td>3.3V output:</td>
<td>5V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N = 4</td>
<td>N = 5</td>
<td>N = 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = 0.29 mm</td>
<td>D = 0.37 mm</td>
<td>D = 0.063 mm</td>
<td></td>
</tr>
<tr>
<td>12V output:</td>
<td>N = 7</td>
<td>N = 19</td>
<td>N = 7</td>
<td>N = 19</td>
<td>12V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>D = 1.18 mm</td>
<td>D = 1.18 mm</td>
<td>D = 1.18 mm</td>
<td>D = 1.18 mm</td>
<td>12V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12V output:</td>
<td>12V output:</td>
<td>12V output:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N = 7</td>
<td>N = 19</td>
<td>N = 19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D = 1.18 mm</td>
<td>D = 1.18 mm</td>
<td>D = 1.18 mm</td>
<td></td>
</tr>
</tbody>
</table>

efficiency, but the user can overrule this option.
In the Cortech systems design, the 5V and 3.3V outputs share same winding (copper foil) which is not the case in the expert system's design: separate windings are used for 5V and 3.3V outputs.
| Design for EMC (for European Standard EN5022) | Standard EMI filter was used. | Allowed Emission = 83.70 dBµV  
Measured Emission = 110.0 dBµV  
The ES suggested that an EMI filter was required. | The emission has been brought down within the allowed limit by adding two common mode capacitors, but in the Cortech Systems design, a full EMI filter (common mode and differential mode inductors and capacitors) was used. This demonstrates that the power supply PCB layout has profound influence on the EMI. |

| N = 32  
D = 1.5 mm | **|
A.3 MINEBEA’S POWER SUPPLY

Specification Summary

- Output power: 230 watts
- Input voltage: 85-264 V rms
- Number of main outputs: 3
- Output requirements:

<table>
<thead>
<tr>
<th>Output 1</th>
<th>Output 2</th>
<th>Output 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage = 5.0 V</td>
<td>Output voltage = 3.3 V</td>
<td>Output voltage = 12.0 V</td>
</tr>
<tr>
<td>Min. current = 2.0A</td>
<td>Min. Current = 0.0A</td>
<td>Min. Current = 0.16 A</td>
</tr>
<tr>
<td>Max. current = 29.0A</td>
<td>Max. Current = 16.0A</td>
<td>Max. Current = 4.0 A</td>
</tr>
<tr>
<td>Ripple = 50mV</td>
<td>Ripple = 50mV</td>
<td>Ripple = 120 mV</td>
</tr>
</tbody>
</table>

Comparison of the Design: (overleaf)
<table>
<thead>
<tr>
<th>Point of Comparison</th>
<th>Minebea Design</th>
<th>XpertPSD Design</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Converter</td>
<td>Forward converter</td>
<td>Forward converter</td>
<td>The same switching frequency was chosen in order to compare the results.</td>
</tr>
<tr>
<td>2. Switching frequency</td>
<td>100 kHz</td>
<td>100 kHz</td>
<td></td>
</tr>
<tr>
<td>3. Input rectifier: Bulk capacitor</td>
<td>470 uF</td>
<td>560 uF</td>
<td>The ES choice seems to be a good compromise between the Cortech systems and Minebea's power supplies.</td>
</tr>
<tr>
<td>4. Filter details:</td>
<td>5V output:</td>
<td>5V output:</td>
<td>The filter inductances could not be compared due to non-availability of the inductances used in the Minebea's design. As in the Cortech Systems' design, the choice of the filter capacitors depended on the availability of the capacitors in the database.</td>
</tr>
<tr>
<td>L = Inductance C = Capacitance</td>
<td>L = NA C = 3300 uF ESR = NA</td>
<td>L = 15.3 uH C = 2200 uF ESR = 0.028Ω</td>
<td></td>
</tr>
<tr>
<td>3.3V output:</td>
<td>L = NA C = 3300 uF ESR = NA</td>
<td>L = 10.2 uH C = 2200 uF ESR = 0.028Ω</td>
<td></td>
</tr>
<tr>
<td>12V output:</td>
<td>L = NA C = 470 uF ESR = NA</td>
<td>L = 461.7uH C = 470 uF ESR = 0.033 Ω</td>
<td></td>
</tr>
</tbody>
</table>
### 4. Devices Selection:

<table>
<thead>
<tr>
<th>a. Power MOSFET</th>
<th>2SK962-01 (1000V, 10A)</th>
<th>2SK962-01 (1000V, 10A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b. Output Rectifiers:</td>
<td>S30SC4M (40V, 30A)</td>
<td>S30SC4M (40V, 30A)</td>
</tr>
<tr>
<td>5V output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.3V output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12V output</td>
<td>BYQ28F-100 (100V, 10A)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>MBR10100 (100V, 10A)</td>
</tr>
</tbody>
</table>

Same comments as in the Cortech Systems design.

### 5. Control System:

- Current-mode control.
  - Both 5V and 12V outputs have been regulated.
  - Feedback control has been implemented with an output voltage error amplifier (TL431) and UC3844.
  - Opto-coupler was used to isolate the output stage of the feedback system.
  - A single-pole compensation topology was used.
- Only one output (5V) is regulated.
- Simple feedback control with UC3844 is designed.
- A single-pole compensation topology is designed in order to achieve a gain margin of 45 degrees.
- Although the control methods are the same in both the designs, but their implementations are different: there is no feedback isolation in the expert system design.

### 6. Magnetics

<table>
<thead>
<tr>
<th>Transformer:</th>
<th>NA</th>
<th>Core: ETD44</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary:</td>
<td></td>
<td>N = 115</td>
</tr>
<tr>
<td>D = Diameter of wire</td>
<td></td>
<td>D = 0.71 mm</td>
</tr>
</tbody>
</table>

The designs could not be compared due to non-availability of the magnetic design data from Minebea.
<table>
<thead>
<tr>
<th></th>
<th>Tertiary:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N = 115</td>
</tr>
<tr>
<td></td>
<td>D = 0.063 mm</td>
</tr>
<tr>
<td>5V output:</td>
<td>N = 8</td>
</tr>
<tr>
<td></td>
<td>D = 2.24</td>
</tr>
<tr>
<td>12V output:</td>
<td>N = 19</td>
</tr>
<tr>
<td></td>
<td>D = 0.85</td>
</tr>
<tr>
<td>3.3V output:</td>
<td>N = 5</td>
</tr>
<tr>
<td></td>
<td>D = 1.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>6. Magnetics:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filter inductor</td>
</tr>
<tr>
<td></td>
<td>NA</td>
</tr>
<tr>
<td>5V output:</td>
<td>Core = ETD44</td>
</tr>
<tr>
<td></td>
<td>N = 8</td>
</tr>
<tr>
<td></td>
<td>D = 2.8 mm</td>
</tr>
<tr>
<td>3.3V output:</td>
<td>Core = ETD29</td>
</tr>
<tr>
<td></td>
<td>N = 13</td>
</tr>
<tr>
<td></td>
<td>D = 2.8 mm</td>
</tr>
<tr>
<td>12V output:</td>
<td>Core = RM14</td>
</tr>
</tbody>
</table>
Design for EMC (European Standard EN5022) | Standard EMI filter was used. | Allowed Emission = 83.70 dBμV
Measured Emission = 41.02 dBμV | The ES suggested that no EMI filter was required which was an under-estimation of EMI due to approximate simulation models used.

\[
N = 54 \\
D = 1.06 \text{ mm}
\]
DECISION SUPPORT SOFTWARE FOR THE DESIGN OF POWER ELECTRONIC SYSTEMS

E. Amarnath Reddy, D.E. Macpherson

Department of Electrical Engineering, King’s Buildings, University of Edinburgh, Edinburgh EH9 3JL

ABSTRACT

This paper describes the design and development of Decision Support Software (DSS) to assist the design of Switched Mode Power Supplies using an Expert System Language called C-Language Integrated Production System (CLIPS)[1]. Various design rules are built into the expert system, which is also linked into a circuit simulator (SPICE). The power supply specification is entered into the system, which produces a preliminary design. The SPICE netlist is automatically produced by the expert system, and the simulation performed. The results may be viewed graphically, in the light of which modifications may be made.

This paper discusses preliminary results of this on-going project. It is expected that the technique may be adapted to other power electronic systems.

1 INTRODUCTION

Power Electronic converters are often difficult to analyse accurately, due to the effect of device parasitic impedances, and also the non-linear characteristics of circuit elements (e.g. wound components). As a result, design of power converters requires considerable expertise: complex and tedious tasks of exploring many different options such as choice of converter topologies, selection of power semiconductor devices, control philosophies, design of wound components, and design for Electromagnetic Compatibility (EMC)[2]. This makes the design very subjective in nature, iterative, and heavily dependent on the designer's experience.

Currently, CAD tools for the design of power electronic systems are limited in their scope. A circuit simulator such as SPICE or SABER is frequently used. This usually has a Schematic Capture to create the NETLIST for simulation, and a Graphics post-processor to view the simulated results. Even with these CAD tools, it is still necessary to modify-retest cycles before a final design is reached. This process involves considerable decision making, which requires substantial expertise in all aspects of power electronics.

An effective way of utilising the CAD tools is to embed decision support in the domain of these CAD tools. Expert Systems (ES), a branch of Artificial Intelligence, fit the role well here as they can be used to offer decision support or advice during the design process. With expert systems, it is easy to alter or update the design process with new advances in the technology.

Many research projects into CAD for power electronic systems have been reported, especially in switched-mode power supply systems, but there is no work which covers all facets of the design, such as design of magnetic circuits and testing for EMC. In [3], the authors identified an approach to design power electronic circuits interactively, but the designer still has to select proper power devices and carry out the initial design, and there is no attempt to solve the electromagnetic compatibility of high switching converters such as SMPS. Hsieh and Liu [4] use both algorithm and knowledge-based methods which reduces the flexibility of the system, and there is no proper co-ordination of the different tasks involved in the design process. It was also observed that there was no attempt to exploit fully the SPICE-simulation tool.

The main aim of this project is to develop an user-interactive and user-friendly CAD package for power electronic systems that covers all facets of the design for a given application. As an initial target of the work, the design of a complete Switched-Mode Power Supply (SMPS) for a given set of input specifications is undertaken, as SMPS are typical power electronic systems. The developed DSS aims to give a complete system design with an optimum design configuration at minimised time and cost.

The following sections describe the architecture of the proposed Decision Support Software: the CLIPS Expert System, Spice-Simulation, Development of Databases, and Methodology of the Design Process. The need and construction of different Knowledge Bases for the Expert System are also explained.

2. DESIGN OF THE DECISION SUPPORT SOFTWARE

The architecture of the DSS is shown in figure 1. The basic building block of the DSS is an Expert System (ES). An expert system, which is a program intended to model human expertise or knowledge, has three major components: User Interface, Inference Engine, and Knowledge Base (KB). The knowledge base is a set of facts and heuristics (rules of thumb) about a specific domain task. Expert systems deal with the specific task by drawing inferences using its inference engine (a set of algorithms) from its knowledge base.

In the DSS, the ES and various interfaces are developed using wxCLIPS, an expert system development tool. WxCLIPS[6] is an extension of CLIPS with graphical user interface (GUI) functionality to write a portable graphical interface which runs under Windows. CLIPS provides a complete environment for the construction of rules and/or object based expert systems and it provides a cohesive tool for handling a wide variety of knowledge with support for three different programming techniques: rule-based, object-oriented and procedural[5]. The rule-based programming allows knowledge to be represented, using the forward-chain mechanism as its inference engine. Many advantages such as free availability of source-code and easy user-interface development prompted the selection of this tool.

Figure 1. Architecture of the Decision Support Software

The ES is embedded with different knowledge bases, such as rules to select a proper converter, and it also co-ordinates the SPICE simulation, processing of simulation results, development and interaction with Databases, Schematic generation of a converter (under development) and a Plotting utility to display graphically any data such as spice-simulation results. The design and development of the individual stages are explained below.

*Presented at UPEC95, University of Greenwich, London, 4-7 September 1995
2.1 User Interface

An User Interface is a dialogue structure that allows the user to interact with the expert system. Since it is an important task of any expert system to communicate with the user, who may or may not be an experienced SMPS design engineer, the design of the User Interface is of paramount importance in any ES design. The GUI functionality of wxCLIPS provides many forms of interface such as windows, dialogue-boxes, message-boxes and on-line help. The user front-ends designed for the SPICE-Simulator and Databases are shown in fig 2.

2.2 Simulation Environment

The simulation environment consists of a SPICE-simulator to simulate any circuit, a MicroEMACS[7] editor to edit the netlist or to view simulation results, GNUPLOT[8] for Windows to view simulation results, and a schematic editor to capture the circuit schematic. Fig. 2b shows the developed simulated environment window.

The SPICE-simulator is fully integrated within the expert system, and can be used either as a stand-alone or as an integrated simulator. The ES interprets any errors encountered during simulation and gives causes and remedies for them, and processes simulation results. The simulation data is suitably formatted by the ES to view them graphically using the GNUPLOT (fig 2c). As a picture is worth a thousand words, any CAD of circuits must include a tool to capture or generate the circuit schematic from a given netlist of the circuit, and this is being developed.

2.3 Databases

For a fully integrated design package, databases of available components such as power semiconductor devices (MOSFETs and diodes), filter capacitors, and magnetic cores are necessary. Since there exist several similar devices for a given application from different manufacturers, the selection of a best-suited device based on optimum ratings and price is often cumbersome. However, this is an ideal task for a DSS.

The databases contain the necessary electrical ratings, manufacturer and cost of the device. All the data in the databases is stored in object-oriented format using CLIPS object oriented functionality. In this type, there exists a super database class and as many derived classes as the number of databases required. The DSS also facilitates construction of new, and up-dating existing, databases. A developed interface to search and update the power MOSFET's database is shown in fig 2d. The DSS is a useful tool even for an experienced engineer, as it minimises the time taken searching through various databases.

3. MODUS OPERANDI OF THE DSS

Figure 3 shows the various design sequences that are carried out by the DSS, where the design of the SMPS is initiated by asking the user to input the specifications required. After correcting any keyboard errors, it performs a realistic analysis on the specifications to determine whether they are practically viable to build a power supply. It is important to query each specification, as these are often written by system engineers who may not have an in-depth understanding of the cost implications of the system. Any modifications that may be needed are suggested to the user.

After identification of a suitable converter for the application (by consulting its knowledge base), the DSS starts designing different stages of the converter, such as the input rectifier and the dc-dc high frequency conversion stages of the SMPS. Appropriate values of switching frequency, transformer turns ratio, filter inductance, and filter capacitance are chosen at this stage.

Device selection is an extremely important area. Some of the important parameters that influence the choice are the cost of the device, availability, reliability of the manufacturer, etc. In the case of output filter capacitor, multiple capacitors are often preferred over a single big capacitor to reduce overall size, but cost can be the single most influential factor. The DSS prompts the user to select all necessary power semiconductors and filter capacitors from the existing databases.

The system then starts the simulation process to validate the design by preparing a netlist for the simulator. Initially, individual circuits are simulated separately to reduce the simulation complexity (and hence simulation time), each time emphasising different aspects of the circuit such as steady state voltage and current waveforms, transient response, stresses on power devices etc. The complexity is gradually increased by adding more circuits. After a successful simulation, the simulation results are processed and if the performance is not satisfactory, the design values are altered and the simulation is repeated. This trial and error process continues until all the specifications are met or the knowledge is exhausted. If, at any stage, the simulation is not successful, the expert system performs a fault diagnosis by reading the error file produced by the simulator, and rectifying the errors.

The design is not over as it still has to comply with Electromagnetic Compatibility (EMC) conditions. As this problem is a somewhat random phenomenon and there are no clear-cut rules to follow, the DSS offers various suggestions using its knowledge base gained from experienced engineers.

After a satisfactory design of the converter, the DSS considers the design of the magnetic components (usually the filter inductor and the isolation transformer). Magnetic components are one of the major devices that contribute to the total size and cost of a SMPS. Careful selection of a suitable core material and style is thus required for a cost-effective design. An extensive knowledge-base containing different design rules is included in the DSS. The DSS currently designs the filter inductors using RM-cores, although this will be extended to other core types.

4 THE KNOWLEDGE BASE

The knowledge principle says that the power of the expert system lies in its knowledge base. The knowledge base is a part of the...
Figure 2. (a) : User interface to seek Specifications

Figure 2. (b) : Spice-Simulation Environment

Figure 2. (c) : GnuPLOT displaying the simulated waveform.

Figure 2. (d) : Front-end to Databases.

Table 2: Netlist of the designed buck converter

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Table 2: Netlist of the designed buck converter

```plaintext
EESPOWER/SPICEBUCK
*INCLUDE DIODE.LIB
*INCLUDE POWMOS.LIB
.TRAN 39.999N 500.0U 480.0U 39.999N UIC
.PRINT TRAN V(5) I(VIO) I(VIL)
.OPTIONS METHOD=GEAR
Vgate 93 PULSE 0.0 10.0 1P 1P 2.37U 10.0U
Df 0 3 DNS380
Vin 1 0 DC 24.0
XMOS 2 3 IRF530
R1 1 2 1M
Rg 8 9 10.0
VIL 3 4 DC 0
Lf 4 5 34.071U IC=1.0
Cf 5 0 470.0U IC=5.0
VIO 5 6 DC 0
Rload 6 0 5.0
END
```

Figure 4: Transient response of the buck converter
4. Device Selection:

4.1 Converter topologies:

Here the different rules for selection and design of SMPS topologies are prepared. To select a converter (e.g. a buck converter) the rule in CLIPS syntax is:

\[
(defrule ConverterSelection::buck
?var <- (go-for-topology selection)
(test (< ?Vin ?Vinmax))
(test (> ?Vout 0))
(test (< Power 100.0))
(test (eq ?Isolation "NO")))
\]

The above rule selects a buck converter if the output voltage is positive and less than the input voltage, and there is no requirement for isolation between the input and output. The knowledge base selects a suitable type for the topology and type of load.

4.2 Control philosophies:

This module handles the choice of feed-back control system and its design. The possible control techniques considered here are direct duty ratio control, voltage feed-forward control and current-mode control. For example, the knowledge base selects current-mode control for a buck converter operating in the continuous current mode due to the well known advantages of current-mode control for buck-family converters. The rules for selecting cross-over frequency, required gain and phase margin are also included in this module.

4.3 Circuit Simulation:

For the SPICE-simulation, the netlist of a selected topology is prepared. To select a converter (e.g. a buck converter) the rule in CLIPS syntax is:

\[
(defrule ConverterSelection::buck
?var <- (go-for-topology selection)
(test (< ?Vin ?Vinmax))
(test (> ?Vout 0))
(test (< Power 100.0))
(test (eq ?Isolation "NO"))
\]

The above rule selects a buck converter if the output voltage is positive and less than the input voltage, the output power is less than 100W, and there is no requirement for isolation between the input and output. The first statement controls the execution of the rule. Once a suitable converter is selected, then the correct inductor current mode (continuous or discontinuous mode) must be chosen. The knowledge base selects a suitable mode based on the topology and type of load.

4.4 Design Validation:

At each design stage, the design is validated by processing the simulated results. All the converter responses will be tested by this module for any violations against the design specifications. If any violations are detected, appropriate rules are activated to modify converter elements and continue the design procedure until all the specifications are met. For example, if the inductor current is discontinuous instead of continuous, a rule will be activated to adjust the selected value of the filter inductor.

4.5 Magnetic Components:

The design of magnetic components mainly concerns the high frequency switching transformer and the filter smoothing inductor. The knowledge consists of several rules for selecting the type and material for the core, the copper wire sizes[2], and the number of turns. The design must meet specifications for maximum losses and space limitations for a cost-effective design.

4.6 Device Selection:

As discussed in the previous sections, the selection of major circuit components depends upon ratings, cost, preferred supplier etc. Apart from the selection of suitable devices, the KB is intended to handle tasks such as SPICE-model development if there are no models available in the model-library.

5. Design Example: Buck Converter

The DSS currently designs a buck converter. A set of specifications, as shown in table 1., entered by the user prompts the DSS to select a buck converter as a suitable choice.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. input voltage</td>
<td>20 volts</td>
</tr>
<tr>
<td>Max. input voltage</td>
<td>28 volts</td>
</tr>
<tr>
<td>Output voltage</td>
<td>5 volts</td>
</tr>
<tr>
<td>Max. output current</td>
<td>5 amps</td>
</tr>
<tr>
<td>Min. output current</td>
<td>1 amps</td>
</tr>
<tr>
<td>Output ripple voltage</td>
<td>100 mvolts</td>
</tr>
<tr>
<td>Isolation</td>
<td>No</td>
</tr>
<tr>
<td>Setting time</td>
<td>2 msec</td>
</tr>
</tbody>
</table>

Table 1: Input specifications

Table 2. shows the generated netlist to test the initial design in open loop configuration. After this design has been checked, the DSS then closes the loop with a proper compensation circuitry. To reduce the simulation time, the converter is simulated using average-models. Fig. 4. shows the transient response of the converter for a step load change.

6 CONCLUSIONS

There is a definite requirement for improved CAD packages for power electronic systems. Circuit simulators such as SPICE are useful, but still leave the designer with a lot to do. Ideally, a design package should be comprehensive in its scope and flexible in its approach if it is to be useful in more than a very narrow application. The techniques described in this paper integrate into a single package preliminary circuit design, component selection, circuit simulation, control loop design, and design for EMC. The approach is suggestive rather than prescriptive, in that the user can over-ride the choices of the DSS if he/she so wishes.

Although the package is written for the design of Switched Mode Power Supplies, it could readily be adapted to other power electronic applications, such as Uninterruptible Power Supplies or motor drives.

REFERENCES

DECISION SUPPORT POWER ELECTRONIC SYSTEMS DESIGN SOFTWARE*

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ABSTRACT

Expert Systems, a branch of Artificial Intelligence, have great potential in applications such as the design of Power Electronic Systems, where considerable expertise in exploring complex and tedious tasks is required. Faster design times and a more efficient design are among the advantages that can be achieved using an Expert System based design. This paper describes the design and development of Decision Support Power Electronic Systems Design Software (DPDS) to assist the design of Switched Mode Power Supplies developed using wxCLIPS, an expert system development tool. Extensive knowledge bases covering the various design rules of power supplies are built into the DPDS, which is also linked to a SPICE simulator and other utilities such as Databases and a Graphical Display. It is expected that the techniques described in this paper can be applied to other Power Electronic Systems.

1. INTRODUCTION

Design of Power Electronic converters requires wide ranging expertise in complex and often tedious tasks, such as exploring the different options in tasks such as choice of converter topologies, selection of power semiconductor devices, design of the feedback loop, design of wound components, and design for Electromagnetic Compatibility (EMC). This makes the design very subjective in nature, iterative, and heavily dependent on the designer's experience.

Currently, CAD tools, such as SPICE or SABER, are limited in their scope for the design of power electronic systems. Even with these CAD tools, it is still necessary to build a prototype to verify the design, usually followed by several test-modify-retest cycles before a final design is reached. This process involves considerable decision making, which requires substantial expertise in all aspects of power electronics.

An effective way of enhancing the CAD tools is to embed decision support into them, using an Expert System (ES). With an ES, it is straightforward to alter or update the design process, and experiment with new technical advances.

Many research projects into CAD for power electronic systems have been reported, especially in switched-mode power supply systems, but there is no work which covers all facets of the design. In [1], the authors identified an approach to design power electronic circuits interactively, but the designer still has to select suitable power devices and carry out the initial design, and there is no attempt to tackle the electromagnetic compatibility (EMC) problems normally found in power electronic systems. Hsieh and Liu [2] use both algorithm and knowledge-based methods which reduces the flexibility of the system, and there is no proper co-ordination of the different tasks involved in the design process. It was also observed that there was no extensive user-interface provided and no attempt to exploit fully the SPICE-simulation tool.

The main aim of this project is to develop an user-interactive and user-friendly CAD package for power electronic systems that covers all facets of the design for a given application, with decision support provided at all levels of the design. As an initial target, the design of a complete Switched-Mode Power Supply (SMPS) for a given set of input specifications has been undertaken, as SMPS are typical power electronic systems. The developed package aims to give a complete system design with an optimum design configuration produced at minimum time and cost.

The following sections describe the architecture of the software, the development of the different knowledge bases, and the methodology of the system.

2. DESIGN OF THE DECISION SUPPORT SOFTWARE

A block diagram showing the architecture of the Decision Support Software is shown in figure 1. The basic building block is an Expert System (ES), a program intended to model human expertise or knowledge. An Expert System has three major components: a User Interface, an Inference Engine, and a Knowledge Base (KB). The knowledge base is a set of facts and heuristics (rules of thumb) about a specific domain task. Expert systems deal with a specific task by drawing inferences using its inference engine from its KB.

In the DPDS, the ES and various interfaces are developed using wxCLIPS, an Expert System development tool. WxCLIPS[3] is an extension of CLIPS [4] with graphical user interface (GUI) functionality to write a portable graphical interface which runs under MS-Windows. CLIPS provides a complete environment for the construction of rules and/or object-oriented ES, and it provides a cohesive tool for handling a wide variety of knowledge with support
for three different programming techniques: rule-based, object-oriented, and procedural. The rule-based programming allows knowledge to be represented, using the forward-chain mechanism as its inference engine. The selection of this tool was prompted by many advantages, such as free availability of source-code and easy user-interface development.

The ES is embedded with different KBs, such as rules to select an appropriate converter topology, and it also co-ordinates the SPICE circuit simulation [5], the processing of the simulation results, and the interaction with the databases and GNUPLOT [6] (a plotting utility to display graphically any data such as SPICE simulation results). The design of the individual stages is explained below.

2.1 User Interface

Since it is an important task of any ES to communicate with the user, who may or may not be an experienced SMPS design engineer, the design of the User Interface is of paramount importance in any ES design. The GUI functionality of wxCLIPS provides many forms of interface, such as windows, dialogue-boxes, message-boxes and on-line help. The user front-ends designed for the SPICE simulation and databases are shown in figure 2.

2.2 Simulation Environment

The simulation environment consists of a SPICE circuit-simulator to simulate the circuit, a netlist editor, and GNUPLOT to view the simulation results. Figure 2a shows the developed simulated environment window.
Figure. 2a. Developed user-interfaces: Design environment.

The SPICE simulator is fully integrated within the ES, and can be used either as a stand-alone or as an integrated simulator. The ES interprets any errors encountered during simulation and suggests causes and possible remedies for them, and it also processes the simulation results. The Pre-plotter formats the simulation results and prepares ‘plot’ files, which are used by the GNUPLOT. The Data-processor contains several routines written in C-language to process simulation data for different analyses.
2.3 Databases

For a fully integrated design package, databases of available components such as power semiconductor devices (MOSFETs and diodes), filter capacitors, and magnetic cores are necessary. Since there are usually several similar devices from different manufacturers all of which may appear appropriate for a given application, the selection of a best-suited device based on optimum ratings and price is often cumbersome. However, this is an ideal task for a DPDS.

The databases contain the necessary electrical ratings, the manufacturer, and the cost of the device. All the data in the databases is stored in ASCII-format, and the databases can be accessed using CLIPS. The DPDS also facilitates construction of new databases, and the up-dating of existing databases. The interface to search and update the power MOSFET database is shown in figure 2b. The DPDS can be a useful tool even for an experienced engineer, as it minimises the time taken searching through various databooks.

3. MODUS OPERANDI OF THE DPDS

Figure 3 shows the various design sequences that are carried out by the DPDS. The design of the SMPS is initiated by asking the user to input the required specifications. After correcting any keyboard errors, it then performs an preliminary analysis on the specifications to check that they fall within the scope of the DPDS to design a viable power supply.

After identification of a suitable converter for the application (by consulting its KB), the DPDS starts designing different stages of the converter, such as the input rectifier and the dc-dc high frequency conversion stages of the SMPS. Appropriate values of switching frequency, transformer turns ratio, filter inductance, and filter capacitance are chosen at this stage.
Device selection is an extremely important area. As well as the electrical ratings, parameters that influence choice are cost, availability, and the reliability of the manufacturer. In the case of the output filter capacitor, multiple capacitors are often preferred over a single big capacitor to reduce overall size, but cost can be the single most influential factor. The DPDS prompts the user to select all necessary power semiconductors and filter capacitors from the databases.

The system then starts the simulation process to validate the design by preparing a netlist for the simulator. Different parts of the power supply are simulated separately to reduce the simulation complexity (and hence simulation time). A number of simulations are carried out, each emphasising different aspects of the circuit such as steady state voltage and current waveforms, transient response, stresses on power devices etc. The complexity is gradually increased by adding device/circuit parasitics (e.g. capacitor resistance, transformer leakage inductance etc.). After a successful simulation, the simulation results are processed, and if the performance is not satisfactory, the design values are altered and the simulation is repeated. This trial and error process continues until all the specifications are met or the knowledge is exhausted. If, at any stage, the simulation is not successful, the ES performs a fault diagnosis by reading the error file produced by the simulator, and rectifying the errors.

The simulation results can be viewed using GNUPLOT. If the design approach fails at any time, the system flags the problem and passes control back to the user.

The design is not complete until it has complied with Electromagnetic Compatibility (EMC) requirements. The EMI problem is a somewhat random phenomenon and there are few clear-cut rules to follow; however, the DPDS offers various suggestions on lay-out of components on PCB using its KB gained from the SMPS-engineers, and assists with the design of an appropriate input filter and snubber circuits.

After a satisfactory design of the converter, the DPDS considers the design of the wound components (usually the filter inductor and the isolation transformer). Magnetic components are bulky devices that contribute considerably to the total size and cost of a SMPS [7]. Careful selection of a suitable core material and style is thus required for a cost-effective design. The DPDS currently designs the filter inductors using RM-cores, although this will be extended to cover other core types.

The DPDS currently designs both buck and forward converters. For the specifications shown in figure 4, a buck converter is selected and designed [8]. The various stages are then designed and evaluated. Figure 4 shows the closed-loop transient response of the buck converter under investigation.
Figure 4. Transient response of the designed buck converter.

4. CONSTRUCTION OF THE KNOWLEDGE BASES

The power of an Expert System lies in its Knowledge Base. The KB represents knowledge about various problem solving modules gathered from experienced power supply design engineers. In CLIPS, it is mainly represented in the form of rules and objects. Construction of the different KB modules, as shown in figure 5, is explained below.

Figure 5. View of the different KB modules in the DPDS.

4.1 Converter Module

The converter knowledge module performs selection of a suitable converter topology based on known constraints such as required power throughput and type of load. It contains the design rules for the power stages of the converter, such as the output filter, and it also contains knowledge about the sensitivity of the converter to its circuit elements. For example, if the inductor current in a continuous mode converter goes into discontinuous-mode, the knowledge module would increase the value of the output filter inductor [7].
4.2 Control Philosophies Module

This module handles the choice of feedback control system and its design. The sequence of operations that are executed by this module is shown in figure 6. The possible control techniques considered are direct duty ratio control and current-mode control. For a forward converter operating in the continuous current mode, for example, the knowledge base selects current-mode control due to the well known advantages of current-mode control for buck-family converters. The rules for selecting cross-over frequency, required gain and phase margin are included in this module.

4.3 Circuit Simulation Module

For the SPICE simulation, the netlist of the selected topology is prepared. If the user subsequently modifies the netlist, rules implemented here check the netlist and flag any mistakes. The various sequences in a simulation-cycle are shown in figure 7. Since there is a possibility of simulation failure, the module identifies any errors and suggests their causes and possible remedies.

![Flow-chart for the design and validation of the control circuit.](image)

Since simulation of circuits with real models, often called brute-force simulation, takes quite a long time, all the initial design stages are simulated with macro-models [9]. Average macro-models are used to predict overall system response, whereas switched macro-models are used to measure open-loop characteristics and device stresses. Different SPICE models such as power supply control ICs are developed and linked with this knowledge module.

4.4 Design Validation Module

At each design stage, the design is validated by processing the simulated results. All the converter responses are tested by this module for any violations against the design specifications. If any violations are detected, appropriate rules are activated to modify converter elements and continue the design procedure until all the specifications are met. For example, if the closed-loop transient response is not satisfactory, a rule will be activated to diagnose the possible causes such as inadequate error amplifier compensation.
Appendix B.2

Figure 7. Different stages in a simulation-cycle.

4.5 Magnetic Components Module

The design of the magnetic components mainly concerns the high frequency switching transformer and the filter smoothing inductor. The most critical elements in the design are the selection of core geometry, core material, and wire dimensions, and designing to reduce skin-effects [7]. The knowledge consists of rules for selecting the type and material for the core, the copper wire sizes, and the number of turns. The design must meet specifications for maximum losses and space limitations for a cost-effective design. The general decision processes taken in the design of the magnetic components are shown in figure 8.

Figure 8. Decision processes in the wound components design.

4.6 Device Selection Module

As discussed in section 3, the selection of circuit components depends upon ratings, cost, preferred supplier etc. Apart from the selection of suitable devices, the KB is intended to handle tasks such as SPICE model development if there are no models available in the model library.

4.7 Design for EMC Module

Solving EMC problems in Power Supplies is largely based on heuristics of experienced design engineers. Since an Expert System is a very efficient tool to capture and model heuristic procedures, it can be used to tackle the EMC problems.
problem. Various options such as the positioning of components on the printed circuit board, design of snubber circuits, and design of the input filter are currently being developed.

5. CONCLUSIONS

There is a definite requirement for improved CAD packages for power electronic systems. Circuit simulators such as SPICE are useful, but are only part of the solution. Ideally, a design package should be comprehensive in its scope and flexible in its approach if it is to be useful in more than a very narrow application. The techniques described in this paper integrate into a single package: preliminary circuit design, component selection, circuit simulation, control loop design, and design for EMC. The approach is suggestive rather than prescriptive, in that the user can over-ride the choices of the DPDS if he/she so wishes.

Although the package is written for the design of Switched Mode Power Supplies, it could readily be adapted to other power electronic applications, such as Uninterruptible Power Supplies or motor drives.

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[5] SPICE: © University of Berkeley, California, USA.
EXPERT SYSTEM BASED SWITCHED MODE POWER SUPPLY DESIGN

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ABSTRACT

The design of power electronic systems requires considerable expertise in exploring a wide range of complex and tedious tasks. Faster design times and a more efficient design are among the advantages that can be achieved using an Expert System to assist with the task. This paper describes an Expert System (XpertPSD) with extensive knowledge bases linked to a circuit simulator (SPICE) to assist the design of Switched Mode Power Supplies. It is expected that the techniques described in this paper can be applied to other power electronic systems.

1. INTRODUCTION

Design of Switched Mode Power Supplies (SMPS), which are typical power electronic systems, requires wide ranging expertise in complex and often tedious tasks, such as choice of converter topologies, selection of power semiconductor devices, design of the feedback loop, design of wound components, and design for Electromagnetic Compatibility (EMC). This makes the design iterative, time consuming, and heavily dependent on the designer’s experience.

Electric circuit simulation tools, such as SPICE or SABER, can be used to assist in the design of power electronic systems. However, the design process still involves considerable decision making, which requires substantial expertise in all aspects of power electronics.

An effective way of enhancing the simulation tools is to embed decision support into them using an Expert System (ES). This results in a comprehensive Computer Aided Design (CAD) environment for the power electronic system. With an ES, it is straightforward to alter or update the design process, and experiment with new technological advances.

Many research projects into CAD for power electronic systems have been reported, especially in Switched Mode Power Supplies, but there is no work which covers all facets of the design. An approach was identified in [1] to design power electronic circuits interactively, but the designer still has to select suitable power devices and carry out the initial design calculations, and there is no attempt to tackle the Electromagnetic Compatibility problems normally found in power electronic systems. In [2] a knowledge-based system was developed with some decision support but without proper user-interaction, and also there is no full co-ordination of the different tasks involved in the design process. It was also observed that there was no extensive user-interface provided and no attempt to exploit fully the SPICE-simulation tool.

The main aim of the work described in this paper is thus to develop a user-interactive and a user-friendly CAD package for SMPS that covers all facets of the design with decision support provided in all areas. The developed package aims to give a near complete system design with an optimum configuration produced at minimum time and cost.

The following sections describe the design and development of the ES, the methodology of the software, and how the various tasks such as wound component design, and design for EMC, are approached.

2. STRUCTURE OF THE XpertPSD

Figure 1 depicts the architecture of the developed software package. The basic building block is an Expert System, a program intended to model human expertise or knowledge. The major components of any Expert System are the User Interface, the Inference Engine, and the Knowledge Base. The Knowledge Base is a set of facts and heuristics about a specific domain task. Expert systems deal with a specific task by drawing inferences from its Knowledge Base using its Inference Engine.

2.1 The Expert System Development Tool

The XpertPSD is developed using wxCLIPS, an Expert

Appendix B.3

System development tool. WxCLIPS [3] is an extension of CLIPS [4] with Graphical User Interface (GUI) functionality to write a portable graphical interface that runs under major platforms, including MS-Windows. The tool provides a complete environment for the construction of rules and/or object-oriented ES, and it provides a cohesive tool for handling a wide variety of knowledge with support for three different programming techniques: rule-based, object-oriented, and procedural. The rule-based programming allows knowledge to be represented, using the forward-chain mechanism, as its Inference Engine. The selection of this tool was prompted by many advantages, such as easy user-interface development and free availability of the source-code.

Since it is an important task of any ES to communicate with the user, who may or may not be an experienced SMPS design engineer, the design of the user interface is of paramount importance in any ES design. The Graphical User Interface functionality of wxCLIPS provides many forms of interface, such as windows, dialogue-boxes, message-boxes and on-line help. The user front-ends designed for the SPICE simulation and databases are shown in figures 2 and 3.

The ES is embedded with different Knowledge Bases covering, for example, selection and design of an appropriate converter topology, design validation and interaction with various Databases.

2.2 Simulation Environment

The simulation environment consists of a SPICE circuit-simulator [5] to simulate the circuit, a Netlist editor, Data-Processor to process the simulation data and GNUPLOT [6] (a plotting utility) to view the simulation results graphically. The SPICE simulator is fully integrated within the ES, and can be used either as a stand-alone or as an integrated simulator. Figure 2 shows the developed simulation environment window.

The ES calls the Data-Processor to process the simulation results. The Data-processor contains several routines written in C-language to process simulation data of transient and ac small-signal analyses. The Pre-plotter, an external C-program, is run to format the simulation results and to prepare ‘plot’ files, that are then used by GNUPLOT to display the results.

For the SPICE simulation, the netlist of the selected topology is prepared. After any subsequent modifications made by the user, the netlist is checked for any mistakes and the user is advised to rectify them. If, at any stage, the simulation is not successful, the ES performs a fault diagnosis by reading the error file produced by the simulator, and rectifying the errors.

Since simulation of circuits with real models, often called brute-force simulation, can take a long time, all the initial design stages are simulated with macro-models [7]. Average macro-models are used to predict overall system response, whereas switched macro-models are used to measure open-loop characteristics and device stresses. Different SPICE models for items such as power supply control ICs have also been developed.

Different parts of the power supply are simulated separately to reduce the simulation complexity and hence simulation time. A number of simulations are carried out, each emphasising different aspect of the circuit, such as steady state voltage and current waveforms, transient response, stresses on power devices etc. The complexity is gradually increased by adding device/circuit parasitics (e.g. capacitor resistance, transformer leakage inductance etc.).

After a successful simulation, the simulation results are processed, and if any input specifications have been violated appropriate rules are activated to modify converter elements and continue the design procedure until all the specifications are met. For example, if the closed-loop transient response is not satisfactory, a rule will be activated to diagnose the possible causes. This trial and error process continues until all the specifications are met or the knowledge is exhausted.

2.3 Design and Development of Databases

For a fully integrated design package, databases of available components such as power semiconductor devices, filter capacitors, and magnetic cores are necessary, as device selection is an extremely important area of the design, in which cost plays a key role. Since there are usually several similar devices from different manufacturers which may appear appropriate for a given application, the selection of a best-suited device based on optimum ratings and price can be a tedious task. However, this is an ideal task for an Expert System.

All the data in the databases is stored in ASCII-format, and the databases can be accessed using CLIPS functionality. The XpertPSD also facilitates construction of new databases, and up-dating of existing databases. Portability and simplicity are among the advantages of using text-format databases. Simple user interfaces have been developed for all the databases: as an example, the interface to search
update the power MOSFET database is shown in figure 3.

The XpertPSD can be a useful tool even for an experienced engineer, as it minimises the time taken searching through various databooks. As well as the electrical ratings, parameters that influence choice are cost, availability, and the reliability of the manufacturer. In the case of the output filter capacitor, multiple capacitors are often preferred over a single big capacitor to reduce overall size, but cost is frequently the single most influential factor.

3. DESIGN OF SMPS USING XpertPSD

In the design of SMPS, there exist distinct design tasks: power circuit (converter), feed-back control system, magnetics and EMC. Figure 4 shows the various design sequences that are carried out by the XpertPSD.

![Design Methodology Flowchart](image)

All the design tasks are embedded with various Knowledge Bases, which are constructed mainly in the form of rules and objects. These represent the experience gathered from several experienced power supply design engineers. Construction of the different design modules with their Knowledge Bases is described below.

3.1 Converter Design

The design of the SMPS is initiated by asking the user to input the required specifications. A preliminary analysis is performed on the specifications to check that the specifications fall within the scope of the XpertPSD to design a viable power supply. A suitable converter topology is selected based on known constraints such as required power throughput and type of load.

To select a converter (e.g. a forward converter) the rule in CLIPS syntax is:

```clips
(defrule ConverterSelection: :forward
  (?var <- (go-for-topology selection)
    (test (< ?Power 200.0))
    (test (eq ?Isolation "YES"))
  )
  =>
  (retract ?var)
  (slot-insert ($(Converter) SuitableConverters 1 FORWARD))
```

The above rule selects a forward converter if there is a requirement for isolation between the input and output and the output power is less than 200W. Once a suitable converter is selected, then the correct inductor current mode (continuous or discontinuous mode) must be chosen. The knowledge base suggests a suitable mode based on the topology and type of load.

After identification of the converter for the application, the XpertPSD starts designing different stages of the converter, such as the input rectifier and the dc-dc high frequency conversion stages of the SMPS. Appropriate values of switching frequency, transformer turns ratio, filter inductance, and filter capacitance are chosen at this stage. All the components needed are selected from the databases.

The system then starts the simulation process to validate the design by preparing a netlist for the simulator. If the design approach fails at any time, the system flags the problem with a possible remedy and passes control back to the user.

The ES is embedded with design rules for the power stages of the converter, such as the output filter, and it also contains knowledge about the sensitivity of the converter to its circuit elements. For example, if the inductor current in a continuous mode converter goes into discontinuous-mode, a rule would be activated to increase the value of the output filter inductor [8].

3.2 Control System Design

After a successful validation of the open-loop stage of the converter, the XpertPSD considers the choice of feedback control system and its design. The sequence of operations that are executed is shown in figure 5. The possible control techniques considered are direct duty ratio control and current-mode control. For a forward converter operating in the continuous current
mode, for example, the Knowledge Base selects current-mode control due to the well-known advantages of current-mode control for buck-family converter.

Decision support exists for selection of the cross-over frequency, and the gain and phase margins to give a good transient response. Based on the required gain and phase margins, an appropriate compensation circuit is designed. The design is then checked by simulating the circuit in the frequency-domain, and, if necessary, adjustments are made to the compensation circuit to achieve the required gain and phase angle characteristics. The whole design is finally tested for over-all closed-loop transient response to a step-load change.

### 3.3 Magnetics Design

After a satisfactory design of the converter has been completed, XpertPSD considers the design of the wound components. This mainly concerns the high frequency switching transformer and the output filter inductor, bulky devices that contribute considerably to the total size and cost of a SMPS [9]. The most critical elements in the design are the selection of core geometry, core material, and wire dimensions, and designing to reduce skin-effects; careful selection of a suitable core material and style is thus required for a cost-effective design.

Rules are built into the Knowledge Base to select the type and material for the core, the copper wire sizes, and the number of turns. The design must meet specifications for maximum losses and space limitations for a cost-effective design. The principal decision processes taken in the design of the magnetic components are shown in figure 6.

![Decision processes in the wound components design.](image)

**Figure 6. Decision processes in the wound components design.**

The XpertPSD currently designs the filter inductors and high frequency transformers using either RM-cores (less than 100 watts) or E-cores; however, this will be extended to cover other core types.

### 3.4 Design for EMC

It is well known that Switched Mode Power Supplies generate broadband noise in the kHz and MHz ranges, propagated either by radiation or through line conduction. EMI Regulatory bodies, such as VDE and FCC, place stringent limits on the amount of emission levels. Solving the EMC problem in power supplies is largely based on heuristics of experienced design engineers. Since an Expert System is a very efficient tool to capture and model heuristic procedures, it can be used to tackle the EMC problem.

As shown in figure 7, the ES starts tackling the EMI problem by showing various options to the user about the positioning of components on the printed circuit board for EMI reduction. As snubbers across power semiconductor switching devices [9] are very effective in reducing EMI emission, the ES designs the snubbers required.

XpertPSD analyses the power supply under design for conducted emission using the SPICE-simulator, and an appropriate input filter is designed. Here, accurate SPICE models for Power MOSFETs are crucial for accurate EMI prediction. The rules for the design of the input filter are built into the Knowledge Base:
Appendix B.3

however, due to the nature of the problem a trial-and-error approach is required.

```
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  however, due to the nature of the problem a trial-and-
  error approach is required.

  DESIGN FOR EMC
  Lay-out Considerations
  Snubbers Design
  BMI Regulatory Bodies
  Measurement of Emission
  Diagnosis of the Emission
  not ok
  Design/Modify BMI Filter

  Figure 7. Designing for Electromagnetic compatibility.
```

4. DESIGN ILLUSTRATION

The XpertPSD currently designs both buck and forward converters. For the specifications, as shown in figure 8, a forward converter is selected and designed. The various stages are then designed and evaluated. The generated SPICE netlist to verify the design is shown in figure 2, where the GNUPLot showing the simulated waveforms can also be seen. Figure 8 shows the closed-loop transient response of the forward converter under investigation.

```
  Specification:
  200 - 240 VAC input / 5 V output
  1 - 5 A output current
  0.1 V max. output ripple voltage
  (Isolation required)

  Design data:
  Filter : 35 uH, 2200 uF, 28mOh.
  Current-mode control with UCE844 control chip.
  Single-pole compensation.

  Figure 8. Transient response of a forward converter.
```

5. CONCLUSIONS

Existing software packages such as SPICE can be extremely useful when designing power electronic systems, as a tool to assist in validating the design.

However, the basic design still has to be carried out by the design engineer. A design package should ideally be comprehensive in its scope and flexible in its approach if it is to be useful in more than a very narrow application. The techniques described in this paper integrate into a single design package: preliminary circuit design, component selection, circuit simulation, control loop design, design of wound components and design for EMC. The approach is suggestive rather than prescriptive, in that the user can over-ride the choices of the XpertPSD if he/she so wishes.

Although this package has been written for the design of Switched Mode Power Supplies, the techniques described here could readily be adapted to other power electronic applications, such as Uninterruptible Power Supplies or motor drives.

REFERENCES


[5] SPICE: © University of Berkeley, California, USA.


Figure 1. Architecture of the Decision Support Software

Figure 2. The Expert System based design environment.

Figure 3. Front-end to Power Mosfets database