1.1 General Background

With the advancement of telecommunication and computer systems, the distributed power architecture and point-of-use power supplies are becoming essential. While operating at a high frequency, these supplies are required to produce high efficiency, high power density and low switching losses. Operation at high frequencies not only increases the power density, but also reduces component size.

The modern world is steadily becoming more and more reliant on high technology electronics and computers, which has led to a dramatic increase in the amount of power that is processed by power electronic converters. The majority of the power electronic converters in the world today are very bulky in the low or medium power range, consuming a significant amount of power, having high noise, high ripple, high EMI (Electromagnetic Interference) and working inefficiently.

To accommodate the ever-increasing requirements for smaller size, lighter weight and higher efficiency power supplies, switched-mode power conversion technologies evolved from basic pulse-width-modulated (PWM) converters to resonant converters, quasi-resonant converters (QRCs), multi-resonant converters (MRCs) and most recently soft switching PWM converters are being used. Due to circuit parasitic and hard-switching condition, operation of a PWM converter involves high switching losses, switching stresses and switching noises. These are the major factors that restrict PWM converters from operating at higher frequency. With the available devices and circuit technologies, PWM converter has been designed to operate with a 50-200 kHz switching frequency. In this frequency range, the power supply is deemed to be optimal in weight, size, efficiency, reliability and cost.

A 5 kV dc source of 0.8 Amp current has been developed as a prototype model. The switching frequency is 50 kHz which is suitable for IGBT switching operation. The research work is focused on two research areas; one is the design of converter and second is the design of the high frequency transformer.

It is desirable to push the conversion frequency as high as the upper-hundreds kilohertz to lower-megahertz range. However, higher switching frequency invariably results in increased switching losses. The switching loss at turn-off is primarily caused by the leakage inductance of the power transformer. As the semiconductor device turns off, the sharp di/dt induces high voltage spike across the
leakage inductance. To reduce switching stress, dissipative snubbers are typically used. At turn-on, switching losses are mainly caused by abrupt discharging of the energy stored in the parasitic capacitance of the semiconductor devices. When the transistor is turned on, the energy stored in its output capacitance is dissipated in the device. In addition, the rectifier's junction capacitance is dissipatively charged through the active switch, increasing switching loss and stress. Also, turn-on at high voltage levels induces a severe switching noise coupled through the Miller capacitance into the drive and control circuits. The aforementioned detrimental effects of the circuit parasitics become much more pronounced as the switching frequency is increased.

The developed technology is suitable for driving electrical loads requiring very large power pulses within short bursts. The system consists of two main parts: One is the low power area and the other is high power output stage. A battery and/or a generator works as primary energy source and its energy is transferred to the energy storage equipment by a step-up dc-dc converter. The converter deals with relatively low average power during the charging period. The energy from the energy source is stored in capacitor bank or superconducting inductive device based on the applications. Then, when a discharging signal exists, the stored energy is released to the load through the pulse forming network, which determines the discharging period and power pulse waveform, generating ultra high peak power up to gigawatts during very short period in the range of micro- and millisecond.

M.A. Kempkes has first introduced the pulse power system for commercial application in 2002. The pulsed power system has a wide spectrum of the applications in the medical, industrial and military areas. The simple example would be an X-ray generator in the medical application where the X-ray is used for medical diagnosis. In general, the X-ray generator is required to properly control the X-ray penetration capability and beam quality such that the contrast, brightness and resolution of X-ray images are good enough for medical diagnosis. In addition, the volume and the weight are the important aspects in the applications such as X-ray scanner, C-arm X-ray systems and portable X-ray machines [1],[2],[3].

Other examples are found in the industrial applications such as food irradiation, radioactive and sewage waste treatment, surface hardening of steels, alloys and semiconductors, surface cleaning, surface polishing and so on. Furthermore,
the efforts are being extended to material fabrication, chemical production, food pasteurization, medical product sterilization or as a treatment method for waste effluents that pollute the air, ground soils or ground water [2],[3].

The developed system will find applications for new military devices such as electric launchers, electrothermal-chemical (ETC) gun, coilgun and active armor system. Especially, ETC gun, coilgun and active armor system utilize an advanced weapon technology. The developed technology also has the future potential to be used into a combat vehicle.

John A. Gaudet and J. Biebach, P. Ehrhart has introduced the compact power supply for military vehicle. For mobile application such as the combat vehicle, the development of compact, light-weight and high efficient pulse power system is strongly required due to the limited space of the military vehicle [4],[5].

This work also focuses on the high density transformer design for high-frequency and high-power applications. Power electronics converters mainly employ transformers for the purpose of galvanic isolation and voltage level changing, which are quite similar to the power system requirements. However, transformers for switching mode converters have distinct characteristics, like high operating frequencies, non-sinusoidal waveforms and predominantly compact sizes. In practice, the transformer is a complex component and the heart of circuit performance. The design, construction and performance of the transformer itself requires a deep understanding of electromagnetism. Parasitic elements of magnetic components would affect the converter operation more and more as the frequency gets higher and higher.

One of the major challenges of the high-density power converter design is to have high-density magnetic components which are usually the most bulky parts in a converter. Increasing the switching frequency to shrink the passive component size is the biggest contribution towards increasing power density. The calculations of losses of high-frequency magnetic components are complicated due to the eddy current effect in magnetic cores and copper windings. Parasitic capacitance of magnetic components, including leakage inductance can significantly change converter behavior. Therefore, controlling of losses due to parasitic mechanism in design of high frequency transformer is major challenge and need to be explored extensively. These issues of high frequency transformer are explored, particularly in regards to
high-power converter applications. Loss calculations accommodating resonant operating waveform and Litz wire windings are explored. The optimal design is developed considering the above issues.

### 1.2 Historical Development of High Frequency Transformer

Transformers for power electronics converters are so varied that it is hard to make comparison without categorizing them according to applications. Power converters nowadays can be used anywhere from few watts to Mega watts, with switching frequency up to several Mega hertz. These features are mainly determined by the kind of semiconductor devices employed by the converter. Therefore, the literature survey of transformer is conducted in three categories: 1) the low power (<1 kW) & Ultra-high frequency (>1 MHz) range that is for purely MOSFET based converters; 2) the high power (>10 kW) & mid frequency (<100 kHz) range that is dominated by IGBT and Thyristor type devices; 3) the mid power (1~10 kW) and high frequency (100~1 MHz) range is the field which can be suitable for IGBT and MOSFET both.
Transformers falling in this range are the interested topic of research.

<table>
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<tr>
<th>Low Power range</th>
<th>Ultra-high-frequency Range (1 MHz - 10 MHz)</th>
<th>High-frequency Range (100 kHz - 1 MHz)</th>
<th>Mid-frequency Range (10 kHz - 100 kHz)</th>
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<td></td>
<td>Goldberg (1989): Ni-Zn ferrite gapped pot core, Planar spiral windings, 5-10 MHz, 50 W, Resonant forward converter</td>
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<td>Ngo (1992): Pot core, Planar spiral windings, 2-3 MHz, 100 W</td>
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<td>Evans (1995): Toroidal core, copper wires soldered on substratemetalisation as windings, 2 MHz, 150 W</td>
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<td>J. T. Strydom (2002): Integratedplanar core, spiral windings L-C-Transformer, 1 MHz, 1 kW, Asymmetrical half-bridge resonant converter Coonrod</td>
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<td>Mid Power range</td>
<td>Coonrod (1986): Ferrite toroidal core, magnet wire windings, 100-300 kHz, Half-bridge converters</td>
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<td>Petkov (1996): Freeite PM core, magnet wire windings, 100 kHz, 2.6 kW, Microwave heating supply</td>
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<td>Canales (2003): Ferrite E core, Litzwire windings, 745 kHz, 2.75 kW, Three-level resonant converters</td>
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<td>Biela (2004): Integrated transformer, ferrite E core, foil windings, 300-600 kHz, 3 kW, Resonant converters</td>
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<td>High Power range</td>
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<td>Research work is done in this area</td>
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- Kheraluwala (1992): Ferrite toroidal core, coaxial windings (primary tube and secondary Litz), 50 kHz, 50 kW, Dual active bridge converter
- J. C. Fothergill (2001): Ferrite C-core, solid magnet wire windings, 25 kHz, 25 kW, 50 kV, Full IGBT bridge converter
- L. Heinemann (2002): Nanocrystalline wound core, coaxial cable windings (inner aluminum tube and outer braided copper), 10 kHz, 350 kW, 15 kV, Dual active full bridge
- Reass (2003): Nanocrystalline cut core, 20 kHz, 380 kW, poly-phase resonant converter Low
1.2.1 Low Power & Ultra-High Frequency Applications

In telecom and computer products, switching mode power supplies have been designed to run between kHz to megahertz to increase power density and reduce footprint. For switching frequency beyond megahertz, switching losses contribute the majority part of the active losses. MOSFET devices are optimized to switch up to megahertz range while keeping loss generation low. As the switching frequency has increased to the megahertz range, magnetic design issues have been extensively explored for low-power applications less than 1 kW [6],[7],[8],[9],[10]. It can be imagined that core and winding loss calculations are critical in this frequency range. Parasitic modeling receives the same attention, because the transformer behavior and performance are highly affected by the leakage inductance and stray capacitance.

Goldberg had used Ni-Zn ferrite materials pot core and planar spiral windings for a 50 W transformer running between 1 and 10 MHz [6-10]. He went through loss and leakage inductance calculations considering skin effects. A design program was developed to search for the minimum footprint of the transformer. His pioneering work demonstrated the possibility, but it has more academic influence and only applies to very low power applications.

P. D. Evans claimed that the conventional E and planar core shapes are not satisfactory at MHz frequency range, so a toroidal core transformer was proposed with copper wires soldered on a substrate as windings [11],[12]. The key idea was to fully realize the interleaved winding structure to cancel the proximity effect. However, no core loss and parasitic calculation methods are reported in this work.

In 2002, J. T. Strydom reported an edge-cutting work on transformer development – 1 MHz, 1 kW integrated passive module [9]. Fundamentally, there is no difference on the planar structure and loss calculation considerations between this work and the Goldberg’s. The inductance and capacitance calculations are critical since they are designed to participate in the resonant converter operation. Other work also recently demonstrated 1 MHz, 1 kW resonant converters for telecom power module with both integrated planar and discrete E core transformers. Low loss ferrite is the choice for the core material [13].

It can be concluded that planar structures are prevailing for magnetic components falling in this range because of their low profile, easy manufacturability.
and good heat removal. Ferrites are the exclusive core material, since they have lowest loss density. The disadvantage of low saturation induction does not bother the designer, since the designed flux level is usually much lower than the saturation level. Correspondingly, high-frequency loss calculations considering eddy current effects are applied to both magnetic cores and spiral windings. Parasitic effects are modeled into lumped equivalent circuit components. However, the planar structure and its corresponding sets of analysis can hardly be applied to a magnetic component with a higher power rating. So choice was to choose larger copper area for higher power applications. Although the interleaving winding scheme could reduce the AC resistance to certain degree, it is still quite impractical to have planar spiral windings for high current at high frequency.

1.2.2 High Power & Mid-Frequency Transformer Applications

Vehicular and aircraft power systems employ more and more power electronics converters which have typical power rating of tens kilowatts. MOSFET switches do not have advantages in this range. Since IGBTs dominate applications that are above the ten kilowatts range, the corresponding magnetics employed in the transformer operates below 100 kHz. Frequencies between 20 and 50 kHz are typical in these applications and power ratings higher than 10 kW can be categorized into this range.

Kheraluwala proposed a novel coaxial wound transformer for 50 kHz and 50 kW dual active bridge DC/DC converter systems [10]. Stemmed formed the idea of reducing leakage and increasing coupling between primary and secondary windings, the coaxial transformer employs a bunch of toroidal cores and has coaxial type wires wound across them. The coaxial wire is composed of outer copper tube and inner Litz wires for two windings. The leakage inductance calculation is explored for this particular structure.

J. C. Forthergill developed a high voltage (25 kV) transformer for an electrostatic precipitator power supply, insulation and electrostatic analysis are the major contribution of this work [12]. No special considerations of loss and parasitic calculation have been discussed for this 25 kHz and 25 kV (pulsed-power) transformers.
Instead of planar structures, high power transformers usually have cable windings and ferromagnetic materials are used to achieve higher density. The accurate and convenient loss and parasitic calculation methods lack for all the above mentioned transformers. Another interesting point is that nanocrystalline magnetic material instead of ferromagnetic material has been applied to achieve higher density.

1.2.3 Mid-Power & High-Frequency Transformer Applications

For applications of several kilo-watts and several hundreds kilo-hertz, IGBT and MOSEFT are both candidates to the converter power stage. With the advancement of semiconductor devices and the application of soft-switching techniques, several-kilowatt converters running at more than 100 kHz have been realized. Transformers are a critical part of the circuit.

From Coonrod in 1986 to Petkov in 1996 [13], high-frequency transformer design procedure has been studied. Core loss and winding loss are modeled and optimally allocated during the design. Simple thermal models have been employed to complete the design loop. Ferrite cores are the primary choice and foil windings are popular for this power and frequency range. Transformer prototypes falling in this range can be found in high-frequency resonant DC/DC converter applications.

1.3 Switch-Mode and Soft-Switching Converters

In many PWM DC/DC converter topologies, the controllable switches are operated in switch mode where they are required to turn the entire load current on and off during each switching cycle [14]. Under these conditions, the switches are subjected to high switching stresses and high switching power losses. Fig. 1.1 illustrates the general switching characteristics of a switch-mode converter. Fig. 1.1(a) shows the switch gating control signal and Fig. 1.1 (b) shows the switching voltage and current, waveforms during both turn-on and turn-off of the switch. Fig. 1.1(c) illustrates the instantaneous power dissipation, $P(t)$. 
Fig. 1.1 Switching Characteristic: a) Control Signal, b) Switch current and Voltage, c) Instantaneous switch power loss

It is obvious from this plot that large instantaneous power dissipation occurs in the switch during the turn-on and turn-off intervals. There are several such turn-on and turn-off transitions per second. The average switching power loss $P_s$ in the switch due to these transitions is given by:

$$P_s = \frac{V_t I_o f_s}{2} \left( t_{on} + t_{off} \right) \quad (1.1)$$

This is an important result because it shows that the switching power loss in a semiconductor switch varies linearly with the switching frequency and the switching times. For converter operation in the megahertz range, this is not a suitable choice. The switch stresses can be reduced by connecting simple dissipative snubber circuits (consisting of diodes and passive components) in series and parallel with the switches in the switch-mode converters. These dissipative snubbers, however, shift the switching power loss from the switch to snubber circuit and therefore do not provide a reduction in the overall switching power loss. To realize high switching frequencies in converters, the switching losses can be minimized if each power switch in the converter changes its status when the voltage across it and/or the current through it is zero at the switching instant. This is done with the combination of proper converter topologies that exhibit the desired characteristics and
are often termed soft-switching converters. The main advantages gained by using soft-switching converters are:

1) very low switching losses and stresses;
2) improved converter efficiency;
3) reduced need for cooling means;
4) achievement of higher switching frequencies.

Many of the topologies that utilize this zero-voltage and/or zero-current switching techniques require some sort of inductive-capacitive resonance, hence the name "resonant converters". Resonant converters is an important category of soft-switching converters and will be discussed in the next section.

1.3.1 Resonant Converter

The operation of resonant converters is quite different from the operation of PWM converters. First, the switches in a resonant converter create a square-wave AC waveform from the DC source. An LC circuit tuned close to the switching frequency then removes the unwanted harmonics from this square-wave. By changing the switching frequency, the resonant current and hence the load current and voltage can be controlled. These LC networks have voltage and current waveforms that vary sinusoidal during each switching period. These sinusoidal waveforms means the absence of high $di/dt$ current compared with square-wave converters. This also results in low levels of electromagnetic interference (EMI). There are many categories of resonant converters, which will be examined briefly.

1.3.2 Load Resonant Converter

There are three basic configurations of load-resonant converters: series, parallel and series-parallel. These are shown in Fig. 1.2(a)(b)(c).

Fig. 1.2(a) shows the series-resonant converter. One of the main advantages of the series resonant converter is that the resonant capacitor on the primary side acts as a DC blocking capacitor. This helps in reducing power losses in the main transformer. Also, leakage inductance associated with the main transformer can be grouped together with the resonant inductor. This is possible due to the series arrangement of the resonant components. The future trend is to operate converters at higher frequencies and reduce the output voltage to one volt or less. The advantages of operation at high frequencies include a faster response time of the converter and increased
bandwidth. Series resonant converters are suitable topologies for high frequency operation because of their lower power losses. The resonant capacitor is in parallel with the transformer, however, the leakage inductance cannot be grouped with the resonant inductor. Power losses increase as the frequency increases. The advantage is that the currents in the power devices decrease as the load decreases. This in turn reduces the power loss in the devices and maintains a high efficiency at low load. At no-load, however, the output voltage shows poor regulation. The output filter capacitor must carry high ripple current (equal in magnitude to almost 50% of the output DC current). This point, however, is becoming less of a problem because of advancements in capacitor design. Fig. 1.2(b) shows the parallel-resonant converter. The main advantage of this converter, unlike the previous one, is that the output voltage can be regulated under no-load conditions as long as the operating frequency is above resonance. Another advantage is that the DC filter at the output is inductive therefore DC output capacitors, capable of carrying very high ripple currents, aren't needed. The main disadvantage, however, is that the current carried by the power IGBTs and the resonant components is relatively independent of the load. The result of this is that the conduction losses in the IGBTs and the reactive components stay relatively constant as the load decreases so that the light-load efficiency of the converter suffers. Also, unlike the series resonant converter, leakage inductances in the transformer cannot be grouped with the resonant inductor. Power losses in the transformer are thus increased. Fig. 1.2(c) shows the series-parallel converter. It is seen that the load is connected in parallel with only part of the capacitance, for example, one-third of the total capacitance and the other two-thirds of the capacitance appears in series. This topology attempts to combine the advantages of both series and parallel converters while eliminating their disadvantages. With proper selection of capacitance values $C_{r1}$ and $C_{r2}$, harmonics contents will be blocked by the series resonant capacitor as well as no-load output voltage regulation will be improved. Also, the resonant current will change with a change in the load resistance.
Fig. 1.2 Load-resonant Converter: (a) Series, (b) Parallel, (c) Series-Parallel
1.3.3 Resonant Switch Converter

With this approach, resonant elements are inserted into the switch network to shape the switch voltage and current to provide zero-voltage and/or zero-current switching. During one switching cycle, there are both resonant and no resonant operating intervals. Therefore, these converters are often termed quasi-resonant converters. There are two categories of resonant switch converters: zero-current switching (ZCS) where the switch changes its state at zero-current and zero-voltage switching (ZVS) where the switch changes its state at zero-voltage. Fig. 1.3 shows both topologies.

Fig. 1.3 DC/DC Resonant Switch Buck-Converter: a) ZCS, b) ZVS
In a ZCS resonant-switch topology, the current produced by LC resonance flows through the switch, thus causing it to turn on and off at zero current. Since the switching losses are minimized and the EMI is reduced, very high switching frequencies can be attained.

In a ZVS resonant switch topology, the resonant capacitor produces a zero-voltage across the switch, at which instant the switch can be turned on or off. At other instant, however, the switch must withstand a peak voltage that is much higher than the input voltage. This requires a switch with a very high voltage rating.

In general, ZCS is usually preferred over ZVS at high switching frequencies. This is related with the internal capacitances of the switch. When the switch turns on at zero-current but at a finite voltage, the charge on the internal capacitance is dissipated in the switch.

Due to continuous improvement of switching characteristics, lower conduction losses and lower cost, IGBTs are gaining wide acceptance in switched-mode power converters/inverters. The ZCS technique eliminates the voltage and current overlap by forcing the switch current to zero before the switch voltage rises. Thus ZCS has been proved more effective than ZVS in reducing IGBT switching losses

1.3.4 Multi Resonant Switch Converter

The main limitations of the quasi-resonant-converters are their high voltage and current stresses. The multi resonant switch concept overcomes these problems. Fig. 1.4 shows a ZVS multi resonant buck converter. With the capacitor in parallel with diode $D$, a new resonant circuit arrangement is formed. The voltage stress across the switch is significantly reduced and the resonant circuit absorbs all major parasitic reactance. By limiting the switching frequency range, the parasitic oscillations found in the ZVS quasi-resonant type are better controlled.
1.4 Objectives of present work and Author’s contribution

Keeping in view the above research gaps, the work is focused on the research area of Institute for Plasma Research. Keeping in focus this area the following objectives were set forth for the present work:

a) There is a need to develop the design of impulse power supply for Plasma Applications giving higher efficiency.

b) There is a need to develop a method, which reduces the stress on resonant inductor

c) To reduce the over all size.

d) To reduce the switching losses.

IGBT based power supply module has compact design, low noise, susceptible high efficiency & low ripple which makes it useful in applications like plasma nitriding, low power defense application etc. The design is modular and switch can be smaller or larger depending on desired current rating.

In this research work, the above mentioned issues of high-frequency transformers are explored, particularly in regards to high-power converter applications. Loss calculations accommodating resonant operating waveform and Litz wire windings are explored. The optimal design procedure based on the models is developed.

Finally, IGBT based power supply has been analyzed and verified experimentally by using the soft switching technique. The theoretical analysis and novel features of the proposed converter are verified experimentally. With the new
device developed, the performance of high-power converters is improved dramatically in terms of dynamics, efficiency, size and protection due to the improved switching speed. The series load resonant topology choice for the switching converter module resulted in minimized switching loss and reduced size of the heat sink. The developed technique has several advantages over conventional scheme such as simple operation, easy analysis and control and improved efficiency.

1.5 Organization of Thesis
The work presented in this thesis is divided into six chapters.

Chapter 1: The first chapter deals with the introduction of the soft switching, basic requirements and the significance of the work. This chapter retraces the history of development of the design from the first generation to the present. It also emphasizes on the research opportunities in this area. The scope of the present work and author's contribution in the related work is discussed.

Chapter 2: This chapter discusses how to select the topology for the specific application. The asymmetrical pulse width modulated resonant converter is surveyed in the viewpoint of power density and efficiency and then converters of each type are compared to select the best one. The modeling and simulation is done with the help of Or-cad software.

Chapter 3: This Chapter is dedicated to the calculation of the transformer losses using an amorphous based magnetic core to reduce the size of the transformer. The comparison between the ferrite-based transformer and the amorphous-based transformer is given to emphasize the significant reduction of the transformer size.

Chapter 4: This chapter deals with the transformer design using the nanocrystalline material core. The unique characteristic of the pulse power operation is utilized to shrink the size of the transformer.

Chapter 5: This Chapter discusses the development of the driver card and design of PCB. A new wavelet based FFT scheme has been proposed using MATLAB. The chapter summarizes with the comparison of the different classified schemes.

Chapter 6: It includes the final experimental set up and test results. It also discusses conclusion of the work and highlights the contributions made by the author. Some suggestions for carrying out further work in this area have also been proposed.