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Multilayered Coreless Printed Circuit Board (PCB) Step-down Transformers for High Frequency Switch Mode Power Supplies (SMPS)

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Dedicated at the lotus feet of

Bhagavan Sree Sathya Sai Baba
&
Sadguru Sree Krishnendra Santani

“LOVE ALL, SERVE ALL”
ABSTRACT

The Power Supply Unit (PSU) plays a vital role in almost all electronic equipment. The continuous efforts applied to the improvement of semiconductor devices such as MOSFETS, diodes, controllers and MOSFET drivers have led to the increased switching speeds of power supplies. By increasing the switching frequency of the converter, the size of passive elements such as inductors, transformers and capacitors can be reduced. Hence, the high frequency transformer has become the backbone in isolated AC/DC and DC/DC converters. The main features of transformers are to provide isolation for safety purpose, multiple outputs such as in telecom applications, to build step down/step up converters and so on. The core based transformers, when operated at higher frequencies, do have limitations such as core losses which are proportional to the operating frequency. Even though the core materials are available in a few MHz frequency regions, because of the copper losses in the windings of the transformers those which are commercially available were limited from a few hundred kHz to 1MHz. The skin and proximity effects because of induced eddy currents act as major drawbacks while operating these transformers at higher frequencies. Therefore, it is necessary to mitigate these core losses, skin and proximity effects while operating the transformers at very high frequencies. This can be achieved by eliminating the magnetic cores of transformers and by introducing a proper winding structure.

A new multi-layered coreless printed circuit board (PCB) step down transformer for power transfer applications has been designed and this maintains the advantages offered by existing core based transformers such as, high voltage gain, high coupling coefficient, sufficient input impedance and high energy efficiency with the assistance of a resonant technique. In addition, different winding structures have been studied and analysed for higher step down ratios in order to reduce copper losses in the windings and to achieve a higher coupling coefficient. The advantage of increasing the layer for the given power transfer application in terms of the coupling coefficient, resistance and energy efficiency has been reported. The maximum energy efficiency of the designed three layered transformers was found to be within the range of 90%-97% for power transfer applications operated in a few MHz frequency regions. The designed multi-layered
coreless PCB transformers for given power applications of 8, 15 and 30W show that the volume reduction of approximately 40-90% is possible when compared to its existing core based counterparts. The estimation of EMI emissions from the designed transformers proves that the amount of radiated EMI from a three layered transformer is less than that of the two layered transformer because of the decreased radius for the same amount of inductance.

Multi-layered coreless PCB gate drive transformers were designed for signal transfer applications and have successfully driven the double ended topologies such as the half bridge, the two switch flyback converter and resonant converters with low gate drive power consumption of about half a watt. The performance characteristics of these transformers have also been evaluated using the high frequency magnetic material made up of NiZn and operated in the 2-4MHz frequency region.

These multi-layered coreless PCB power and signal transformers together with the latest semiconductor switching devices such as SiC and GaN MOSFETs and the SiC schottky diode are an excellent choice for the next generation compact SMPS.
SAMMANDRAG


En ny flerlager kärnfri kretskortstransformator för applikationer inom kraftöverföring har designats och karakteriserats. Dessa transformatorer visar fördelar såsom hög energitäthet, spänningsförstärkning, hög kopplingskoefficient och hög ingångsimpedans kan uppnås med hjälp av resonant teknik. Fördelar med att öka antal lager jämfört med en tvälagerstruktur för en given tillämpning är förbättrad kopplingskoefficient, resistans och verkningsgrad. Den bästa verkningsgrad som uppmätts i en trelagers transformatorer ligger inom intervallret 90-97% för frekvensområdet 1-10MHz. De konstruerade i flerlagertransformatormna är designade för effektnivåerna 8, 15 och 30W och jämfört med kommersiella transformatorer i samma effektnivå är volymen reducerad med ca 40-90%. Uppskattad utstrålad EMI för designade trelagerstransformatorer är mindre än för en motsvarande tvålagers transformator på grund av den mindre radien för en given inductans.
Flerlagers kärnfria kretskorttransformatorer är även designade för högfrekvent gate-drivning och har använts framgångsrikt i högfrekventa två-transistors topologier såsom halv och helbryggor med gate-effekter up till ca 0.5W.

Utvecklade transformatörerna är dessutom karakteriserade tillsammans med en högfrekvensferrit av NiZn i frekvensområdet 2-4MHz.

Utvecklade flerlagers kärnfria kretskortstransformatorer tillsammans med de senaste halvledarkomponenterna i kiselkarbid och GaN MOSFET och SiC SCHOTTKY dioder är ett utmärkt val i nästa generations kompakte spänningsomvandlare.
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Sundsvall, May 2011
Radhika Ambatipudi
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CISPR</td>
<td>Comité International Spécial des Perturbations Radioélectriques</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>DVD</td>
<td>Digital Versatile Disc</td>
</tr>
<tr>
<td>EMC</td>
<td>Electro Magnetic Compatibility</td>
</tr>
<tr>
<td>EMI</td>
<td>Electro Magnetic Interference</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FR4</td>
<td>Flame Retardant 4</td>
</tr>
<tr>
<td>IP</td>
<td>Internet Protocol</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>IPM</td>
<td>Intelligent Power Modules</td>
</tr>
<tr>
<td>MEEF</td>
<td>Maximum Energy Efficiency Frequency</td>
</tr>
<tr>
<td>MIF</td>
<td>Maximum Impedance Frequency</td>
</tr>
<tr>
<td>MHz</td>
<td>Mega Hertz</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PSU</td>
<td>Power Supply Unit</td>
</tr>
<tr>
<td>PoE</td>
<td>Power over Ethernet</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>SMPS</td>
<td>Switch Mode Power Supplies</td>
</tr>
<tr>
<td>SPICE</td>
<td>Simulation Program with Integrated Circuit Emphasis</td>
</tr>
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<td>WLAN</td>
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This thesis is mainly based on the following five publications, herein referred to by their Roman numerals:

Paper I  Coreless Printed Circuit Board (PCB) Step-down Transformers for DC-DC Converter Applications,
Radhika Ambatipudi, Hari Babu Kotte, and Kent Bertilsson,
Proceedings of World Academy of Science Engineering and Technology (WASET), Paris, France, October 2010, Issue. 70, pp. 380-389, ISSN 1307-6892

Paper II  Comparison of Two Layered and Three Layered Coreless Printed Circuit Board (PCB) Step-down Transformers,
Radhika Ambatipudi, Hari Babu Kotte, Kent Bertilsson,

Paper III  Radiated Emissions of Multilayered Coreless Printed Circuit Board Step-Down Power Transformers in Switch Mode Power Supplies,
Radhika Ambatipudi, Hari Babu Kotte and Kent Bertilsson,
Accepted for publication in 8th international Conference on Power Electronics, ICPE 2011 - ECCE Asia, May 30- June 3, 2011, Jeju, Korea

Paper IV  A ZVS Flyback DC-DC Converter Using Multilayered Coreless Printed Circuit Board (PCB) Step-down Power Transformer
Kotte Hari Babu, Radhika Ambatipudi and Kent Bertilsson
Proceedings of World Academy of Science, Engineering and Technology, Issue 70,ISSN:1307-6892,pp. 148-155,October 2010

Paper V  High Frequency Half-Bridge Converter using Multilayered Coreless Printed Circuit Board Step-Down Power Transformer
Abdul Majid, Hari Babu Kotte, Jawad Saleem, Radhika Ambatipudi, Stefan Haller and Kent Bertilsson,
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Related papers not included in Thesis:

**Paper VI**  
**Comparative Results of GAN And Si MOSFET in a ZVS Flyback Converter Using Multilayered Coreless Printed Circuit Board Step Down Transformer.**  
Hari Babu Kotte, Radhika Ambatipudi and Kent Bertilsson  

**Paper VII**  
**High Speed Cascode Flyback Converter Using Multilayered Coreless Printed Circuit Board (PCB) Step-Down Power Transformer**  
Hari Babu Kotte, Radhika Ambatipudi and Kent Bertilsson  

**Paper VIII**  
**High Frequency Full Bridge Converter using Multilayer Coreless Printed Circuit Board Stepup Power Transformer**  
Jawad Saleem, Abdul Majid, Radhika Ambatipudi, Hari Babu Kotte, and Kent Bertilsson  
1 INTRODUCTION

The most essential unit required for all the electronic devices is the power supply unit (PSU). The demand for a power supply in most modern electronic equipments is rapidly increasing. In order to match the swift growth of semiconductor technology, there has been an increase in the technical requirements of the AC/DC and DC/DC switch mode power supplies (SMPS).

The increasing demands placed on the requirements such as a small size, being lightweight, possessing a high speed voltage regulation and having a cost effective power supply can be achieved by increasing the switching frequency of converter. High frequency operation of converter leads to a reduction in costs due to the absence of bulky power transformers, a huge reduction in volume due to the reduced size of the passive components such as the transformers, inductors and capacitors [1], [2].

1.1 IMPORTANCE OF MAGNETIC ELEMENTS IN SMPS

The most irreplaceable components in SMPS are the magnetic elements i.e., the inductors and transformers. If a buck, boost, buck-boost and cuk converter is considered then the inductor is one of the essential parts. In single/double ended isolated topologies such as forward, fly-back and half-bridge, full-bridge, the resonant converters, transformer is a crucial element as it provides an electrical isolation, step down/step up conversions and multiple outputs for such as telecom applications [3].

1.1.0 Planar transformer technology

The traditional core based wire wound transformers which are heavy and bulky in size have been replaced by the planar transformers enabling the enhancement in relation to the switching frequency of converters. Due to the increased switching speeds of the converter, the number of turns of primary/secondary winding can be noticeably reduced. Therefore, the total number of turns in planar transformers is always less than that of the conventional wire wound transformers for the given power transfer application.

Generally planar transformers use flat copper foils instead of round copper wires in order to reduce the eddy current loss [1]. A side view of an assembled planar transformer with a typical EE core given in [4] is illustrated in fig. 1. In these types
of transformers, the distance between the primary and the secondary always remains constant in order to meet the isolation requirement which results in same inter-winding capacitance, in addition to the tight control of leakage inductance. The insulation material used in between the windings and the core material is of Kapton or Mylar insulation [5].

The insulation material used in between the windings and the core material is of Kapton or Mylar insulation [5].

The reasons [1], [4-5] why the planar transformers have become popular in switch mode power supplies are listed as follows.

- Low profile, Lightweight
- Low leakage inductance
- Uniform construction
- High power density
- High efficiency, reliability
- Excellent repeatability
- High frequency of operation compared to wire wound transformers

Even though the planar transformers possess the above mentioned advantages there are also some disadvantages associated with them such as high design and tooling costs for both PCBs and ferrite cores, a temperature rise of the magnetic materials, core losses, an inefficient means for the termination wires within the board etc.,

1.1.1 Problems associated with high frequency magnetics

For the miniaturization of AC/DC and DC/DC converters, one of the challenges to be faced involves the design of the magnetic elements such as the
inductors and transformers. If the commercially available core materials commonly used for 20-500 kHz frequency region were used in the MHz frequency, the hysteresis and eddy current losses, which are a function of the operating frequency, will rise rapidly. The other major obstacles in the high frequency magnetic components are the leakage inductance, skin and proximity effects, eddy currents and unbalanced magnetic flux distribution. Eddy currents and the unbalanced magnetic flux distribution became barriers in relation to high frequency transformer design. Core loss became one of the limiting factors in core type transformers while operating in the MHz region and thus it became the driving force for the evolution of coreless type transformers.

1.2 Thesis Background

As discussed previously, one of the high frequency magnetic limitations, core loss became the basis for the coreless type transformer. Therefore, in this process several coreless transformers came into existence which will be discussed in this section.

1.2.0 Twisted coil transformer

A new type of high frequency transformer without a core [6] has been introduced. This type of transformer consists of a simple twisted pair of coils as illustrated in fig. 2 and its operation is based upon the skin effect of a current carrying conductor. In these types of transformers it has been demonstrated that the coupling factor is about 0.8 at an operating frequency of 1MHz. The corresponding energy efficiency of these transformers for different load resistances as a function of frequency is shown in fig. 3.

Figure 2. Twisted Coil Transformer [6]

Figure 3. Energy efficiency of twisted Coil Transformer [6]
It can be observed from fig. 3, that the energy efficiency of these transformers is strongly dependent upon the load resistance and the operating frequency. The disadvantages of these transformers are

i. Difficulty in the mass production manufacturing process to produce identical coils

ii. Difficulty in controlling the parameters for the twisted coils

iii. Limitations on high frequency operating region

Hence, the motivation towards printed planar windings on PCB has been increased.

1.2.1 Thin film transformer

An interesting attempt, involved the printing of the copper windings on the PCB without any magnetic core [7] and this caused the focus of the research to be on the high frequency coreless printed circuit board (PCB) transformers. In this case, both the primary and secondary windings of the transformer are on a single layer and they are arranged coaxially as shown in fig. 4.

![Figure 4. Thin film Transformer [7]](image)

The principle of operation of these transformers is based on the skin effect and mutual effect between the windings at higher frequencies. In order to attain the parameters for the transformers, an integral equation analysis method has been utilized. However, the problems such as low coupling factor and high leakage inductance have not been solved.
1.2.2 Coreless PCB transformer

Due to the above mentioned disadvantages of the thin filmed transformer, an alternative approach involved printing the windings on two sides of the PCB as shown in fig.5 has been introduced in [8]. The late arrival of coreless transformers is based on the incorrect belief that these transformers would result in a low coupling factor, voltage gain, input impedance and high radiated EMI due to the absence of magnetic core.

![Coreless PCB transformer on two sides of PCB](image)

Figure 5. Coreless PCB transformer on two sides of PCB [8]

However, these misunderstandings were clarified by incorporating the resonant technique in late 90s i.e., by the connection of an external resonant capacitor across the secondary terminals of the transformer which was reported in [8], [9] and also explained as follows in a somewhat brief manner.

1.2.2.1 Operating principle and important features

1. **Voltage gain**: Even though the coreless PCB transformers do not consist of any magnetic core material which results in low magnetic coupling, based on the connection of an external resonant capacitor across the secondary windings, due to the resonance phenomenon between the leakage inductance and this resonant capacitor, there is an improvement to the voltage gain of the transformer. The voltage gain, which is the ratio of the secondary voltage to that of the primary voltage for a given 1:1 transformer with an external resonant capacitor [9], is illustrated in fig. 6.

The frequency at which the voltage gain is at its maximum is known as the no load resonant frequency and it depends on the leakage inductance and the equivalent capacitance of the circuit.
Figure 6. Voltage gain of coreless PCB transformer of unity turns ratio [9]

From fig. 6 it can be observed that the voltage gain of the 1:1 transformer is greater than 1 from 6.5-11MHz which shows that the voltage gain can be improved with the assistance of an external resonant capacitor. The low voltage gain is obtained for this transformer at below and after this frequency region. Hence the operating region of this transformer lies in this region where the gain of the transformer is greater than 1.

This also proves that the disadvantage of having a higher leakage inductance as compared to the core based transformers became an apparent advantage in the coreless PCB transformer.

2. **Low input impedance:** Because of the reduced number of turns of the transformer, there is a misplaced belief in relation to the coreless PCB transformers that they act as short-circuit windings. However, because of the resonance phenomenon, these transformers consist of a sufficient amount of input impedance. The input impedance of the same transformer for which the voltage gain is discussed when using an external resonant capacitor is illustrated in fig. 7. The input impedance of the transformer is sufficiently high in the frequency region of 7-8.5MHz which shows that these types of transformers do not behave as short circuit windings. The frequency at which the input impedance of a transformer is at a maximum is known as the maximum impedance frequency and from figures 6 and 7, it can be observed that it is less than that of the no load resonant frequency.
3. **Energy efficiency**: Due to the low coupling factor, low voltage gain and skin and the proximity effects of the coreless PCB transformer, it is presumed that the energy efficiency of these transformers is very low compared to those of the core based transformers. However, because of the high voltage gain and input impedance obtained by the resonant technique it is possible to achieve higher energy efficiencies for these transformers. For example the energy efficiency of the 1:1 transformer at different load resistances for a power transfer application is illustrated in fig. 8.

When the load power is very low i.e., for signal transfer applications, the maximum energy efficiency frequency approaches its maximum
impedance frequency. For power transfer applications, the maximum energy efficiency frequency is below the maximum impedance frequency. The desired operating frequency of the transformer can be obtained by varying the resonant capacitor across the secondary terminals of the transformer.

4. **Radiated EMI:** Since, the transformers are not covered by the magnetic cores, the magnetic field, which is not confined, results in radiated emissions from the coreless PCB transformers. According to antenna theory, a good loop radiator must possess a radius which is closer to that of the wavelength corresponding to the operating frequency. However, for these transformers, the radius is of a few mm compared to that of the wavelength corresponding to the operating frequency which is of the order of several meters. Hence the radiated emissions from these transformers by considering the fundamental component have been proved to be negligible.

Apart from clarifying the above mentioned misconceptions, these transformers exhibit the following advantages over the core based transformers.

1.2.2.2 **Advantages of Coreless PCB transformers**

- **Operating Frequency:** There is no upper frequency limitation imposed on these types of transformers unlike that for the case involving core based transformers. However, a lower operating frequency limit does exist because of the low magnetizing reactance/impedance of the transformer.

- **Magnetic Saturation:** Since, these type of transformers do not contain any core material, no magnetic saturation and core losses exist

- **High Power Density:** As there is no core, there is a drastic reduction in the vertical dimension of the transformer which results in a high power density

- **Easy to manufacture low profile transformers with a high power density**

- **Capable of meeting stringent height and space requirements**
- Elimination of manual winding and Bobbin
- Cost effective solution

Due to the above mentioned advantages, the research has been focused on the coreless PCB transformers required for switch mode power supplies.

1.3 Motivation

In this modern era, in which it is possible to find miniaturized electronic circuits, planar technology plays a prominent role because of the small size and reduced weight with a high power density [4], [10]. In addition, these transformers possess very low leakage inductance and low losses. Although, planar transformers exhibit several aforementioned advantages, it cannot be operated at higher operating frequencies because of the increased core losses, temperature effects and, additionally, the winding losses.

For this purpose, a great deal of research has focused on designing the magnetics for high frequency applications without a core, as has been previously discussed. Recently, the coreless PCB transformers [6], [8-9] have been developed; however, it was the case that these transformers were discussed in relation to signal and power transfer applications with a turn’s ratio of 1:1. However, as many SMPS demand the step-down/step-up conversions, the research was focussed on investigating the possibilities of using coreless PCB transformers for step down conversion applications. The purpose of this thesis is to discover whether or not the multi-layered coreless PCB step down transformers for both signal and power transfer applications will be a potent alternative to the existing core based transformers in order to meet the stringent height applications. The question is whether these transformers offer the advantages in terms of energy efficiency, coupling coefficient as compared to their counterparts’ core based transformers by providing the step-down/step-up voltage conversions. If this is the case, it is also necessary to determine whether the advantage is significantly better and thus making it sufficiently worthwhile to design the stringent height power supplies by increasing the operating frequency of these transformers. Therefore, the main focus of the thesis was on the design and analysis of the multi-layered coreless PCB step down power transformers operating at higher frequencies i.e., in the MHz frequency region suitable for AC/DC and DC/DC converters.
1.4 Method

In general, the method for research work is initiated, in the first place, by background discussions, investigating the associated theory, producing simulations and then a design and finally by means of testing and measurements. The method used for this work covers all the above mentioned procedures. The initial electrical parameters such as self, leakage and mutual inductances required for the design of coreless PCB transformers in relation to a given power application were estimated by solving the analytical equations proposed by Hurley and Duffy using a MATLAB tool. After the estimation of the parameters, by using Siemens/Simplis software the performance characteristics were determined with the assistance of a high frequency model. The achievement of consistent results from the simulation of the designed transformers then enabled the transformers to be designed using CADint PCB design software. The parameters for the designed transformers were measured by using the high frequency RLC meter and the measured performance characteristics were matched to that of the modelled performance characteristics obtained either by the high frequency model using the simulation software or by MATLAB. The actual parameters of the transformers were obtained by this means. After obtaining the knowledge in relation to the exact parameters of the transformers, the power tests were carried out in order to determine the energy efficiency at their optimal operating frequency region, with the assistance of a signal generator, radio frequency power amplifier and Tektronix oscilloscope. These waveforms were fetched by using the LAB view software and the energy efficiency and the corresponding measured performance characteristics were displayed on the PC. These measurements were also carried out for different excitations such as sinusoidal and square waves in the view of different converter topologies both for the determination of the energy efficiency and for the estimation of the radiated EMI.

1.5 Thesis Outline

The main contents of the thesis were organized as follows. Initially, some basic background and the motivation behind the requirement for the high frequency PCB transformers for power transfer applications have been provided and this included the method to be used. The second chapter provides a comparison of the designed two layered and three layered step down transformers for a given power transfer application together with a discussion in relation to the necessary theory.
In this chapter, the analytical equations for obtaining the desired electrical parameters of the transformer followed by the high frequency model of coreless PCB transformers are also presented. The performance characteristics required for the optimal operation of the transformers is also presented together with some experimental results relating to the two layered and three layered transformers. In the third chapter the comparison is made in relation to the four different three layered transformers of the same series in terms of the performance characteristics and the energy efficiencies with different loads and resonant capacitors. In this chapter the importance of the resonant capacitor, which is a determining factor for the optimal operating conditions of transformers, is also described. In the next chapter, the radiated emissions of the transformers are presented which have been previously estimated from a number of simulations and experiments for different excitations. In the fifth chapter, the designed multi-layered coreless PCB transformers used for the signal transfer applications are presented. Finally in chapter six, the contents of the thesis are summarized together with conclusions and some future work related to that presented.

In the end, some papers related to the work proposed have been included in order to provide a ready reference.
2 CORELESS PRINTED CIRCUIT BOARD (PCB) STEP DOWN TRANSFORMERS

As discussed in the introduction, recent investigations [8, 9] have shown that coreless PCB transformers can be used as an isolation transformer for both signal and power transfer applications. However, various AC/DC and DC/DC converter applications such as Power over Ethernet (PoE), WLAN Access-points, IP phones, a wide variety of telecom applications and laptop adapter, set top box, DVD players demand a high frequency transformer for different step-down turn’s ratio to obtain compact switch mode power supplies. Due to this reason for a given power transfer application, two different transformers with the same inductance, one in two layers and the other in three layers have been designed and evaluated. In this case, the comparative results for both these transformers in terms of their resistances, leakage/self inductances, coefficient of coupling by measuring their performance characteristics such as transfer function $H(f)$, input impedance $Z_{in}$ under the same conditions have been discussed.

2.1 TWO LAYERED AND THREE LAYERED 2:1 STEP-DOWN TRANSFORMER

A coreless PCB transformer consists of two parts, namely the dielectric material of FR4 and copper tracks on PCB Laminate. FR4 material is the most commonly used material as an electrical insulator whose breakdown strength is 50kV/mm [11]. The primary and secondary windings of the transformer are etched on both sides of the PCB laminate. A four layered PCB of thickness (z) of approximately 1.48 mm is considered on which a two layered and three layered transformer have been designed. The dimensions of these transformers are illustrated in fig. 9.

![Figure 9. Dimensions of two layered (a)-left and three layered (b)-right 2:1 step down transformer](image-url)
In the two layered transformer, the primary and secondary windings are in the second and third layers of the four layered PCB with primary/secondary turns of 24/12 respectively.

In the three layered transformer, the two primaries are on the second and fourth layer of the PCB and these are connected in series with the assistance of the first layer. The secondary winding of the transformer is sandwiched in between the two primaries as shown in fig. 10.

![Figure 10. Structure of Three layered transformer [12]](image)

### 2.2 Geometrical parameters of Transformers

Based upon the given power transfer application, the amount of primary/secondary inductance of transformer is estimated. Following on from this and in order to obtain the optimal design of coreless PCB transformer, consideration had to be given to two important parameters i.e., coefficient of coupling (K) and the resistances of the step-down transformer. The electrical parameters of the coreless PCB step-down transformers depend on the following geometrical parameters [13].

- Number of turns of primary \(N_p\)/secondary \(N_s\)
- Width of the conductor \(W\)
- Height of the conductor \(H\)
- Lamination Thickness \(Z\)
- Track separation \(S\)
- Inner/outermost radius \(R_i/R_o\)
- Shape of the winding (Circular Spiral)
In this case, the spiral winding structure is considered because the higher value of the inductance can be obtained when compared to other structures such as hoop type, meander and closed type coils for the given geometrical parameters [14]. From this it can be also observed that, for a given amount of inductance, the spiral structure for the transformer gives the lower value of resistance compared to the other structures. The geometrical parameters of the above two transformers are given in Table 1.

Table 1. Geometrical parameters of two layered and three layered 2:1 transformer

<table>
<thead>
<tr>
<th>S.No</th>
<th>Geometrical parameters of two transformers</th>
<th>Parameters</th>
<th>Two layered</th>
<th>Three layered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>N_p:N_s</td>
<td>24:12</td>
<td>12:12:12</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>W_p/W_ac[mm]</td>
<td>0.3/0.64</td>
<td>0.6/0.6</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>H[µm]</td>
<td>70</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Z[mm]</td>
<td>0.4</td>
<td>0.4/0.4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>S_p/S_ac[mm]</td>
<td>0.37/0.74</td>
<td>0.4/0.4</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>R_o[mm]</td>
<td>18.5</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Shape</td>
<td>Spiral</td>
<td>Spiral</td>
<td></td>
</tr>
</tbody>
</table>

2.3 **ELECTRICAL PARAMETERS OF TRANSFORMERS**

The electrical parameters such as the inductance and capacitance of these coreless PCB transformers can be obtained from the above mentioned geometrical parameters. The inductive parameters such as self, leakage and mutual inductances of transformer can be obtained by using the following two methods.

I. Analytical equations given by Hurley and Duffy method [15] can be implemented by using MATLAB programs.

II. Finite Element Analysis (FEA) method.
Since, FEA is a time consuming method particularly for multi-layered coreless PCB transformers, the above parameters were estimated by using method I. The required analytical equations to obtain the electrical parameters of transformers are discussed in this section.

For estimating the self and mutual inductances of transformer, the spiral windings are approximated to the concentric circles as shown in fig. 11 which are connected in series infinitesimally [13],[15].

![Approximated Circular windings as series concentric circles](image)

Figure 11. Approximated Circular windings as series concentric circles [13]

A transformer consisting of ‘\(N_p/N_s\)’ number of turns on the primary/secondary windings, possesses total self inductance [13] which is given as a summation of the mutual inductances between the two concentric circular coils \(M_{ij}\) where \(i, j\) runs from 1 to \(N\). Therefore, the self inductance of the primary and secondary can be given as follows:

\[
L_p = \sum_{j=1}^{N_p} \sum_{i=1}^{N_p} M_{ij}
\]  
\[
L_s = \sum_{j=1}^{N_s} \sum_{i=1}^{N_s} M_{ij}
\]

The mutual inductance of the transformer between the primary and secondary windings is given as the summation of the mutual coupling inductance between them and is given by equation (3)
The mutual inductance between two circular tracks is given as

\[ M_{ij} = \sum_{j=1}^{N_p} \sum_{i=1}^{N_s} M_{ij} \quad (3) \]

\[ M_{ij} = \frac{\mu_0 \pi}{H_1 \ln \left( \frac{R_{o2}}{R_2} \right) H_2 \ln \left( \frac{R_{o1}}{R_1} \right)} \int_{0}^{\infty} S(kR_{o2}, kR_2) S(kR_{o1}, kR_1) Q(kH_1, kH_2) e^{-k|\rho|} dk \quad (4) \]

where

\[ S(kR_{o2}, kR_2) = \frac{J_0(kR_{o2}) - J_0(kR_2)}{k} \quad (5) \]

\[ S(kR_{o1}, kR_1) = \frac{J_0(kR_{o1}) - J_0(kR_1)}{k} \quad (6) \]

\[ Q(kH_1, kH_2) = \frac{2}{k^2} (\cosh k \frac{H_1 + H_2}{2} - \cosh k \frac{H_1 - H_2}{2}), \text{where} 'Z' > \frac{H_1 + H_2}{2} \quad (7) \]

\[ Q(kH_1, kH_2) = \frac{2}{k^2} (H - \frac{e^{-kH}}{k} - 1), \text{where} 'Z' = 0, H_1 - H_2 = H \quad (8) \]

Here,

\( \mu_0 \) Permeability of vacuum

\( J_0(.) \) First kind Bessel function of order zero

\( R_{oi}/R_{o2} \) Inner radius of i\textsuperscript{th}/j\textsuperscript{th} circular track

\( R_{oi}/R_{o2} \) Outermost radius of i\textsuperscript{th}/j\textsuperscript{th} circular track

\( H_1/H_2 \) Height of the i\textsuperscript{th}/j\textsuperscript{th} circular track

\( Z \) Lamination thickness

Therefore, the primary/secondary leakage inductances of a transformer are obtained by subtracting the mutual inductance ‘\( M_{ij} \)’ from their corresponding self inductances and turn’s ratio ‘\( n \)’.

\[ L_{ip} = L_p - M_{ps} \cdot n \quad (9) \]

\[ L_{is} = L_s - \frac{M_{ps}}{n} \quad (10) \]

\[ n = \sqrt{\frac{L_p}{L_s}} \quad (11) \]
The dc resistances of the primary/secondary windings of the transformer are also calculated from the geometry and resistivity [16] as follows.

\[ R = \frac{\rho \cdot l}{A} \]  

(12)

Where
\( \rho \) Resistivity of copper conductor, 1.68x10\(^{-8} \) Ω-m
\( l \) Length of the conductor
\( A \) Area of copper tracks

Initially, the capacitance of the coreless PCB transformers are calculated by assuming two planar windings as two parallel conducting plates [17] and is given as follows.

\[ C_{ps} = \frac{\varepsilon \cdot A_p}{Z} \]  

(13)

\[ \varepsilon = \varepsilon_0 \cdot \varepsilon_r \]  

(14)

Where
\( \varepsilon_0 \) Permittivity of air, 8.854x10\(^{-12} \) F/m
\( \varepsilon_r \) Relative permittivity of dielectric material, 4.4
\( Z \) Distance between two parallel plates
\( A_p \) Area of conducting plates

The above equation (13) is valid for the plates which are densely packed and also since it does not take fringing effects into account, the following equation from [17] can be utilized for determining the capacitance between the parallel plates.

\[ C_{ps} = \frac{\varepsilon (w + \frac{1}{2}Z) \cdot l}{Z} \]  

(15)

All the above mentioned electrical parameters for both transformers are calculated by using MATLAB.
2.4 High Frequency Model of Coreless PCB Step Down Transformer

The high frequency model of multilayered coreless PCB step down power transformer operating in MHz frequency region is shown in fig. 12. In this case, the intra winding/self capacitance of both the primary ($C_{pp}$)/secondary ($C_{ss}$) windings are very small and hence can be ignored.

![Diagram](image)

**Figure 12.** High Frequency model of Coreless PCB step down transformer

where,

- $R_p/R_s$: Primary/Secondary resistance of transformer
- $L_{lp}/L_{ls}$: Primary/Secondary leakage inductance of transformer
- $L_{mp}/L_{ms}$: Primary/Secondary mutual inductance of transformer
- $C_{ps}$: Interwinding capacitance of transformer
- $R_L$: Load resistance

The primary/secondary mutual inductances of transformer are obtained as follows:

$$L_{mp} = L_p - L_{lp}$$  \(16\)

$$L_{ms} = L_s - L_{ls}$$  \(17\)

Therefore, the mutual inductance of transformer is obtained by using equations (16) & (17) as follows.

$$L_m = \sqrt{L_{mp} \cdot L_{ms}}$$  \(18\)
2.4.1 Coupling coefficient, \((K)\)

The coefficient of coupling ‘\(K\)’ for the transformers can be obtained by using the following equation

\[
K = \frac{L_{m}}{\sqrt{L_{p} \cdot L_{s}}} \tag{19}
\]

The initial electrical parameters of these designed coreless PCB transformers were measured at 1MHz using an HP4284A high precision RLC meter. The primary self inductance \(L_{p}\) and resistance \(R_{eq}\) are obtained by open circuiting the opposite winding i.e., the secondary winding of the transformer and vice versa. Also, the preliminary primary/secondary leakage inductances of the transformer, which are less than 1μH, were obtained by using the four wire measuring method [18]. By using this method the leakage inductances are obtained as follows.

\[
L_{lk} = \left( \frac{50}{2\pi f} \right) \left( \frac{V_{dut}}{V_{50\Omega}} \right) \tag{20}
\]

where,
- \(L_{lk}\) Leakage inductance
- \(f\) Excitation frequency
- \(V_{dut}\) Voltage across device under test
- \(V_{50\Omega}\) Voltage across 50Ω resistor

Since these parameters are not the exact parameters of the coreless PCB transformers, the measured parameters were passed into the above high frequency model and fine tuned such that the measured performance characteristics such as \(H(f)\), and \(Z_{in}\) are in good agreement with that obtained for the modelled ones. Hence the actual parameters of the transformers were obtained by using the high frequency model and the measured parameters. The comparison of the actual parameters and the analytical parameters obtained by using MATLAB are shown in Table 2. The percentage deviations of the analytical values from the modelled ones in terms of self inductances \(L_{p}/L_{s}\) of the two layered transformer were found to be 1.65/6.69% respectively. In the case of the three layered transformer, this was found to be 2.3/3.1% respectively for \(L_{p}/L_{s}\). In both cases, the deviations in the interwinding capacitance ‘\(C_{ps}\)’ were found to be 17.7/8.4% respectively for
two/three layered transformers. From table 2, it can be verified that the parameters obtained by solving the analytical equations using MATLAB are to a certain extent in good agreement, in terms of the self inductances of the transformers with that of the modelled parameters by passing the measured ones into the high frequency model shown in fig. 12.

Table 2. Modelled and Analytical electrical parameters of two layered and three layered coreless PCB transformers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Two layered (Analytical)</th>
<th>Two layered (Modeled)</th>
<th>Three layered (Analytical)</th>
<th>Three layered (Modeled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_p$ [$\mu$H]</td>
<td>9.49</td>
<td>9.65</td>
<td>8.44</td>
<td>8.25</td>
</tr>
<tr>
<td>$L_s$ [$\mu$H]</td>
<td>2.71</td>
<td>2.54</td>
<td>2.27</td>
<td>2.2</td>
</tr>
<tr>
<td>$L_{lk_p}$ [$\mu$H]</td>
<td>0.70</td>
<td>0.9</td>
<td>0.371</td>
<td>0.4</td>
</tr>
<tr>
<td>$L_{lk_s}$ [$\mu$H]</td>
<td>0.19</td>
<td>0.28</td>
<td>0.1</td>
<td>0.18</td>
</tr>
<tr>
<td>$L_{mp}$ [$\mu$H]</td>
<td>8.80</td>
<td>8.75</td>
<td>8.07</td>
<td>7.85</td>
</tr>
<tr>
<td>$R_p$ [$\Omega$]</td>
<td>2.52</td>
<td>2.26</td>
<td>2.17</td>
<td>2.02</td>
</tr>
<tr>
<td>$R_s$ [$\Omega$]</td>
<td>4.70</td>
<td>4.53</td>
<td>4.18</td>
<td>3.98</td>
</tr>
<tr>
<td>$C_{ps}$ [$\mu$F]</td>
<td>1.68</td>
<td>1.9</td>
<td>0.75</td>
<td>0.84</td>
</tr>
<tr>
<td>$K$</td>
<td>0.40</td>
<td>0.47</td>
<td>0.35</td>
<td>0.41</td>
</tr>
</tbody>
</table>

2.4.2 AC Resistance

The winding resistance of the transformers increases as the operating frequency of the currents is increased because of skin and proximity effects. Therefore, the requirement is to determine the ac resistance of the primary and secondary windings of the designed transformers. By approximating the model to a circular spiral winding [19] the AC
resistances of primary/secondary windings for the designed transformers were calculated by using the following expression:

\[ R_{ac} = \frac{R_{dc} \cdot H}{\delta \left( 1 - \exp\left(\frac{-H}{\delta}\right)\right)} \]  

(21)

where

- \( R_{dc} \) DC resistance of winding
- \( H \) Height of conductor
- \( \delta \) Skin depth

The equation for skin depth or depth of penetration of conductor by magnetic flux [20] is as follows:

\[ \delta = \frac{1}{\sqrt{2\pi \mu \sigma f}} \]  

(22)

- \( f \) Operating frequency
- \( \mu \) Permeability of medium
- \( \sigma \) Conductivity

The DC resistance of primary/secondary winding of both transformers is given in table 2 and their corresponding calculated AC resistances were shown in fig. 13.

![Figure 13. AC resistance of Coreless PCB step down transformer](image-url)
2.5 PERFORMANCE CHARACTERISTICS OF CORELESS PCB TRANSFORMERS

In order to determine the operating frequency of the coreless PCB transformers, the performance characteristics such as the transfer function \( H(f) \), input impedance \( Z_{\text{in}} \) and phase angle \( \phi \) were measured under a light load condition. The performance characteristics, which are useful for determination of the operating conditions, can be obtained by using the high frequency equivalent circuit referred to as the primary side \([21]\) of the coreless PCB step down transformers, are depicted in fig. 14.

![High frequency equivalent circuit of coreless PCB transformer referred to primary](image)

**2.5.1 Transfer Function \( H(f) \) and Input Impedance \( Z_{\text{in}} \)**

Transfer function \( H(f) \) is defined as ratio of secondary voltage \( (V_s) \) to primary voltage \( (V_p) \) and is given as follows.

\[
H(f) = \frac{V_s}{V_p} = \frac{1}{X_1} + j(2\pi f)C_{ps}Y_1
\]

Whereas the input impedance \( (Z_{\text{in}}) \) of coreless PCB transformer can be given as

\[
Z_{\text{in}} = \frac{1}{sC_{ps}(1-n\cdot\frac{V_s}{V_p}) + (1-A)\frac{1}{X_1} + sC_{pp}}
\]

where ‘\( n \)’ is the turn’s ratio of the transformer

\[
R'_{s} = n^2 R_s
\]
\[ L_{lks}' = n^2 L_{lks} \]  
(26)

\[ C_{pp}' = C_{pp} + \frac{n-1}{n} C_{ps} \]  
(27)

\[ C_r' = \frac{1}{n^2} C_r + \frac{1-n}{n^2} C_{ps} \]  
(28)

\[ C_{ps}' = \frac{1}{n} C_{ps} \]  
(29)

\[ X_1 = R_p + sL_{lks}' \]  
(30)

\[ X_2 = R_s' + sL_{lks}' \]  
(31)

\[ Y_1 = X_2 \left[ \frac{1}{X_1} + \frac{1}{sL_{mp}} \right] + 1 \]  
(32)

\[ Y_2 = \frac{1}{X_2} + sC_{ps'} + sC_r' + \frac{1}{n^2 R_L} \]  
(33)

\[ Y = \frac{1}{X_2} + Y_1 Y_2 \]  
(34)

\[ A = \frac{sC_{ps'} + \frac{X_2}{X_1} Y_2}{Y} \]  
(35)

2.5.2 Maximum gain frequency, \( f_r \)

The frequency at which the transfer function is a maximum is known as the maximum gain frequency, \( f_r \).

\[ f_r = \frac{1}{2\pi \sqrt{L_{eq} \cdot C_{eq}}} \]  
(36)

\[ L_{eq} = L_{lks}' + L_{mp} \parallel L_{bp} \]  
(37)

\[ C_{eq} = C_r' + C_{ps'} \]  
(38)
2.5.3 Maximum Impedance frequency (MIF)

The frequency at which the input impedance of transformer is at a maximum is known as the maximum impedance frequency. The maximum impedance frequency of the transformer is always less than the maximum gain frequency of the transformer.

2.5.4 Maximum Energy Efficiency Frequency (MEEF)

The frequency at which the energy efficiency of transformer is at a maximum is known as the maximum energy efficiency frequency. The maximum energy efficiency frequency of transformer is always less than the maximum gain frequency of the transformer. The relation between the maximum gain frequency, maximum impedance frequency and the maximum energy efficiency frequency can be derived as follows.

\[ MEEF \leq MIF < f_r \]  \hspace{1cm} (39)

For signal and low power applications, the maximum energy efficiency frequency (MEEF) of the transformer is equal to the maximum impedance frequency (MIF). The measured performance characteristics \( H(f) \) and \( Z_{in} \) of the two layered and three layered transformers with a load resistance of ‘\( R_L \)’ of 500Ω and resonant capacitor ‘\( C_r \)’ of 1.2nF is illustrated in fig. 15 and fig. 16 respectively.

![Figure 15](image1.png)

Figure 15. Transfer function \( H(f) \) of the two layered and the three layered Coreless PCB step down power transformers with \( R_L=500\Omega \) and \( C=1.2nF \)

![Figure 16](image2.png)

Figure 16. Input impedance \( Z_{in} \) of the two layered and the three layered Coreless PCB step down power transformers with \( R_L=500\Omega \) and \( C=1.2nF \)
The maximum gain frequencies of two/three layered transformers are 7.5/9MHz respectively and can be observed from fig. 15. Here, the maximum gain frequency of the three layered transformer is higher compared to that for the two layered transformer because of the reduced leakage inductance. As has been previously mentioned the maximum impedance frequency of both these transformers is lower as compared to their corresponding maximum gain frequencies and from fig. 16, it can be observed that they are 2.9/3.4 MHz.

2.6 EXPERIMENTAL SET-UP AND POWER TESTS OF DESIGNED CORELESS PCB STEP-DOWN TRANSFORMERS

The experimental set-up for characterizing the transformers for power transfer applications is illustrated as a block diagram in fig. 17.

![Block diagram of experimental set-up for coreless PCB transformers](image)

Figure 17. Block diagram of experimental set-up for coreless PCB transformers

In order to evaluate the performance of these two layered and three layered transformers in terms of their energy efficiencies, power tests were carried out
using an EMPOWER BBM0A3FKO radio frequency power amplifier. This power amplifier is capable of delivering 100Watts with an adjustable frequency range of 0.01MHz-230MHz. The input given to the power amplifier can be adjusted by varying the amplitude, frequency and type of the excitation such as sinusoidal, square wave etc., from the signal generator, HP 33120A. The output of the power amplifier is fed to the designed transformers and the energy efficiency of the transformers are determined by fetching the $V_{pri}/V_{sec}$ and $I_{pri}/I_{sec}$ of the transformers from the Tektronix TPS2024 oscilloscope, consisting of four isolated channels with 200MHz bandwidth and 2Gs/sec sampling rate. The load test of the transformers was carried out as illustrated in fig. 18.

![Power Amplifier Diagram](image)

**Figure 18. Load test of coreless PCB transformers**

Primary ($I_{pri}$) and secondary current ($I_{sec}$) measurements were made by utilizing Tektronix AC current probes CT2 [22] of 1.2 kHz-200 MHz bandwidth with a propagation delay of 6.1nS. The voltage measurements $V_{pri}/V_{sec}$ were made by Tektronix P2220 passive probes [23] whose bandwidth is in the range of DC-200MHz with a typical probe capacitance of 17pF in 10X mode of attenuation. The retrieved primary/secondary voltages and currents from the oscilloscope were processed by using the LABVIEW 8.5 professional and the energy efficiency of transformers can thus be obtained.

The measured average input/output powers per cycle of the designed transformers are obtained by solving the following equations

$$P_{in} = \frac{1}{T} \int_{0}^{T} v_{pri}(t) \cdot i_{pri}(t) dt$$  \hspace{1cm} (40)
\[ P_{\text{out}} = \frac{1}{T} \int_{0}^{T} v_{\text{sec}}(t) \cdot i_{\text{sec}}(t) \, dt \]  

(41)

where

- \( V_{\text{pri}}/V_{\text{sec}} \) Instantaneous primary/secondary voltage of transformer
- \( I_{\text{pri}}/I_{\text{sec}} \) Instantaneous primary/secondary current through transformer
- \( T \) Period of a cycle, \( T=1/f \) (frequency)

Therefore, the energy efficiency of transformer can be obtained by using equations (40) and (41) as follows

\[ \eta_{\text{meas}} = \frac{P_{\text{out}}}{P_{\text{in}}} \cdot 100\% \]  

(42)

The measured energy efficiency of two layered and three layered transformers with a load resistance \( R_L \) of 30\,Ω and 50\,Ω is illustrated in fig. 19. Here, a resonant capacitor of 1.2n\,F was placed across the secondary winding of the transformers.

![Figure 19. Measured energy efficiency of the two/three layered transformers for different loads](image)

It can be observed from fig. 19 that the energy efficiency of the three layered transformer is higher for both loads as compared to the two layered transformer. This can be explained by two major factors, namely the coupling coefficient and the AC resistances. From fig. 13, it can be observed that the AC resistance of the
two layered transformer is higher as compared to that for the three layered transformer. Since no core exists in these coreless PCB transformers, the majority of the losses are due to copper losses which are dependent on the AC resistance of the transformers. Also from table 2, it can be observed that the coupling coefficient of the three layered transformer is higher because of the sandwiching of the secondary in between the two primaries as compared to the two layered transformer and it is also the case that the magnetic losses in the two layered transformer are higher as compared to those for the three layered transformer.

The designed coreless transformers are tested at their maximum energy efficiency frequencies (MIF) up to a power level of about 25Watts and the corresponding results are depicted in fig. 20.

![Figure 20. Measured energy efficiency of transformers with load resistance $R_L$ of 30Ω](image)

It can be also observed from fig. 20, that throughout the load power range, the three layered transformer is better compared to the two layered transformer.
3 MULTI LAYERED CORELESS PCB STEP-DOWN TRANSFORMERS

From the analysis of chapter 2, it has been found that for a given power transfer application, the three layered 2:1 transformer is better when a comparison is made with the two layered 2:1 transformer because of the increased coupling coefficient \( K \) and the reduced copper losses. Since the coefficient of coupling \( K \) and the AC resistance both have an impact on the performance of the coreless PCB transformer, the requirement is to have an optimized coupling coefficient and resistance. In order to design a coreless PCB transformer for the given power transfer application, the coupling coefficient of the transformer can be improved by increasing the area of the transformer with or without increasing number of turns [13]. However, if the area of the transformer is increased by increasing the number of turns, the rate of increase of the self inductance of the transformers is higher in comparison to its leakage inductance. Therefore, a series consisting of four different three layered 2:1 step-down transformers shown in fig. 21 were designed and compared in terms of their self, leakage and mutual inductances, AC resistances, coupling coefficient, and energy efficiencies.

![Figure 21](image.png)

Figure 21. Dimensions of same series coreless PCB transformers

These transformers were designed by having the same conductor width \( W \) of 0.6mm, track separation \( S \) of 0.4mm and conductor height \( H \) of 70µm for isolated DC/DC converter applications. The corresponding number of turns in each layer were tabulated and shown in table 3.

3.1 EFFECT OF RESONANT CAPACITORS ON TRANSFER FUNCTION OF TRANSFORMERS TR1–TR4

As mentioned in chapter 2, the initial parameters of these transformers were measured with the assistance of an RLC meter at 1MHz. These measured
parameters were passed into the high frequency equivalent circuit as shown in fig 14 and then fine tuned in order to match the measured and modelled performance characteristics of the transformers such as $H(f)$, $Z_{in}$ and phase angle $\phi$. The magnitude of the transfer functions $H(f)$ referred to the primary side for two different resonant capacitors of 1.5nF and 2.2nF at a load resistance of 470Ω for the designed transformers are illustrated in fig. 22 and fig. 23 respectively.

Table 3. Number of turns of designed transformers

<table>
<thead>
<tr>
<th></th>
<th>TR₁</th>
<th>TR₂</th>
<th>TR₃</th>
<th>TR₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary(P₁)</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Primary(P₂)</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Secondary(S)</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 22. Modelled (solid line) and measured (markers) transfer function $H(f)$ of the transformers with $C=1.5nF$ and $R_L=470Ω$.

From these figures it can be observed that the measured transfer functions of the transformers are in good agreement with those calculated by using the model equations discussed in chapter 2. It can also be observed that both the magnitude of the peak and resonant frequencies decrease as the number of turns increases.
According to equation (36) the resonant frequency of the transformers decreases for larger resonant capacitors across the secondary winding of the transformers.

For example in fig. 22 it can be observed that the resonant frequency of the transformer TR1 with $C=1.5\text{nF}$ is close to 9.7MHz whereas in fig. 23 it is 8.0MHz when $C=2.2\text{nF}$.

### 3.2 Effect of Resonant Capacitors on Input Impedance, Phase Angle of Transformers TR1-TR4

As discussed in the previous chapter and, in a similar manner to the other performance characteristics, such as the measured and modelled input impedance ($Z_{in}$) and the phase angle ($\phi$) of the transformers (TR1-TR4), with an external resonant capacitor of 1.5nF connected across the secondary windings and $R_L$ of 470Ω, these are plotted in fig. 24 and fig. 25 respectively. From fig. 22 the maximum gain frequency of transformer TR1 is approximately 9.7MHz as discussed in the previous section. For the same transformer TR1, from fig. 24 it can be observed that the input impedance peaks at 4.8MHz approximately which is known as the MIF. From figs. 22 and 24, the maximum impedance frequency of the transformer is less than the no load resonant frequency which agrees with expression (39). From fig. 25 it can be observed that before the MIF, the transformer is highly inductive in nature and at the MIF, the phase angle of the transformer TR1
is very small.

The operating frequency region is that in which the transformer possesses sufficient input impedance and also where it is highly inductive in nature. Hence, for power transfer applications with these types of transformers, the maximum impedance frequency determines the operating frequency region of the transformer. The input impedance of the transformer $T_{R1}$ at 3MHz is sufficiently high and has a magnitude of approximately 85Ω and thus the corresponding

**Figure 24.** Modelled (solid line) and measured (markers) input impedance $Z_{in}$ of the transformers with $C=1.5\text{nF}$ and $R_L=470\ \Omega$

**Figure 25.** Modelled (solid line) and measured (markers) phase angles of transformers with $C=1.5\text{nF}$ and $R_L=470\ \Omega$
operating frequency region of this transformer lies approximately in the frequency range of 3-4.8MHz. After this frequency region, the input impedance of the transformer decreases as is shown in fig. 24 and additionally the transformer is not inductive in nature as illustrated in fig. 25, hence it is not possible to operate the transformer after the MIF. The same phenomenon i.e., the maximum impedance frequency, operating frequency region is observed for the remaining transformers TR1-TR4. The input impedance of the transformers TR1-TR4 is observed to be increasing in nature as the number of turns of the transformer because of the increased inductance of the transformer as shown in fig. 24.

The effect of the resonant capacitor on the input impedance and phase angle is also observed by connecting a 2.2nF resonant capacitor across the secondary winding of the transformers TR1-TR4 and the results are plotted in fig. 26 and fig. 27 respectively. In this case, from fig. 23 and fig. 26, it can be observed that the maximum gain frequency and maximum impedance frequency of transformer TR1 are 8MHz and 4MHz respectively.

It can also be observed that these frequencies were shifted towards the lower operating frequencies when the resonant capacitor value is increased. Here, the input impedance of the transformer is sufficiently high and has a magnitude of 85Ω at a frequency of 2.75MHz and thus, the operating frequency region of the transformer TR1 is observed to be in the frequency range of 2.75MHz-4MHz.

However, as has been previously discussed, the operating frequency region of transformer TR1 with the resonant capacitor $C_r=1.5nF$ is 3MHz-4.8MHz. From this it was concluded that the wide operating frequency region is obtained with the assistance of lower resonant capacitors.

The same criteria are observed for the remaining transformers TR2-TR4. From fig. 24 and fig. 26, and it can be observed that the magnitude of the input impedance becomes reduced when the resonant capacitor value is increased which also agrees with equation (24).
3.3 AC RESISTANCE AND COUPLING COEFFICIENT OF DESIGNED TRANSFORMERS

The AC resistances of designed transformers were calculated by using equation (21) and depicted in fig. 28. In these transformers, since the secondary winding is half of the primary winding, the secondary resistance is considered to be half of the obtained primary resistance of transformers.
The coupling coefficients of all these transformers were calculated according to equation (19) and illustrated in fig. 29.

From fig. 29, it is evident that the coupling coefficient ‘$K$’ is increasing in nature as the area of the transformer increases. The coupling coefficient is highest for the transformer TR$_4$; however the AC resistance from fig. 28 is also greatest for that transformer and, in addition, the interwinding capacitance is higher according to table 4. Therefore, for the given power transfer application, the first two transformers TR$_1$, TR$_2$ were considered and the power tests were carried out by following the procedure discussed in chapter 2. As discussed previously, by
matching the measured and modelled performance characteristics, the actual parameters of transformers TR1-TR4 were obtained and given in Table 4.

Table 4. Modelled electrical parameters of three layered coreless PCB step-down power transformers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TR1</th>
<th>TR2</th>
<th>TR3</th>
<th>TR4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_p(\Omega)$-DC</td>
<td>0.62</td>
<td>0.84</td>
<td>1.10</td>
<td>1.62</td>
</tr>
<tr>
<td>$R_s(\Omega)$-DC</td>
<td>0.30</td>
<td>0.41</td>
<td>0.55</td>
<td>0.82</td>
</tr>
<tr>
<td>$L_p(\mu H)$</td>
<td>2.86</td>
<td>8.25</td>
<td>17.3</td>
<td>31.9</td>
</tr>
<tr>
<td>$L_s(\mu H)$</td>
<td>0.78</td>
<td>2.20</td>
<td>4.54</td>
<td>8.10</td>
</tr>
<tr>
<td>$L_{lkP}(\mu H)$</td>
<td>0.35</td>
<td>0.40</td>
<td>0.46</td>
<td>0.72</td>
</tr>
<tr>
<td>$L_{lkS}(\mu H)$</td>
<td>0.09</td>
<td>0.18</td>
<td>0.23</td>
<td>0.35</td>
</tr>
<tr>
<td>$L_m(\mu H)$</td>
<td>1.30</td>
<td>3.97</td>
<td>8.50</td>
<td>15.5</td>
</tr>
<tr>
<td>$C_p(pF)$</td>
<td>57.0</td>
<td>119</td>
<td>176</td>
<td>260</td>
</tr>
<tr>
<td>$% (L_{lkP}/L_p)$</td>
<td>12.24</td>
<td>4.85</td>
<td>2.66</td>
<td>2.26</td>
</tr>
<tr>
<td>$% (L_{lkS}/L_s)$</td>
<td>11.54</td>
<td>8.18</td>
<td>5.07</td>
<td>4.32</td>
</tr>
</tbody>
</table>

From this table, it can be observed that the interwinding capacitance $C_p$ of the transformer is increasing in nature because of the increased area of the plates ($A_p$) since the distance between plates ($Z$) is maintained as a constant. Additionally, the rate of increase of leakage inductance with respect to self inductance is reducing as
the number of turns of the transformer is increased as discussed at the beginning of chapter 3.

3.4 ENERGY EFFICIENCY OF TR₁, TR₂ WITH DIFFERENT LOADS (Rₗ)

The measured energy efficiencies of the transformers TR₁, TR₂ with different load resistances and an external resonant capacitor of 1.5nF were illustrated in fig. 30 and fig. 31 respectively. The maximum energy efficient frequencies (MEEF) of TR₁ and TR₂ were found to be at 4MHz and 2MHz respectively. From this it is also verified that the MEEF is less than the MIF according to equation (39). The MEEF is independent of the loads for both transformers and can be examined from these figures. The maximum energy efficiency of transformers TR₁/TR₂ is found to be 97% at their corresponding MEEF with respective load powers of 12W/10W approximately. The efficiency of transformers TR₁/TR₂ is found to be approximately 93.8%/94.5% at an output power of 23W/20W respectively under the same maximum energy efficiency frequencies.

![Figure 30](image1.png) Measured efficiency of TR₁ at C=1.5nF with different loads

![Figure 31](image2.png) Measured efficiency of TR₂ at C=1.5nF with different loads

3.5 ENERGY EFFICIENCY OF TR₁, TR₂ WITH DIFFERENT RESONANT CAPACITORS (Cᵣ)

As, the external resonant capacitor plays an important role in these transformers; the energy efficiency was also measured for different resonant capacitors at a load resistance of 30Ω and is shown in figs. 32 and 33 for transformers TR₁ and TR₂ respectively. As the resonant capacitor value is decreased, the MEEF moves towards higher frequencies because the corresponding fᵣ and MIF are increased according to equation (36) which can be observed from figs. 32 and 33. In addition,
with a lower value of \( C \), the energy efficiency of the transformers remains constant for a wide range of frequencies. Thus with the proper selection of resonant capacitors across the secondary winding of the transformer, the energy efficiency of the transformer can be maintained at a high level even at the desired operating frequencies.

3.6 EFFICIENCY WITH SINUSOIDAL AND SQUARE WAVE EXCITATION

For the majority of the SMPS applications utilising single and double ended topologies such as flyback, forward, half bridge, full-bridge etc., the power fed to the high frequency transformer is not sinusoidal in nature. Therefore, it is required to determine the energy efficiency of the transformers when the power processing is not sinusoidal in nature. Hence, power tests were also carried out for square wave excitations along with sinusoidal excitations. The comparative results of the power tests for both the transformers TR\(_1\) and TR\(_2\) under these conditions are illustrated in fig. 34. The load resistance considered is of 30\( \Omega \) with a resonant capacitor of 1.5nF. At their MEEF, the energy efficiencies of transformers TR\(_1\)/TR\(_2\) are 96.0%/96.3% for sinusoidal excitations. Only a slight variation exists in terms of energy efficiency for the square wave and sinusoidal excitation in the case of both transformers because of the current harmonics.
This provides the scope for utilizing these transformers with the combination of the latest semi conductor devices such as GaN MOSFETs and SiC schottky diodes at higher operating frequencies in the upcoming new generation converters.

3.7 CAPTURED WAVEFORMS OF POWER TRANSFORMER

The measured waveforms such as $V_{pri}/V_{sec}$ and $I_{pri}/I_{sec}$ of transformer $TR_1$ at its MEEF were captured using the oscilloscope and shown in fig. 35. The operating conditions of this transformer $TR_1$ are given in section 3.6 where its energy efficiency is approximately 96%.

![Figure 34. Efficiency with sine and square wave excitation](image)

![Figure 35. Measured primary/secondary voltages $V_{pri}/V_{sec}$ and currents $I_{pri}/I_{sec}$](image)
3.8 APPLICATION POTENTIALS OF DESIGNED TRANSFORMERS

The designed three layered 2:1 step-down coreless PCB power transformers were compared to the existing core based ones [24] for various power levels such as 8, 15 and 30 Watt utilized for Telecom and PoE applications. The core based transformers in terms of their dimensions, electrical characteristics such as input/output voltage; load current and power were tabulated and given in Table.5.

Table 5. Existing core based Power transformers

<table>
<thead>
<tr>
<th>$V_{in}$ (Volts)</th>
<th>$V_{out}$ (Volts)</th>
<th>$I_{out}$ (Amps)</th>
<th>Power (Watts)</th>
<th>Dimensions mm &amp; part number (Coil craft)</th>
<th>%Volume reduction of TR1, TR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-36</td>
<td>15</td>
<td>0.53</td>
<td>8</td>
<td>15.24x12.7x11 FCT1-150L2SLB</td>
<td>72, 37</td>
</tr>
<tr>
<td>36-75</td>
<td>15</td>
<td>1.00</td>
<td>15</td>
<td>17.7x13.4x12 FCT1-150M2SLB</td>
<td>79, 53</td>
</tr>
<tr>
<td>36-72</td>
<td>24</td>
<td>1.25</td>
<td>30</td>
<td>30x20.5x11.4 POE300F-24LB</td>
<td>91, 81</td>
</tr>
</tbody>
</table>

For these power transfer applications, the energy efficiency of transformer TR2 is slightly better as compared to that for the TR1 because of its increased coupling coefficient in spite of its high AC resistance.

When compared to existing core based transformers, the volume reductions of the designed coreless PCB transformers were also estimated and listed in table 5. It can be observed that the percentage volume of coreless PCB transformers is drastically reduced as compared to the core based transformers. With these coreless PCB transformers the height of the transformer can be reduced from 12mm to 1.48 mm which leads to a huge reduction in the volume of the transformer and hence the converter. Therefore, these core based transformers can be replaced by the coreless PCB step-down transformers in the case of compact SMPS applications.
4 RADIATED EMISSIONS OF MULTILAYERED CORELESS PCB STEP-DOWN POWER TRANSFORMERS

In the above two chapters, the modelling, performance characteristics, power tests and energy efficiency of multi-layered coreless PCB step-down power transformers have been discussed. These coreless PCB transformers have proven to be highly energy efficient in the MHz frequency region for power transfer applications.

4.1 NEED FOR DETERMINATION OF EMI EMISSIONS FROM MULTILAYERED CORELESS PCB TRANSFORMERS

One of the other major misconceptions of coreless transformers is that they possess a high radiated EMI, because of the absence of a core. Even though the transformers do possess high energy efficiency, if it fails the EMC tests, it is of no use. Therefore, it is necessary to determine the amount of radiation emitting from these transformers when used for power transfer applications in SMPS in order to minimize the malfunctioning of the other devices in the circuit. In order to obtain commercialization of the product, it is necessary for a product to satisfy the requirements set by the American FCC, or European CISPR standards. Before commercialization of the product can take place it must be sent for an EMC test. If it fails these tests, it can neither be sold nor bought by anyone. This would result in a product delay and increased costs of production until the problem has been dealt with by the researchers/engineers. Hence, the prior estimation of the amount of EMI generated from transformers has many advantages such as providing the solution to improvements in the design criteria, sources of EMI, remedies, recommended topologies, reduction in the cost of production of transformers etc., Fig. 36 [25] illustrates the required cost for correcting the EMI problems at different stages of product development.
The radiated emissions of coreless PCB transformers for signal transfer applications were proven to be negligible considering the fundamental component of current through the transformer [26]. However, for power transfer applications in various single ended and double ended topologies, since the waveforms are not sinusoidal in nature, it is also required to consider the harmonic currents as well as the nature of the waveforms. For example in a flyback converter topology, as the currents are saw tooth in nature, it consists of both even and odd harmonic components. Whereas in the case of half bridge converter topologies, the current is of a square wave in nature and consists of only odd harmonic components. The other factors which also determine the radiated emissions of a transformer are the structure of the transformers such as whether they are two layered or multi layered.

Therefore, in this section, the simulated and measured EMI emissions of two layered and three layered coreless PCB step-down transformers for power transfer applications for different excitations have been assessed using antenna theory.

### 4.2 Far Field Radiation- Antenna Theory

The designed coreless PCB transformers discussed in chapters 2 and 3 are circular spiral in structure in order to reduce the inter winding capacitance ‘Cps’ of transformer. Here, each turn of the transformer can be considered as a loop antenna [27], [28]. From the antenna theory [9], when current flows through the loop in the X-Y plane with an angular frequency of ‘ω’, the energy gets radiated into the air. This energy is perpendicular to the X-Y plane and possesses the intrinsic impedance of 377Ω in free space. At each frequency of operation, the associated wavelength of the radiated signal can be calculated as follows.

\[
\lambda = \frac{c}{f \sqrt{\varepsilon_r}}
\]

Where, ‘\(\lambda\)’ is the wavelength, ‘\(c\)’ is the speed of light, ‘\(f\)’ is the frequency, ‘\(\varepsilon_r\)’ is the relative permittivity. In air core transformers, ‘\(\varepsilon_r\)’ is considered to be 1. The signal and its corresponding components will be electrically large if the wavelength of the signal becomes reduced as the harmonic frequency increases. Any loop can be considered as a good radiator if the outermost radius of the loop is equal to or is
half of the wavelength of the signal. For a loop antenna, the amount of time averaged radiated power \( P \) is given as

\[
P = 160\pi^6 I_o^2 \left( \frac{f}{c} \right)^4
\]

(44)

where, \( I_o \) is RMS current through the loop, \( r' \) is radius of loop. From this equation, it is clear that the radiated energy not only depends on the current and its nature as discussed earlier, but also on the frequency and radius of the transformer.

4.2.0 Estimation of radiated emissions from two layered and three layered transformers

Based on the above discussed parameters, such as the current harmonics, the nature of the current, radius and the structure of the transformer, EMI emissions for three different transformers, TR0, TR1, and TR2 were estimated by using antenna theory. The computations were estimated when these transformers were excited with both sinusoidal and square waves at a fundamental/operating frequency of 2MHz and a load power of 20W by using the procedure mentioned in Chapter 2. These tests were carried out at their MEEF which was maintained at 2MHz by adjusting the resonant capacitors across the secondary winding of the transformer. The load resistance considered is of 30Ω. Three methods used for the estimation of the EMI from the transformers are described in this section. The following computations were made

1) By taking the primary/secondary currents from the measured waveforms of the transformers excited with a Power Amplifier.
2) By taking the primary/secondary currents obtained from the simulations of the high frequency model of the transformers.
3) By considering the ideal sinusoidal/square waves of primary/secondary current waveforms generated from MATLAB.

The measured waveforms of the primary/secondary voltages and currents of transformer TR2 at its operating frequency of 2MHz for both sinusoidal and square wave excitations are depicted in figs. 37 and 38 respectively.
Similarly, the simulated waveforms of the primary/secondary voltages and 
currents of transformer TR\textsubscript{2} at its operating frequency of 2MHz for both sinusoidal 
and square wave excitations are depicted in figs. 39 and 40 respectively.

**Figure 37.** Measured waveforms with $R_L=30$ $\Omega$. CH1 – $V_{\text{pri}}$ (50V/div), CH2 – $I_{\text{pri}}$ (500mA/div), CH3 – $V_{\text{sec}}$ (20V/div), CH4 – $I_{\text{sec}}$ (1A/div) - Sinusoidal

**Figure 38.** Measured waveforms with $R_L=30$ $\Omega$. CH1 – $V_{\text{pri}}$ (50V/div), CH2 – $I_{\text{pri}}$ (500mA/div), CH3 – $V_{\text{sec}}$ (20V/div), CH4 – $I_{\text{sec}}$ (1A/div) - Square wave

Similarly, the simulated waveforms of the primary/secondary voltages and 
currents of transformer TR\textsubscript{2} at its operating frequency of 2MHz for both sinusoidal 
and square wave excitations are depicted in figs. 39 and 40 respectively.

**Figure 39.** Simulated waveforms of TR\textsubscript{2} with $R_L=30$ $\Omega$ for Sinusoidal excitations
From fig. 37 to fig. 40, the simulated and measured waveforms of transformer can be observed to be in good agreement with each other and hence the modelling of the transformer described in chapter 2 has been once again verified.

4.2.1 Current harmonics corresponding to sinusoidal and square wave excitations

In order to calculate the radiated power of the transformer, the harmonics of the measured/simulated primary/secondary currents were obtained by using a Fast Fourier Transform (FFT). In addition, the FFT of the sinusoidal/square wave currents generated by using MATLAB were also obtained. The FFT of the sinusoidal/square wave primary currents are displayed for both the measured and the simulated waveforms and those generated from MATLAB in fig. 41 and fig. 42 respectively.

From fig. 41 and 42, it can be observed only a fundamental component exists in the case of sinusoidal excitation whereas in the square wave excitation odd harmonic components also exist.

Figure 40. Simulated waveforms of TR2 with $R_c=30 \, \Omega$ for the square wave excitations.
4.2.2 Radiated power calculations for sinusoidal and square wave excitations

The above harmonic components including the fundamental were put into the equation (44) for obtaining the radiated power of the transformers at their corresponding frequencies and illustrated in figs. 43 and 44 for sinusoidal and square wave excitations. Whilst computing these powers, not only the outermost radius is considered [15] but also the remaining loops such as for TR₁, since $N=8$, eight number of loops were considered and for TR₂ $12$ is the number of loops and so on. From fig. 43, it can be observed that the radiated power obtained for the simulated, measured and MATLAB generated waves are almost zero except at the fundamental frequency. In all three cases, the radiated power at this frequency of the fundamental is caused by the secondary waveform which carries an RMS current of 0.8 Amp and is found to be approximately 0.0332 nW.

From fig. 44, the radiated power obtained is increasing in nature for the square wave excitation because of the presence of odd harmonic components together with the high frequencies as discussed at a previous stage. In this case, the measured and simulated radiated powers are considered to be in good agreement with each other compared to the MATLAB generated one because of the wave distortion. Comparing the radiated powers obtained with the square and sinusoidal excitations reveals that for the square wave excitation, it is higher in comparison to that of the sinusoidal wave forms. Here, the radiated powers were shown up to the 7th harmonic component.
However, for class B equipment, according to FCC and CISPR regulations, the radiated limits are applicable from 30MHz-300MHz [29], hence the radiated power for all these transformers for both sinusoidal and square wave excitations is depicted from figs. 45-47.

![Figure 43. Radiated power of TR2 for Primary/secondary currents with sinusoidal excitations](image)

Figure 43. Radiated power of TR2 for Primary/secondary currents with sinusoidal excitations

![Figure 44. Radiated power of TR2 for Primary/secondary currents with square wave excitations](image)

Figure 44. Radiated power of TR2 for Primary/secondary currents with square wave excitations
From figs. 45 and 46, it can be observed that the radiated power due to harmonics of the secondary currents from transformer TR₁ was reduced by a factor of 4 compared to that for the TR₂ which is because of the reduced radius of the transformer. In this case the measured waveforms were limited to 50MHz only because of the limitation of probe and oscilloscope bandwidths.

Figure 45. Radiated power of TR₁ with square wave excitation

Figure 46. Radiated power of TR₂ with square wave excitation
From figs. 45 and 47, the radiated power obtained in the case of the three layered transformer \( TR_3 \) is lowered by a factor of 2.6 as compared to that for the two layered transformer, \( TR_0 \). This is because of a reduction in the radius of the transformer as well as an increased coupling in the case of the three layered transformer when it is compared to the two layered transformer. It has already been proven in chapter 2 that the energy efficiency of \( TR_3 \) is greater than \( TR_0 \) and in this case, the radiated power is less in the case of \( TR_3 \) as compared to that for \( TR_0 \).

Based on the point of view from the estimation of the radiated EMI, it can be concluded that the radiated EMI in the case of the three layered transformer is less than that of the two layered transformer because of a reduced radius for the same amount of inductance.

Figure 47. Radiated power of \( TR_0 \) with square wave excitation
5 GATE DRIVE TRANSFORMERS FOR DOUBLE ENDED TOPOLOGIES

As discussed in the previous chapter, if the power processing in the converter circuit is of a sinusoidal manner, the radiated EMI from power transformers is reduced. Usually for this process, resonant converter topologies such as a series resonant converter, a parallel resonant converter, a series parallel and LLC resonant converters are used. In these converter topologies, both a high side and low side MOSFET exist. In order to switch the high side MOSFET, a high side MOSFET gate driver operating at a few MHz and at higher input voltages is required. However, the commercially available high side gate drivers are limited to 1MHz with 125 V input voltage [30]. Generally, in gate drive circuits, in order to switch power MOSFET’s, galvanic isolation is required. For this purpose, either pulse transformers or optocouplers are utilized. However, at higher operating frequencies such as in a few MHz, it is not possible to use pulse transformers/core based transformers because of the limitations imposed by the core materials at these frequencies. In addition, because of the high manufacturing costs involved in manually wound transformers, a great deal of research has been focussed on the planar winding transformers and inductors either on PCB or thin film [31]-[34] during the past few years. Since, coreless PCB transformers possess good high frequency characteristics, this eliminates manual winding process, and there has subsequently been significant research over the few years regarding coreless PCB gate drive transformers on two layered PCBs. In addition, by printing the windings on the FR4 material, as discussed previously, this possesses a much higher isolation of 15-40kV compared to that obtained from the opto coupler i.e., only 1.5-7.5kV [35]. However, by designing the gate drive transformer on a two layered PCB does not provide the optimal solution in comparison to pulse transformer in terms of gate drive power consumption. In [36], it has been shown that for the same load of 10nF parallel to a 100Ω resistor, it was stated that for a core based transformer, the current drawn at 1.1MHz frequency was found to be 0.08A whereas for the coreless PCB transformer it is 0.18A. This increase in the current for the coreless PCB transformer on the two layered PCB is due to the increased winding resistance for a given amount of inductance in a two layered transformer and thus it is necessary to design a multi-layered coreless PCB transformer in order to reduce the winding resistance as well as the transformer area which in turn reduces the amount of radiated EMI. Therefore, in order to achieve these characteristics, multi-layered coreless PCB transformers were designed which can
be highly integrated into the converter circuit for gate drive applications instead of merely a two layered transformer.

In further sections, the structure, geometrical, electrical parameters and their performance characteristics are discussed.

5.1 MULTILAYERED GATE DRIVE CORELESS PCB TRANSFORMER

The structure of the transformers is primary-secondary-secondary-primary (PSSP) in order to ensure a better coupling between the primary and secondary windings. The transformer is also spiral in shape so as to reduce the inter winding capacitance which limits the bandwidth compared to other shapes [33]. The primaries of the two transformers are connected in series by reversing one of the primary windings and the dimension of one of the gate drive transformer is illustrated in fig. 48 and is the same for two transformer secondary windings.

![Figure 48. Dimension of Gate drive transformer](image)

5.2 GEOMETRICAL AND ELECTRICAL PARAMETERS OF GATE DRIVE TRANSFORMERS

Two different multilayered coreless PCB transformers (TrA and TrB) with the following geometrical parameters were designed and evaluated. The geometrical parameters required to obtain the electrical parameters of these gate drive transformers are tabulated as shown in table 6.

Table 6. Geometrical parameters of the gate drive transformers, TrA and TrB

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TrA</th>
<th>TrB</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>16</td>
<td>22</td>
</tr>
<tr>
<td>W[mm]</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>Sp[mm]</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td>Rin/Rout[mm]</td>
<td>0.9/8.8</td>
<td>1.1/9</td>
</tr>
<tr>
<td>Height [µm]</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Board Thickness[mm]</td>
<td>1.48</td>
<td>1.48</td>
</tr>
</tbody>
</table>
These transformers were also used by using high frequency ferrite plates which is like a large air gapped core. The high frequency core material of Ni-Zn whose permeability is 80 is evaluated by using coreless PCB transformers for gate drive applications. The evaluated core material’s shape is circular with a radius of 10mm and a thickness of approximately 1.5mm.

The electrical parameters for these transformers were estimated by using the Hurley and Duffy method as discussed in chapter 2. The measured DC resistance and the remaining electrical parameters for the transformers with and without the ferrite core material at 1MHz using an RLC meter are given in table 7.

Table 7. Electrical parameters of the gate drive transformers, TrA and TrB

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TrA</th>
<th>TrA with Ferrite</th>
<th>TrB</th>
<th>TrB with Ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_p[µH]</td>
<td>0.91</td>
<td>1.95</td>
<td>1.56</td>
<td>3.39</td>
</tr>
<tr>
<td>L_{lp}[µH]</td>
<td>0.34</td>
<td>0.45</td>
<td>0.56</td>
<td>0.72</td>
</tr>
<tr>
<td>L_s[µH]</td>
<td>1.16</td>
<td>1.85</td>
<td>1.89</td>
<td>3.4</td>
</tr>
<tr>
<td>L_{ls}[µH]</td>
<td>0.44</td>
<td>0.44</td>
<td>0.71</td>
<td>0.72</td>
</tr>
<tr>
<td>C_p[pF]</td>
<td>11</td>
<td>11.4</td>
<td>11</td>
<td>11.4</td>
</tr>
<tr>
<td>R_{g,dc}[Ω]</td>
<td>0.43</td>
<td>0.64</td>
<td>0.94</td>
<td>1.05</td>
</tr>
<tr>
<td>R_{c,dc}[Ω]</td>
<td>0.55</td>
<td>0.68</td>
<td>1.17</td>
<td>1.22</td>
</tr>
<tr>
<td>K</td>
<td>0.624</td>
<td>0.766</td>
<td>0.626</td>
<td>0.788</td>
</tr>
</tbody>
</table>

From table 7, it can be observed that the self and mutual inductance of the transformers using the ferrites increases while the leakage inductance of the transformers remains more or less the same. The coupling coefficient for the transformers also increases with the use of the ferrite material.

Since, these gate drive transformers are designed with the aim of driving the power MOSFETs, the load which is considered is a combination of both the resistor and the capacitor. Therefore, the gate drive circuitry of the power relating to the MOSFETs considered for performance evaluation of the transformer is a parallel combination of the resistor and capacitor. In general, for low-medium power converter applications, the input capacitance of the MOSFET, which acts as load for the transformer, ranges from 100-1500pF. This input capacitance for the MOSFET determines the bandwidth of the coreless PCB gate drive transformers.
5.3 PERFORMANCE CHARACTERISTICS OF GATE DRIVE TRANSFORMERS

The performance characteristics of the designed gate drive transformers such as the voltage gain/transfer function, input impedance and phase angle discussed in chapter 2 have been presented. These performance characteristics were obtained by considering the load resistance of 100Ω and the capacitor of 680pF. For the measured parameters of the transformers, a 680pF capacitor is considered so that the operating frequency region of the gate drive transformers is within the range of 1-4MHz which can be described by means of the calculated performance characteristics. The voltage gain of the transformers under these conditions is illustrated in fig. 49.

![Figure 49. Voltage gain of gate drive transformers TrA and TrB](image)

The maximum voltage gain of transformers TrA and TrB were found to be approximately 1.1 and 1 respectively at their corresponding maximum gain frequencies 6 and 4.5MHz. The maximum gain frequencies of transformers with and without ferrites were unchanged because there was no significant difference in the leakage inductance. The input impedance and the phase angle of these transformers under the same load conditions are shown in fig. 50 and 51. The input impedance frequency of the transformers is found to be less than that of the maximum gain frequency as discussed in chapter 2.
From figs. 50 and 51, it can be observed that before the maximum input impedance frequency, the phase angle of transformer is found to be sufficiently high to ensure that the transformer is inductive in nature.

By operating the transformers at their maximum impedance frequency the gate drive power consumption of the circuit can be minimized which is a desirable characteristic for SMPS. The calculated energy efficiency of these gate drive
transformers at a resonant capacitor of 680pF with a parallel resistance of 100 Ω with and without ferrites for sinusoidal signal is depicted in fig. 52. The efficiency for these transformers is between 70-90% but this is not a big issue as, in total, it corresponds to some 100mW in relation to the 50-100W converter.

![Figure 52. Energy efficiency of gate drive transformers TrA and TrB](image)

The input impedance and energy efficiency of the transformers was improved by means of the ferrite material which also reduces the overall power consumption of the gate drive circuit.

### 5.3.0 Estimation of maximum energy efficiency frequency, MEEF

It is necessary to determine the maximum impedance frequency of the transformers for different load conditions since the MOSFETs utilized for different applications do in fact vary. Therefore, the maximum energy efficiency frequency /maximum impedance frequency of the gate drive transformer TrA was estimated for several combinations of load resistances and capacitors and is illustrated in fig. 53. In this case, the load resistance is varied from 100-1000Ω and the capacitance from 100-1500pF.
For this transformer, TrA, the maximum energy efficiency which can be obtained at the corresponding maximum energy efficiency frequency with the combinations of load resistance and capacitors is estimated and shown in fig. 54.
5.3.1 Gate drive signals using gate drive transformer, TrA

The designed gate drive transformer was utilized in high frequency converters such as a half bridge converter, two switch flyback and a series resonant converter operating within the MHz frequency region to drive the high side MOSFET. The lower MOSFET was directly driven from the MOSFET driver LM5111 whereas the high side MOSFET was driven by using a multi-layered gate drive transformer. The signals corresponding to the low side and the high side MOSFETs are illustrated in fig. 55. In this instance, the typical input capacitance of the MOSFETs, namely the ZXMN15A27K is considered to be 169pF.

![Gate drive signals at 2.3MHz using TrA with Ferrite plates](image)

In fig. 55, Channel ‘1’ represents the low side MOSFET gate signal whereas Channel ‘2’ represents the high side gate drive signal. The rise/fall times of the low side and high side signals were 5.6/5.5ns and 19.2/20.2ns respectively. Under these conditions the measured gate drive power consumption using the transformer is found to be 0.37W.

The rise/fall times of high side gate signal can be further improved by redesigning the transformers.
6 THESIS SUMMARY AND CONCLUSIONS

In this section the thesis is summarized by chapters:

First Chapter: In this chapter the basic introduction to the importance of high frequency magnetics and the challenges facing in the high frequency transformers have been discussed. A brief introduction to coreless PCB transformers including the advantages and misconceptions has been provided. The motivation in relation to the thesis and thesis outline have also been presented.

Second Chapter: In the second chapter, the design and analysis of two layered and three layered coreless PCB step-down power transformers operating in the MHz frequency region have been discussed. Geometrical and electrical parameters which govern the design of the transformers were discussed in detail. An analytical method useful for determining the electrical parameters by using the Hurley and Duffy method has been presented. A high frequency model and the parameter extraction of coreless PCB transformer were also examined. The parameters obtained by the high frequency model and MATLAB program for two layered and three layered transformers were verified. The major factors such as the resistance and the coupling coefficient of the transformers affecting the energy efficiency of transformers have also been presented. A depiction of the experimental set-up required in order to determine the energy efficiency of transformers for power transfer applications was provided. The conclusion to be drawn is that for the same power transfer application a three layered transformer is better in comparison to that of the two layered transformer because of the increased coupling coefficient and the reduced AC resistance. The energy efficiency of the three layered transformer was improved by 3% (losses reduced with 62.5 %) and the area of the transformer was reduced by 32% as compared to that for the two layered transformer.

Third Chapter: In this case, a series consisting of a set of 4 different transformers had been designed for power transfer applications. These transformers were evaluated in terms of their performance characteristics based on the modelling procedure and measurements described in chapter 2. The coupling coefficient of the transformer consisting of a large radius achieved by increasing the number of turns was found to be high when it was compared to a smaller transformer. At the
same time the smaller transformer possessed a low value for the AC resistance when compared to the other transformers. Because of the increased area and resistance of the transformers, the power tests were carried out for the first two transformers for a given power transfer application and it was discovered that these transformers possessed higher energy efficiencies. From the comparison of the designed transformers and the existing core based transformers, it can be concluded that a vast volume reduction can be obtained in terms of height. Hence for the very stringent height applications coreless PCB transformers can be utilized.

**Fourth Chapter:** In this chapter, the radiated emissions from the two layered and three layered transformers were estimated and compared. These radiated emissions were calculated according to antenna theory for the power transformers at a load power of 20W. For both sinusoidal and square wave excitations, the harmonic magnitudes of the simulated, measured and idealized current waveforms were obtained from which an estimation of the radiated power from the transformer was obtained. It can be concluded from the results that the multi-layered coreless PCB transformers have a low radiated EMI compared to the two layered transformer for the given power. In addition, for the sinusoidal excitation, the radiated power obtained is low compared to that for the square wave excitation. This shows that these transformers are best suited for resonant converter topologies in terms of EMI radiation.

**Fifth Chapter:** In chapter 5, two different multi-layered coreless PCB gate drive transformers designed for high speed SMPS were described. The high frequency commercially available ‘NiZn’ ferrite materials were used to evaluate their performance with coreless PCB transformers. The geometrical and electrical parameters of these transformers with and without ferrite materials were provided. The performance characteristics and energy efficiencies of the two transformers with and without ferrite plates were illustrated and it was determined that there was an improvement in the input impedance and energy efficiency with ferrite plates. By operating the transformers at their maximum impedance frequencies the energy efficiency and gate drive power consumption of the converter circuit was found to be reduced. Since for different converter applications, the MOSFETs utilised varies, the maximum energy efficiency frequency and the corresponding maximum energy efficiency were estimated for different combinations of resistance and capacitance. The gate drive signals of the
double ended converter utilizing the transformer TRA were illustrated and it was discovered that the gate drive power consumption is less than half a watt.

6.1 FUTURE WORK

The majority of the work presented in the thesis is according to analytical and practical based results. For further studies the work should be more focussed on the optimization of the geometrical and electrical parameters for a given power transfer application. As discussed in the thesis, a trade-off exists between the resistance and coupling coefficient of the transformers. In order to obtain the best design for the transformers, this trade off should be considered and a great deal of work can be performed on the winding technologies and optimization. Additionally, the high frequency problems such as skin and proximity effects should be further mitigated by using different winding structures in multi-layered PCBs. In relation to the commercialisation of these transformers, measurements of EMI emissions from the transformers should be performed. Based on the energy efficiency of the designed transformers, further step-down transformers for different converter applications are possible. The analysis of these transformers and their challenges should be studied. It would also be advantageous to verify the performance of the transformers by using a Finite Element Analysis (FEA) with the assistance of 2D and 3D simulations.
6.2 AUTHORS CONTRIBUTIONS

The contributions of authors for the five papers in this thesis are summarized in table 8. In this table M and C represent the main author and co-author respectively.

Table 8. Author’s Contributions

<table>
<thead>
<tr>
<th>Paper</th>
<th>RA</th>
<th>HK</th>
<th>KB</th>
<th>MA</th>
<th>Contributions</th>
</tr>
</thead>
</table>
| I     | M  | C  | C  | -  | RA: Estimation of inductive, resistive and capacitive parameters using MATLAB code, Design and modelling of transformers, Power tests of transformers, Experiments and results  
HK: Modelling, Analysis and discussion on application potentials  
KB: Suggestions, Review of paper and Supervision |
| II    | M  | C  | C  | -  | RA: Design and modelling of transformers, power tests of transformers  
HK: Idea of comparing two different layer transformers, Suggestions, Power tests of transformers and Analysis  
KB: Suggestions and Supervision |
| III   | M  | C  | C  | -  | RA: Design of transformers, Implementation of MATLAB code for EMI calculations and analyzing the theoretical and experimental results  
HK: Implementation of Idea using different transformers, discussions and suggestion of topology for the designed transformers  
KB: Idea, review of paper and Supervisor |
| IV    | C  | M  | C  | -  | RA: Transformer design, parameter extraction and experimental analysis of transformer in converter circuit  
HK: Implementation of flyback topology, experimental and theoretical analysis of hard switching and soft switching of converter, Loss estimation of converter  
KB: Review of paper and Supervision |
| V     | C  | C  | C  | M  | RA: Power and Signal transformer design, secondary inductor design, parameter extraction  
HK: Discussion, design of gate drive circuitry and review of paper  
KB: Supervisor  
MA: Implementation and experiments of Half bridge Converter |

1. Radhika Ambatipudi (RA)  
2. Hari Babu Kotte (HK)  
3. Kent Bertilsson (KB)  
4. Majid Abdul (MA)
7 REFERENCE

24) www.coilcraft.com

