



**Mittuniversitetet**

MID SWEDEN UNIVERSITY

Thesis for the degree of Doctor of Technology  
Sundsvall 2020

## **Wide Range Isolated Power Converters**

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ISSN 1652-893X

Mid Sweden University Doctoral Thesis 328

ISBN 978-91-88947-59-8

Akademisk avhandling som med tillstånd av Mittuniversitetet i Sundsvall framläggs till offentlig granskning för avläggande av dissertation examen i elektronik, **tisdag, 09 June 2020, klockan 0930 i sal C312**, Mittuniversitetet Sundsvall.

Seminarier kommer att hållas på engelska.

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Printed by Mid Sweden University, Sundsvall, Sweden, 2020

*Dedicated to my family*



## ABSTRACT

Power electronics technology is rapidly growing in most industrial applications. There is an increasing demand for efficient and low profile power converters in the industry like automotive, power grids, renewable energy systems, electric rail systems, home appliances, and information technology. In some applications, there is an increasing demand for power converters showing a stable performance over a wide variation in input voltage, whereas in others the demand is for converters showing a stable performance over a wide variation of output voltage. In this regard, not so much work has been done to combine both requirements into one solution; this is the primary focus of the dissertation. It presents a unique solution to the industry, which addresses both requirements. The technique can be applied in a one size fits all solution which not only extends the range of the line voltage and the output voltage but also provides the flexibility to adjust the required set of line/output voltage. The variation in line voltage severely degrades the performance of power converters because of the extended freewheeling interval, more circulating current, narrow range of zero voltage switching and increased EMI. To overcome this, the converter consists of two reconfigurable modes on the input side that can be configured following the variation in line voltage to maintain a stable performance. In addition, it proposes three reconfigurable steps for the output voltage, which can be used to adjust the output voltage from base level  $X$  to  $2X$  and  $4X$  in discrete steps and/or from  $X - 4X$  volt while showing stable performance. This makes the proposal a  $2 \times 3$  reconfigurable modes power converter, which means that the gain of the proposed converter can be raised to 4 or 8. Furthermore, the flexibility in the reconfigurable structure simplifies the implementation of the proposed single solution in a range of applications. Each concept proposed in the thesis is verified analytically, experimentally and modelling it into a SPICE simulation. Then the whole concept is confined into a single entity, which is applied in an example application of a phase shifted full bridge converter. The full converter is characterized for input voltage  $100-400V_{dc}$ , the output voltage  $24-96V_{dc}$ , and up to the load power of  $1kW$ .



## SAMMANDRAG

Kraftelektroniktekniken växer snabbt i många industriella tillämpningar. Det finns en ökande efterfrågan på effektiva kraftomvandlare med låg bygghöjd inom fordonsindustrin, elnät, förnybara energisystem, järnvägar, hushållsapparater och informationsteknik. I vissa tillämpningar finns det en ökande efterfrågan på kraftomvandlare som visar en stabil prestanda över mycket varierande inspänning, medan andra omvandlare ska kunna hantera stora variationer i utspänning. Fram tills nu så har inte så mycket arbete gjorts för att kombinera båda kraven till en lösning vilket är den primära målsättningen för denna avhandling. Tekniken kan appliceras i 'one-size-fits-all' lösning som inte bara utökar området för in- och utspänning utan ger också flexibilitet att justera spänningar inom ett bredare område. Stora variationer i inspänning försämrar kraftigt omvandlarnas verkningsgrad på grund av det utökade cirkulerande ström, och svårigheter att uppnå mjukswitchning och ökad EMI. För att övervinna detta består omvandlaren av två konfigurerbara lägen på ingångssidan som kan justeras efter variationen i inspänning för att upprätthålla en stabil prestanda. Dessutom föreslås tre konfigurerbara steg för utgångsspänningen, som kan användas för att justera utgångsspänningen från en basnivå  $X$  till  $2X$  och  $4X$ . Detta resulterar i en omvandlare med  $2 \times 3$  konfigurerbara lägen, vilket innebär att omvandlarens spänningsomsättning kan varieras med en faktor 8 jämfört med 2 för en traditionell omvandlare. Den konfigurerbara strukturen kan förenkla systemimplementationen då samma omvandlare kan användas för flera olika tillämpningar. De koncept som föreslås i avhandlingen har designats analytiskt, modellerat i en SPICE-simulering samt verifierats experimentellt. Slutligen har hela konceptet kombinerats i en enhet som klarar inspänningar mellan 100-400V DC och utgångsspänningen 24-96V<sub>dc</sub> och upp till belastningseffekten på 1kW.



## ACKNOWLEDGEMENTS

I would like to express my deep and sincere gratitude to my supervisor, Professor Kent Bertilsson, for his constant mentoring, encouragement, guidance, and friendly attitude. I have learned a lot from his creativity and research capabilities, which has enabled me to develop an understanding for the work presented in this Doctoral thesis. I would also like to give many thanks to my co-supervisor Associate Professor Johan Sidén for his kind guidance and for his precious time as reviewer.

I am very grateful to Professor Bengt Oelmann for reviewing my thesis and providing such valuable feedback. I would also like to express my gratitude to all my colleagues at the department for their tremendous support, co-operative attitude and administrative support.

I also offer my great regards and blessings to my family and father. Without their support and understanding, this would have not been achieved. I am also very thankful to all those who keep praying and supporting me for a better future.

The dissertation has been presented during the COVID-19 pandemic, where the whole world is under lockdown. I would like to express my deep sympathies to all victims around the world. My sincere gratitude to all researchers, healthcare personnel and volunteers who are fighting this disease. I hope their efforts will soon bring the world back to normal. I would also like to remember my beloved late mother from the bottom of my heart. Dear mother, your UN-CONDITIONAL love, prayers and services enabled me to do this. You left us beautiful memories. Although I can't see you, you are always by my side. Mother you are so missed. May you rest in peace and comfort.



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## LIST OF ABBRIVIATIONS

ADC	Analog to Digital Converter
BJT	Bipolar Junction Transistor
BMC	Boundary Mode Conduction
CCM	Continuous Conduction Mode
DAC	Digital to Analog Converter
DC	Direct Current
DCM	Discontinuous Conduction Mode
DSP	Digital Signal Processor
EMC	Electro-Magnetic Compatibility
EMI	Electro-Magnetic Interference
FEA	Finite Element Analysis
FEM	Finite Element Method
FET	Field Effect Transistor
GaN	Gallium Nitride
HEMT	High Electron Mobility Transistor
HF	High Frequency
IGBT	Insulated Gate Bipolar Transistor
IPM	Intelligent Power Module
kHz	Kilo Hertz
kW	Kilo Watts
MHz	Mega Hertz
MIF	Maximum Impedance Frequency
MOSFET	Metal Oxide Semi-Conductor Field Effect Transistor
MW	Mega Watts
PCB	Printed Circuit Board
PID	Proportional Integrative Derivative
PSU	Power Supply Unit
PSFB	Phase Shifted Full Bridge
PWM	Pulse Width Modulation
QRC	Quasi Resonant Conduction
RF	Radio Frequency
RMS	Root Mean Square
SiC	Silicon Carbide
SMPS	Switched Mode Power Supplies
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching



## LIST OF PAPERS

This thesis is mainly based on the following nine papers:

- Paper I M. A. Bakar, M. F. Alam and K. Bertilsson, “**Modeling and Characterization of Series Connected Hybrid Transformers for Low-Profile Power Converters,**” IEEE Access, vol. 8, pp. 53293-53306, 2020.
- Paper II M. A. Bakar, F. Alam, R. S. Alishah, and K. Bertilsson, “**Characterization of phase shifted full bridge converter along with four series-connected hybrid transformers for medium power applications,**” Accepted in PCIM Europe 2020, Nuremberg, Germany, conference is planned to proceed on 7–8 July, 2020.
- Paper III M. A. Bakar, F. Alam, and K. Bertilsson, “**Dual-mode stable performance phase shifted full bridge converter for wide input applications,**” Conditionally accepted in IEEE Transactions on Power Electronics.
- Paper IV M. A. Bakar, and K. Bertilsson, “**A Modified Higher Operational Duty Phase Shifted Full Bridge Converter for Reduced Circulation Current,**” Accepted in IEEE Open Journal of the Industrial Electronics Society.
- Paper V M. A. Bakar, F. Alam, M. Das, S. Barg, and K. Bertilsson, “**Reconfigurable three state dc-dc power converter for the wide output range applications,**” in IECON 2019 – 45th Annual Conference of the IEEE Industrial Electronics Society, 2019, vol. 1, pp. 4911–4916.
- Paper VI M. A. Bakar, F. Alam, S. Barg, and K. Bertilsson, “**A 2x3 Reconfigurable Modes Wide Input Wide Output Range dc-dc Power Converter,**” Submitted in IEEE Access Journal, (under review).

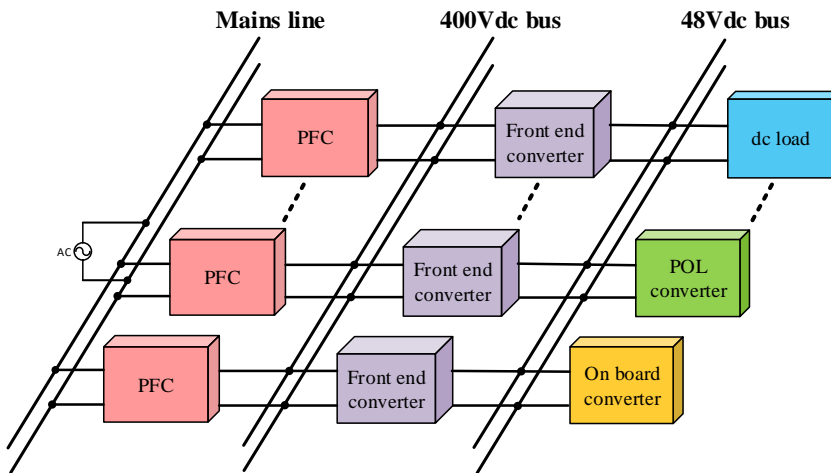
- Paper VII M. A. Bakar and K. Bertilsson, “**An improved modelling and construction of power transformer for controlled leakage inductance,**” IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC), 2016, pp. 1–5.
- Paper VIII M. A. Bakar, F. Alam, and K. Bertilsson, “**A phase shifted full bridge converter with novel control over the leakage inductance,**” 18th IEEE, European Conference on Power Electronics and Applications (EPE’16 ECCE Europe), 2016, pp. 1–10.
- Paper IX M. A. Bakar, S. Haller, and K. Bertilsson, “**Contribution of Leakage Flux to the total Losses in Transformers with Magnetic Shunt,**” Accepted in International Journal of Electronics.

Papers not included in this thesis

- Paper X M. A. Bakar, K. Bertilsson, and R. Ambatipudi, “**High frequency (MHz) soft switched flyback dc-dc converter using GaN switches and six-layered PCB transformer,**” 8th IET International Conference on Power Electronics, Machines and Drives (PEMD 2016), 2016, pp. 6 .
- Paper XI R.S Alisha, M. A. Bakar, K. Bertilsson “**A New Seven-Level Grid-Connected Converter Using Model Predictive Controller**” (Accepted in PCIM Europe 2020, Nuremberg, Germany, conference is planned to proceed on 7–8 July, 2020).
- Paper XII S. Haller, M. A. Bakar, K. Bertilsson “**CPLD and dsPIC Hybrid-Controller for Converter Prototyping driving a Reconfigurable Transformer Phase-Shifted Full-Bridge**” (Accepted in PCIM Europe 2020, Nuremberg, Germany, conference is planned to proceed on 7–8 July, 2020).

# 1 INTRODUCTION

A power supply unit or a power converter is an essential part of all electronic applications. It ranges from applications of a few watts to applications of Megawatts at different voltage levels. The main reason for the use of a power converter is to match the line voltage with load voltage and/or to isolate the load from the line source. However, with the advent of more functionalities and the size constraints of modern technologies, the electronics industry is currently moving towards smaller and high-density board solutions and applications. In most of the industrial applications, the approach of embedded system design is mainly adopted, which requires several converters to have different input/output specifications for the proper operation of the system. A typical distribution of power converters in a modern system is presented in Figure 1.1, where converters operate at different levels of input voltage and output voltage. This adds complexity to the system. To this end, development of a compact and smarter [1], [2], [3] power system is necessary to fulfil the requirements of the industry. In the following, a solution to meet current power requirements of the industry is discussed.



**FIGURE 1.1** A block diagram of a typical distributed system, where each section requires power with different specifications.

## 1.1 Background

There are many topologies available for the design of a power solution. Any design technique could work for any specification. However, each topology has its own merits and demerits. Some topologies are easier to design, some have fewer components and some are complex to control. Some topologies provide isolation between the input power and the output power. The selection of topology mainly depends on the specification of the given application. The main factors that contribute to the selection of the most suitable topology for the given specifications are: power requirements, input to output isolation, size and cost, and finally efficiency. Design simplicity, compact size, low cost and high efficiency have not been effectively combined in a single solution and typically require trade-offs. In today's modern world, efficiency, cost and compactness have become the dominating factors [4], [5], in the selection of appropriate topology. Making the power converters low profile and efficient opens the discussion of how to handle both issues simultaneously. Improvement in one issue increases the degree of complexity in the other. The power density of a converter is directly proportional to the switching frequency of the converter [6]. For instance, to improve the power density, reducing the component packages is required, as a consequence, the board size is reduced. This can only be achieved by increasing the switching frequency of the converter. However, the increased switching frequency increases the losses in the power devices and the magnetics such as switching loss, copper and core loss [7]. Moreover, high  $di/dt$  and  $dv/dt$  makes it difficult for the converter to qualify the electromagnetic interference (EMI) compliance testing.

The goal of efficient and better power density cannot be achieved using traditional hard switching since losses increase linearly as the frequency increases. In this regard, alternative soft switching techniques have been presented [8] to eliminate traditional hard switching. Soft switched power converters are increasingly replacing the traditional hard switched converters in most application areas ranging from a few watts to Megawatts. Generally, power converters are designed for an optimum range of operating conditions. The performance is also characterized for the optimum range. The performance degrades as the operating conditions cross this limit. In soft switched techniques, the most common approach is the utilization of intrinsic parasitic elements of the circuit components such as the leakage inductance and the junction capacitance. The value of intrinsic parasitic elements is usually not sufficient to maintain the soft switching characteristics for wider

range of input voltage and/or output load. This limits the scope of traditional soft switched power converters in today's industry. Presently, the requirement is the ability to handle wide variations on the input as well as on the output side. For example in electric vehicles (EV), the battery bank voltages varies from 200 to 450 V [9], and in photovoltaic applications the solar panel voltage varies from 125 to 550 V [10] [11], [12], therefore it requires a power converter capable of handling this wide range while maintaining the performance stable. In some applications like on-board chargers, charging of super capacitors and electric drives require a converter that can handle a wide variation in output voltage, where it is sometimes necessary that the system starts out from low voltage/high current to high voltage/low current.

## 1.2 Motivation

As mentioned, power converters are generally designed for nominal working conditions. Converters show desired performance while working under such conditions. The operational duty cycle is usually set to maximum at the minimal level of input voltage. As the supply voltage increases, to maintain the output voltage constant, the duty cycle needs to be decreased; this reduces the gain of the converter. A small duty cycle causes additional losses, such as loss of soft switching, more conduction loss and large ripple current, more ringing/overshoot and high electromagnetic interference (EMI). These drawbacks limit the operational range of power converters. Therefore, it makes difficult to meet the present industrial applications like automotive, dc grid, server stations, renewable energy and consumer products, which require power converters to have a stable performance over the entire operational voltage.

Another demand from the industry is for the power unit to have characteristics of a wide dc conversion ratio as well as fulfill the need of high reliability, high power density and stable efficiency [13]. Generally, power converters with wide output voltage range exhibit unstable performance compared to fixed voltage gain converters [14]. The most common approach for the extended range of voltage gain is a frequency modulated LLC power converter. LLC converters show optimum performance when operating at the resonant frequency, the switching frequency has to swing in a wide range to achieve extended voltage gain, this results in degraded overall performance [15]. Moreover, the voltage regulation of LLC converters is load dependent and is affected by circuit parameters like resonant capacitance and magnetizing/resonant inductance [16]. The other traditional solution used to

obtain a wide range of output voltage is the bench type variable output power supplies [17]. These solutions could be linear power supplies or switch-mode power supplies. However, none of the solutions meets the present requirement because of their bulkiness and lower efficiency. To meet the requirement of a wide range of output voltage, multiple power converters are usually stacked together, which increases the cost and complexity of the system [18]. Moreover, it degrades the reliability and efficiency of the overall system.

Traditional power converters are not able to meet the aforementioned requirements. Although some power converters propose optimum performance in a wide range of input voltage, the output voltage of the converters remains constant. Similarly, some have reported stable performance for a wider range of output voltage while keeping the input voltage constant. The focus of power engineers and scientists has been either on extending the operational range on the input side or the output side. Both problems have not so far been addressed together.

### **1.3 Literature review**

An extensive work is in progress to build power converters that fulfil the requirements of the industry. The focus is either improvement on the input side or on the output side. For example, in order to extend the range of input voltage/load in medium power applications, the range of zero voltage switching (ZVS) is usually increased either by increasing the intrinsic leakage inductance or by adding an inductor in series with the main transformer [11], [19], [20]. However the increased leakage inductance reduces the effective duty cycle, the consequences of which are an extended freewheeling interval, reduced gain, and high voltage spikes [21], [22]. A large amount of stored energy also results in a large circulating current, which increases the loss both in primary devices and in transformers. In [23]–[25], the circulating current is reduced by the addition of an auxiliary circuit. This resets the circulating current down to zero during the freewheeling period, and the converter enters into partial hard switching. To overcome this, zero current switching is proposed [25] for the lagging leg by the replacement of MOSFETs with IGBTs. However, the tail current associated with IGBTs becomes the main constraint in increasing the switching frequency of the converters [26]. This makes this approach less feasible for today's space constraint applications. In [27], [28], it is suggested that the ZVS range can be extended by increasing the magnetizing current. For this, a design of a transformer with reduced

magnetizing inductance is suggested. However, this increases the primary current, which adds more loss in primary devices and transformer. In [23], [29], an external inductor along with clamping diodes have been introduced to minimize overshoot on rectifiers. The clamping diode improves overshoot in secondary rectifiers, however, it results in excessive reverse recovery loss in rectifiers and clamping diodes and it further extends the freewheeling interval [30],[31]. The increased freewheeling interval also increases the interval of the flow of circulating current, which results in more conduction loss. In [32], adopting a control strategy according to the load conditions minimizes the circulating current loss only under light load conditions; moreover, it makes the design more complex. The addition of a boost capacitor in [33] reduces the conduction loss during the freewheeling interval, however, it narrows the range of ZVS

To extend the range of the output voltage, many research efforts [13], [17], [34]–[39] have been reported to widen the range of the output voltage. Most of the works are based on the variable frequency LLC power converters. In addition to various advantages, LLC converters have few limitations. The zero current switching in rectifiers is lost as the switching frequency crosses above the resonance frequency, which makes it hard to keep the output voltage constant [39]. The variable frequency operation further adds complexity regarding EMI. In [40], the secondary side phase shifted control is proposed to extend the range of the output voltage, however, the addition of buck, balance and boost modes makes the control complex.

## 1.4 Contribution of this thesis

The literature does describe solution that do meet the requirements of the industry to some extent, but there is still plenty of room for improvement. Moreover, most of the literature either addresses the range of the input side or the output side. For example, [18], [41]–[43] provide a solution for server power applications to reduce the size of the link capacitors during a hold-up time of approximately 20 ms. The performance of the converter is optimised only for the nominal operating range. This limits the scope of the proposal. [15], [44]–[46] reports an extended range of input voltage for photovoltaic and EV applications. Although they report stable performance over the extended range of the input voltage, the output voltage remains fixed. Similarly, the proposals [14], [16], [47] report a stable performance over the extended range of the output voltage, however, the input voltage remains fixed.

## Chapter 1: - Introduction

This thesis discusses a unique one-box solution to widen the range of both the input voltage and the output voltage, as well as keep the performance of the converter stable. The proposal not only keeps the performance stable for a wider range but also provides a flexible solution to control the gain of the converter. There are two reconfigurable modes on the input side and three reconfigurable modes on the output side, which together, depending on the application, can raise the gain to eight times higher than the base value. For fixed output and wide input applications, the gain of the converter can be optimized by using two modes for the input configuration. For wide output applications or applications where it is necessary for the system to start with low voltage and high current towards high voltage low current, the three reconfigurable modes available on the output side can be utilized. These modes can be configured manually or by pre-programming certain limits. The flexible reconfigurable structure extends the scope of application range. This simplifies the deployment of one design in other applications by programming it to new specifications.

### 1.5 Thesis outline

The thesis summarizes the outcome of the research omitting details regarding methodologies and results. For further details, please refer to the published/ submitted work. In addition to the introduction chapter, the work is outlined in the following chapters:

**Chapter 2** introduces the development of the proposal. It summarizes the published/ submitted articles in relation to their occurrence and contribution to the development.

**Chapter 3** partially covers the basic theory and concepts used in this research work. It also summarizes the methods used to achieve the outcome of the proposal.

**Chapter 4** presents a short discussion on the achievements/shortcomings of the work that has been done so far.

**Chapter 5** concludes the work presented in this thesis. It also presents suggestions for future work to further improve the work presented.

# 2 RESEARCH FORMULATION

This chapter summarizes the development of the research. It explains how the complete research proposal is divided into a number of research articles. As shown in Figure 2.1, the pieces of the research work have been shaped into the development of the main objective, the wide range isolated power converters (WIRIC). Each published work contributes to the main objective. Here, published articles have been summarized in terms of contribution to achieving the defined milestones. Moreover, for better understanding, the articles are prioritized in the order of set milestones.

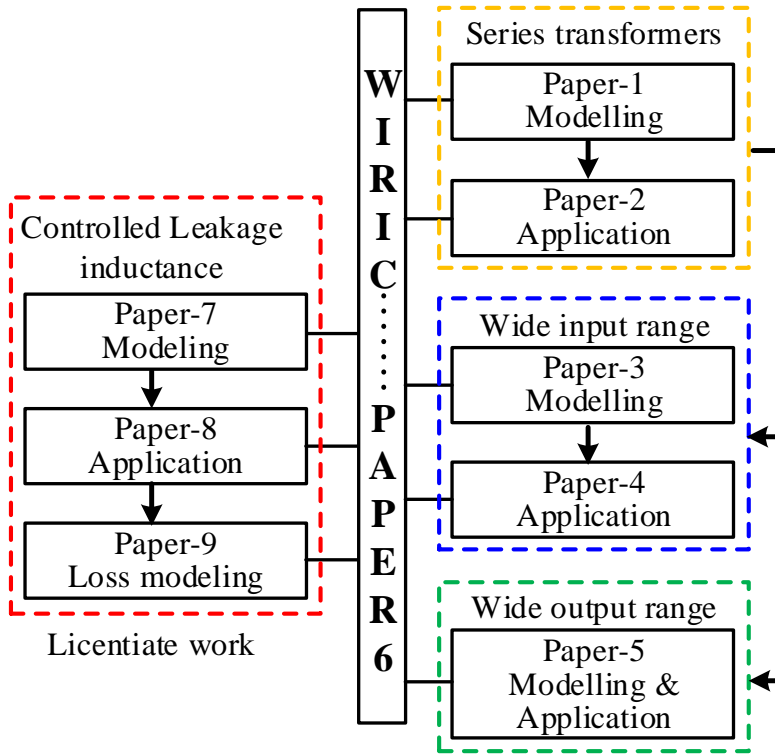
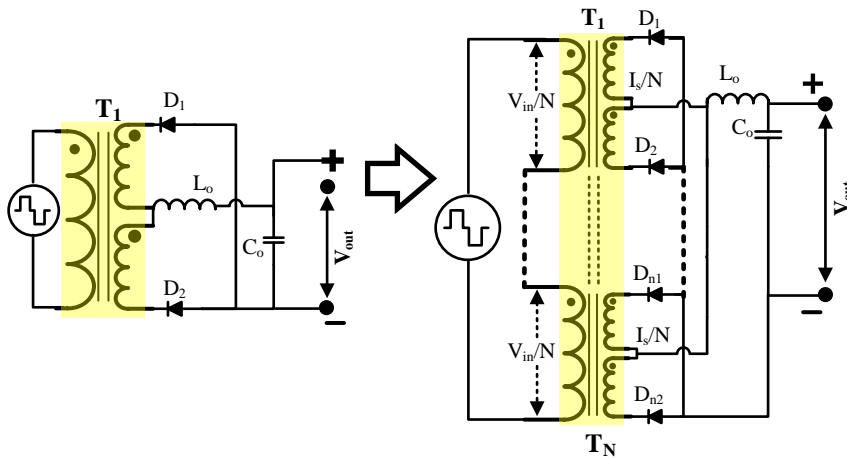


FIGURE 2.1 The tree describing the development of the main objective (WIRIC) - the research paper 6 is based on the contribution of each published work.

## 2.1 Paper-1 and 2, low profile transformers

The power transformer is an essential part of isolated power converters. It isolates the load from the input source. It is also one of the heaviest parts, as well as the part occupying the most space in the power converter. Therefore, the size of the power transformer is what mainly prevents a reduction of the volume of the power converters. The increased power level increases the volume and weight of the transformer, which makes it even more difficult for the converters to meet present industrial requirements. These articles addresses a solution to reduce the size and weight of the main transformer and ultimately reduce the volume and weight of the converter. Paper-1 proposes to split a single heavy volume into a number of small transformers, whereas, paper-2 discusses an application. The concept is shown in Figure 2.2.



**FIGURE 2.2 Transformation of a converter from a single transformer to several transformers.**

As seen, traditional single transformer is proposed to be split into a number of  $N$  transformers. On the primary side, the inter-connection of windings is suggested in series, whereas on the secondary side the windings are connected in parallel. With this configuration, the input voltage and the load divides into  $N$  transformers. This reduces the stress on the transformers, secondary rectifiers and filtering components. Therefore, the design of power converters by splitting the main transformer into number of transformers not only makes the converter low profile but also reduces the stress on the

transformer and on secondary side element, which simplifies heat management.

The concept is applied on an example application of a phase-shifted full bridge converter where the specifications are set as given in Table 2.1. An analytical comparison in terms of total transformer loss/weight is made for the design of the transformer either by using a traditional single transformer or splitting it into 2/4 transformers.

**TABLE 2.1 Specifications of the example application investigated in papers 1-2**

<b>Input voltage (<math>V_{in}</math>)</b>	400V <sub>dc</sub>
<b>Output Voltage (<math>V_{out}</math>)</b>	48V <sub>dc</sub>
<b>Load power (<math>P_{out}</math>)</b>	2.2kW
<b>Number of transformers (<math>N_T</math>)</b>	1, 2 and 4
<b>Core shape/material</b>	PQ/3C95
<b>Core size</b>	20, 32, 40

As a comparison of the contribution of total transformer loss in the example application, the configuration of four transformers shows better characteristics than the other two configurations. The comparison is shown in Figure 2.3, at 2kW load power. The sum of the loss of all the four transformers for the configuration  $T = 4$  is approximately 20% less than the traditional single transformer, and 10% less than the configuration with two transformers. The combined weight of all four PQ-20 cores is 45% lower than the weight of a single PQ-40 core. This helps to make the power converter compact and light-weight.

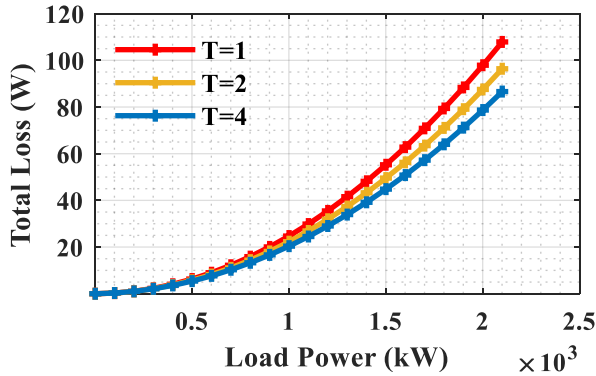
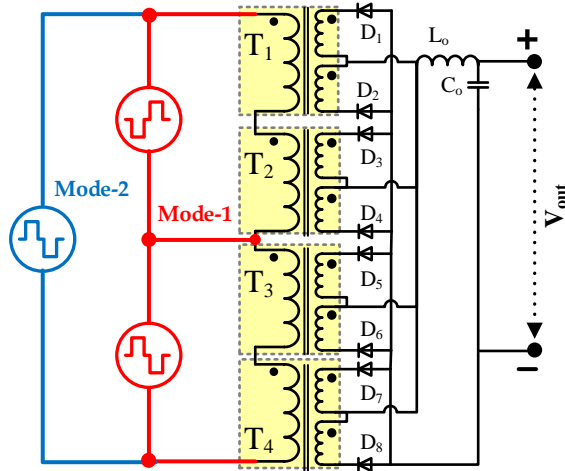


FIGURE 2.3 Comparison of the contribution of the total transformer loss in the example application, T=1 PQ40, T=2 PQ32 and T=4 PQ20.

## 2.2 Paper-3 and 4, wide input range

In Paper 3 and 4, a new concept has been introduced to make use of more than one transformers to extend the operational input range of power converters. Generally, the power converters are designed at minimal supply voltage, where the duty cycle is set to maximum. As the supply voltage increases, decreasing the duty cycle to regulate the output voltage is required; this reduces the gain of the converter. Small duty cycle causes additional losses such as extended freewheeling interval, higher circulating current, more conduction loss, large ripple current and higher electromagnetic interference. Paper 3 and 4 suggest a solution to overcome these problems. The solution adjusts the gain of the converter by reconfiguring the effective conversion ratio of the converter, which results in an extended range of input voltage. The proposed idea is shown in Figure 2.4.



**FIGURE 2.4 Conceptual diagram of a reconfigurable structure of transformers.**

Depending upon the operating conditions, transformers can be configured either all in series or in a combination of series/parallel. This makes it a dual mode configuration. When all four transformers are configured in series, it divides the input voltage by four, and when transformers are connected in series/parallel combination, it divides the input voltage by two. As a result, the effective transformer's conversion ratio turns out to be half of Mode-1 in Mode-2. This means that if the concept is applied in any converter application, the effective dc voltage gain of the converter also varies accordingly. In order to keep the output voltage constant, the duty cycle has to be increased in Mode-2. For example, if the converter is configured to operate in Mode-1 up to half of the maximum level of the input voltage and above half level in Mode-2, the duty cycle of the converter with the proposed configurations varies as plotted in Figure 2.5. To increase the input voltage from 100V to 400V, the reduction in duty cycle is 75% in a conventional converter, while it is 50% in the proposed converter. This helps to extend the operational range of power converters with the proposed configuration. The operation with higher duty cycle also improves the performance of the converter. It cuts the freewheeling interval, which minimizes the flow of the circulation current. The result of this is better switching characteristics and reduced conduction losses, which maintains the performance of the converter stable over an extended range of input voltage.

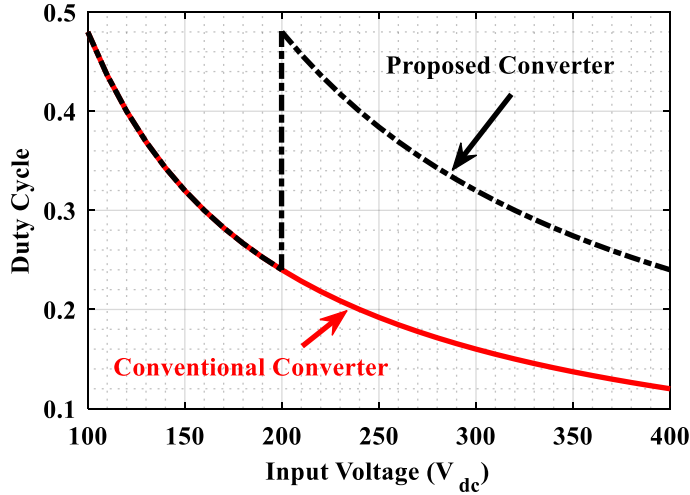


FIGURE 2.5 Comparison of duty cycle of the converter between the proposed structure and a conventional structure.

### 2.3 Paper-5, wide output range

There is also a growing demand for power converters with an extended range of output voltage. In many industrial applications, supercapacitors and electric vehicles for instance, different levels of voltage are required to power sub-systems. Power converters are generally designed for a fixed level of output voltage. Multiple power converters are stacked together to achieve different levels of output voltage. This degrades the reliability and performance of the system as well as adds additional cost and complexity. The concept of using multiple transformers in previous articles provides an opportunity to extend the range of output voltage. Therefore, in Paper 5, a new concept has been introduced to extend the range of the output voltage. The proposal is shown in Figure 2.6. By utilizing the availability of four transformers, four independent blocks of output voltage have been created. These blocks are isolated not only from the line voltage but also from each other. This resembles four batteries, which can be configured as either parallel or series. By using this strategy, a unique one-box solution has been suggested for the applications that require frequent switchover between different levels of output voltage. This strategy in combination with any converter application sets three reconfigurable modes to obtain the desired level of output voltage and current. For example, in case of high current demand, the

output voltage can be configured to  $X$  volt, whereas if medium current is demanded, it can be configured to  $2X$  volt, for high voltage and less current, the output voltage can be configured to  $4X$  volt.

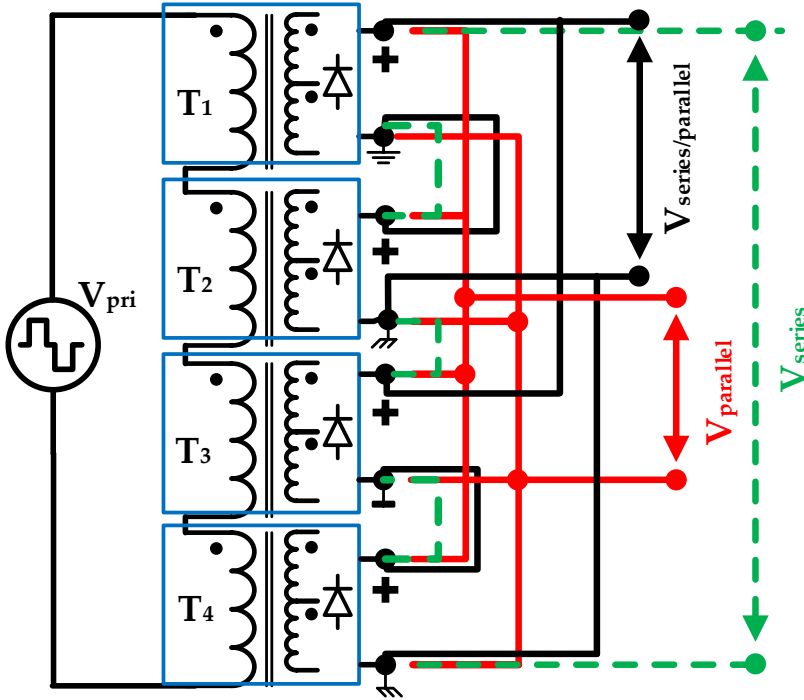


FIGURE 2.6 Conceptual diagram of four isolated blocks of the output voltage and arrangement of interconnections.

## 2.4 Paper-6, wide range isolated power converters (WIRIC)

By combining the ideas proposed in the previous five papers, another concept can be introduced as a solution for the industry to meet both present requirements, i.e., extended input voltage and extended output voltage. It shapes the proposed concept as a one size fits all solution. It could be a potential candidate for applications where a wide variation in line voltage is a prime concern, and different levels of output voltage are required. It

provides 2x3 reconfigurable modes that can be controlled either as a pre-programmed configuration or by connecting the converter with a terminal. As discussed, power converters are generally designed for nominal operating conditions, beyond this, the performance of the converter deteriorates. This is not acceptable for today's performance conscious industry. The converter using the proposed idea keeps the performance stable over wide variations in both input voltage and output voltage.

### **2.5 Paper-7, 8 and 9, Controlled leakage inductance**

These papers relate to previous work presented in the licentiate thesis that helped to recognise the importance of leakage inductance in transformers. The amount of leakage inductance plays a vital role in soft switched power converters. The energy stored in the intrinsic leakage inductance of the transformer is not usually sufficient to observe the zero voltage switching for the entire operating condition. In order to ensure ZVS, a shim inductor is added in series with the primary winding of the transformer to increase the total leakage inductance. This shim inductor adds extra cost to the design and reduces the power density of the board. These papers propose a solution to increase the amount of leakage inductance of the main transformer instead. A comprehensive method has been discussed to control the value of leakage inductance inside the main transformer.

# 3 THEORY AND METHODS

This chapter discusses the theory and methods used in this research work. A brief discussion regarding the theoretical background of the research work will be presented in a generalized way; only topics necessary to explain the research work have been selected.

## 3.1 Power converters

A power source is mandatory for each electronic device. It ranges from tiny wrist watches to huge warships. The main purpose of a power source is to condition the input source to meet the requirement of the loading device. It can be power storage units like batteries or a live power conversion unit. Live power conversion units can be classified as isolated power converters and non-isolated power converters. For safety reasons in offline applications, it is necessary to isolate the source from the load, therefore isolated power converters are a requirement for the commercial and consumer electronics industry. Any power converter consists of four essential parts: ac source filter, an isolation transformer, an output stage filter and a control unit. Depending on the control strategy, power converters can further be categorised into linear power converters and switched mode power converters.

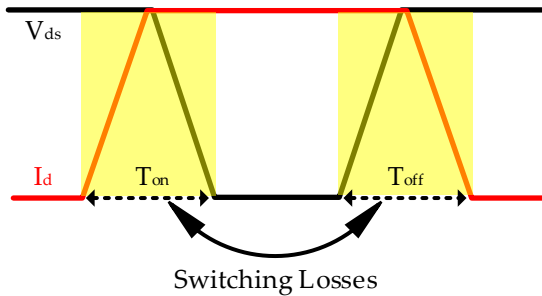
Linear power converters are mainly used in ground-based devices where heat, space and efficiency are not a primary concern. The main reasons behind the selection of linear power supplies are cost, short design time and, most importantly, the low noise and electromagnetic interference (EMI) issues. The main part of linear power converters is the linear regulator. The average efficiency of a linear regulator is about 30% to 50% [48]. Linear regulators can only be designed for one output voltage level and the output level is always less than the input levels. Hence, the rest of the energy dissipates in the form of heat.

Switched mode power converters is the most popular alternative for linear power converters, as these converters are more flexible, much smaller in size, light weight and more efficient. Switched mode power converters can easily be designed for multiple output levels, and it does not matter if the output level is higher or lower than input levels. There are many topologies such as flyback, push-pull and resonant available to design a switched mode power converter. Traditional switched mode power converters being hard-switched

cannot meet the present challenge of the industry because of increased de-rating factors such as losses due to hard switching, conduction losses and electromagnetic issues. These factors become severe with the increase in line voltage and load power. To overcome this, soft switched power converters observing zero voltage/zero current switching have been introduced.

### 3.2 Soft switching

Any real switching device requires finite time to completely turn ON or OFF. During the transition of the power switch from ON state to OFF state or vice versa, there are overlaps of the current and voltage [49], [50]. This type of transition is known as hard switching, shown in Figure 3.1, demonstrating a switching example of power MOSFET [51], [52]. In the overlap period, shown as the shaded area, the current rises to its final state before the drain voltage starts decreasing in the ON state. In the case of turn OFF transition, the drain voltage rises to its final state before the current starts to decrease. During these transitions, there is a loss of energy, which causes degradation of efficiency



**FIGURE 3.1. Hard switched MOSFET, typical waveform of drain current and voltage, and the overlapping regions of switching losses.**

In soft switching, the switch device voltage or current is reduced to zero before the switch is turned ON or OFF [50]. This reduces the stress on the switching device, resulting in a significant improvement of efficiency. This reduced stress allows the converter to operate at higher frequencies and within the limits of EMI. Two popular types of soft switching techniques are Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS).

### 3.2.1 Zero Voltage Switching (ZVS)

In ZVS, the signal to turn ON the gate of the MOSFET is applied when the drain-source voltage is zero. This way, the switching device turns ON at zero voltage, hence the zero switching losses. This switching technique is preferred for very high frequency converters [53].

### 3.2.2 Zero Current Switching (ZCS)

In ZCS, the drain current drops to zero before the power switch turns OFF, so there is zero turn OFF losses. This switching scheme is best applied in power converters using IGBTs due to a tail current at turn-OFF [53]. Figure 3.2 below explains the switching action in ZVS and ZCS.

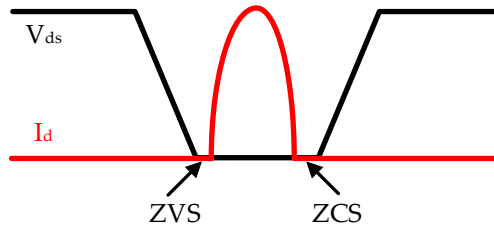


FIGURE 3.2. Soft switching

## 3.3 Leakage inductance

The leakage inductance is the inductance of the transformer, which is normally unwanted and a result of the imperfect linking of the flux between the windings of the transformer [54]. In real transformers, there is some flux that links with one winding but not the other windings of the transformer. This flux leaks into the air or by other mediums and is known as the leakage flux [55]. This flux leads to leakage inductance, which is the additional effective inductance in series with the windings [54]–[57]. The leakage inductance stores and releases magnetic energy, which normally leads to the system's undesirable behaviour. For example, high voltage and current spikes may cause device failure. The leakage inductance of the transformer could either be a desirable or undesirable component, depending on the application. For example, in communication circuits it is undesirable and needs to be as low as possible, whereas, in resonant power converters, it is utilized and

needs to be as high as possible to meet the requirement [54], [58]–[60] of achieving soft switched power conversion.

Along with the intrinsic capacitance of the power devices, oscillations are created to enable the power switch to turn ON when the voltage across the drain-source node is zero. The energy stored in the leakage inductance determines the ZVS operating range of the converter [61]. The converter observing ZVS in one state could enter hard switching for other operating conditions. For example, the phase shifted full bridge (PSFB) converter enters into the hard switching state when the drawn output power is reduced. It is also difficult to maintain the ZVS balanced in both legs of the converter. The value of leakage inductance needs to be controlled very intelligently to observe the ZVS for the entire operating condition.

### 3.4 Soft switched power converters

Soft switched power converters are classified as pulse width modulation (PWM) based converters and resonant technology-based power converters. Resonant power converters are the upgraded version of PWM-based power converters. Resonant power converters contain resonant L-C networks whose voltage and current waveforms vary sinusoidally during one or more subintervals of each switching period. These sinusoidal variations are large in magnitude, and the small ripple approximation does not apply. Some types of resonant converters:

- High frequency dc to ac inverters
- Resonant dc-dc converters
- Resonant inverters or rectifiers producing line-frequency ac converters.

This technology is becoming more popular in the application area where compact size and higher efficiency is required. However, resonant converters rely on frequency modulation (FM) to achieve voltage or current regulation instead of traditional pulse width modulation (PWM). Therefore, the input-to-output voltage gain of a resonant converter can no longer be derived from the inductor volt-second balance like PWM converters and becomes much more complex than a PWM converter. In addition, this converter design requires high professional skills, more time and eventually it will be more expensive.

A number of PWM-based soft switched power converters have been proposed, aimed at combining the desirable features of both the traditional PWM and resonant converters while avoiding their respective limitations. Amongst, the phase shifted full bridge (PSFB) converter is a more promising choice in medium power applications due to its soft switching of all power devices.

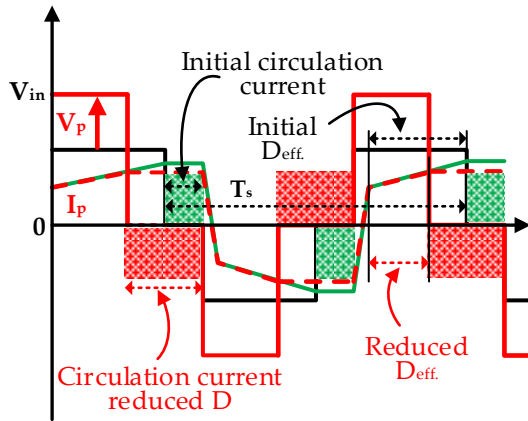
### **3.5 Phase shifted full bridge converters**

The phase shifted full bridge (PSFB) converter is the modified form of the conventional full bridge converter. In full bridge converters, both diagonal switches are turned ON/OFF simultaneously, which results in excessive switching losses, which further increases at high switching frequency. The performance deteriorates as the power level increases [87]; in soft switched full bridge converters, a phase shift control is implemented between the diagonal switches at constant frequency. This arranges the soft switching of power devices, which makes this converter the best candidate for reduced dynamic switching losses, better power conversion efficiency, and low electromagnetic interference. The control strategy of the PSFB converter is implemented in such a way that both the diagonal power switches turn ON/OFF one after the other. This introduces the concept of leading leg and lagging leg in phase shifted full bridge converters. In PSFB converters, the transformer leakage inductance, along with the intrinsic parasitic capacitance of the power devices, is generally used to switch the power devices when they are in the zero voltage state. Like the others, PSFB converters also have the problem of circulating current, which becomes worse with the increase in input voltage.

### **3.6 The concept of circulating current**

In pulse width modulation based power converters, there is a disadvantage in the form of circulating current, which flows through the transformer and the power devices during the freewheel intervals. The regulation of the output voltage in power converters is generally maintained by adjusting the operational duty cycle in line with the operating conditions. As shown in Figure 3.3, the duty cycle has to decrease when the line voltage increases. This extends the freewheeling interval where the primary current circulates through power devices. This circulating current is the sum of the magnetizing current and the output inductor current referred to the primary

side. During this interval, the input voltage  $V_p$  at the primary winding of the transformer effectively remains zero and there is no transfer of power; primary current circulates only through the primary devices. This contributes to the increase in conduction losses. The wider the freewheel interval the greater the loss. The useful intervals of a complete switching cycle are the intervals when power is delivered from the input side to the output side.



**FIGURE 3.3 Reduction of duty cycle with increase in input voltage.**

The same phenomena can be found in phase shifted full bridge converters. A typical timing diagram of a PSFB converter where both the leading leg and the lagging leg comprises of power devices  $S_a$ - $S_b$  and  $S_c$ - $S_d$  respectively, along with transformer primary voltage and current is shown in Figure 3.4. As seen, the power is transferred alternately from  $t_5$ - $t_6$  and  $t_{11}$ - $t_{12}$ . The rest of the time is referred to as a freewheeling interval. The only significant duration within this interval is the length of dead time between the devices of the same leg, which is required to ensure zero voltage switching of the devices. The primary current  $I_p$  circulates at its peak through power devices, which results in greater conduction loss.

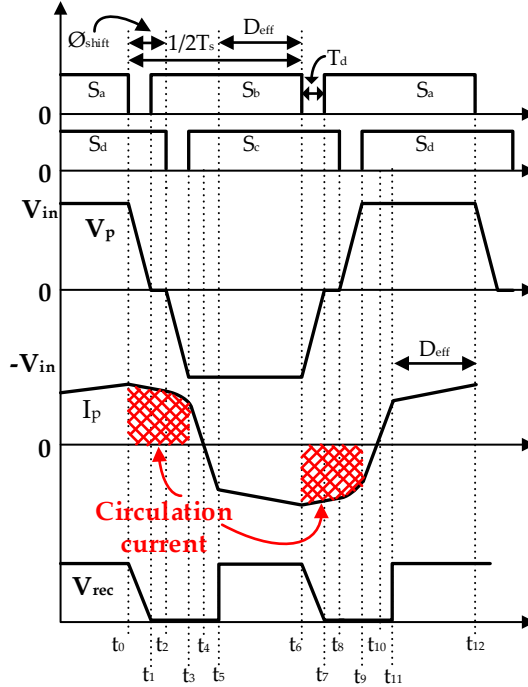
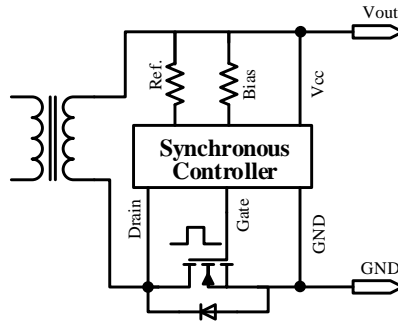


FIGURE 3.4 Typical waveform of a phase shifted full bridge converter.

### 3.7 Proportional gate drive control

To extend the range of the output voltage in the proposed concept, the output section of each transformer has been made electrically isolated. It means, the synchronous rectifiers of each block should also be isolated. To this end, an approach of proportional gate drive synchronous rectification is adopted in this work. This approach not only eliminates the need of an external gate driver for the synchronous devices but also minimizes the conduction time for the body-diodes [62]. This improves the efficiency and reduces the component count. It also simplifies the synchronous rectification by eliminating the necessity of external command signals. A typical application of proportional gate drive control for synchronous rectification is shown in Figure 3.5. The generated dc voltage provides the necessary power and biasing to the respective gate controller. This makes each block of the synchronous rectification completely isolated. The drain sense terminal of the controller constantly monitors the drain-source voltage of the synchronous

device. As the voltage on the secondary winding goes negative, the body diode of the synchronous device becomes forward biased. The moment drain voltage reaches a threshold voltage set by the controller; a positive voltage is applied on the gate of the synchronous device. The controller starts sourcing the current and turns ON the device. The applied voltage on the gate becomes proportional to the drain-source voltage of the device. This keeps the device turned ON for the majority of the cycle and minimizes the conduction loss due to the body diode. When drain current decays, the drain-source voltage also decays, this in turn, decreases the applied gate-source voltage to turn OFF the synchronous device.



**FIGURE 3.5** Typical circuit of synchronous rectification with proportional gate drive controller.

### 3.8 Methodologies used

The main objective of this research is to propose a low profile dc-dc converter that fulfils both the need of wide input range and wide output range. The main objective of the research is divided into four main sections. These can be classified as:

1. Splitting the big volume of a single transformer into a number of small transformers.
2. Extending the range of input voltage.
3. Building electrically isolated blocks of secondary voltage of each transformer.
4. Extending the range of output voltage.

By combining all these sections with the necessary control strategy results in the final objective: the wide range isolated converter (WIRIC). Here each section requires a different set of methods. Therefore, four different methods have been implemented to make the whole research work a single entity. The methods adopted for each will be explained separately in the following discussion.

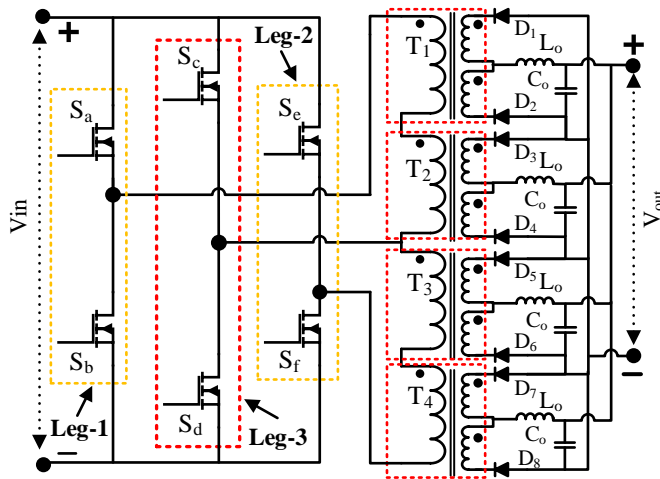
### **3.8.1 Transformer section**

In any power converter application, the power transformer occupies a significant volume, and it is the heaviest part in the converter. This section describes the methodology of how a single large volume has been split into a number of small transformers. The power handling capability of a transformer depends on the type and characteristics of the core material as well as the physical geometry, i.e. the area and length of the magnetic path. Furthermore, the choice of appropriate core geometry for the intended specification always needs a number of iterations throughout the design phase. The design procedure of the transformer consists of a few general considerations, for example the selection of core material, size, and form of the core, winding space and the diameter of the wires. Each consideration requires many iterations to meet the goal of acceptable performance. The first measure is the choice of appropriate size of the transformer for the intended application. To make the implementation simple, a generalized methodology has been adopted to estimate the initial size of the transformer. The effective geometry of the core geometry,  $K_{gfe}$  [55] has been evaluated for the specifications of the intended application. Then the volume is split into a number of small transformers, e.g., two and four transformers. The required flux density and the respective winding turns have been calculated for each case. The iterative script is implemented in Matlab and the necessary parameters like effective volume, copper's ac resistance, core and copper loss have been calculated. Finally, a comparison is made of the use of a single, two and four transformers.

### **3.8.2 Extended range of input voltage**

In wide input range power converters, the performance of the converter declines when it has to operate with a low duty cycle at higher input voltage. It adds more circulating current and ringing. This results in increased losses and EMI. To overcome this, the proposed work adopts a methodology to keep the operational duty cycle high for a wider range of the input voltage. The

effective gain of the converter is controlled according to the changes in the line voltage. This idea is implemented in a phased shifted full bridge converter. In addition to the traditional two legs, i.e., a leading leg and a lagging leg, a third leg has been introduced. The modified converter along with the configuration of four transformers is shown in Figure 3.6. The third leg in combination with the use of different transformer configurations operates the converter in dual mode. Each mode sets the effective gain of the converter differently. For example, in one mode, it configures two-series transformers in parallel and in the other mode, it configures all four transformers in series. This sets the effective gain in mode one two times higher than the gain in the other mode. Consequently, the duty cycle has to be set to high when all four transformers are configured in series. Therefore, the converter can be programmed to set all transformers in series when the line voltage increases above a certain limit. Contrary to the traditional converter, it keeps the duty cycle high over a wide range of the input voltage.



**FIGURE 3.6** Diagram of the proposed circuit for the extended range of input voltage.

### 3.8.3 Isolated secondary voltage of each transformer

In order to electrically isolate each transformer's output voltage, independent synchronous rectification of the secondary winding of each transformer is required. For this, a proportional gate drive control is adopted. Four independent gate drive controls have been implemented for the rectification of secondary voltage of each transformer. It makes four independent blocks of the output voltage.

### 3.8.4 Extended range of output voltage

The range of the output voltage is extended by arranging the electrically isolated output blocks of all four transformers in series or parallel in response to the demands of the operating conditions. This is arranged by using nine active switches. The most important consideration in the placement of these switches is preventing any risk of short-circuit. For this, electrically isolated gate drivers have been installed for each switch. The placement of all nine switches is shown in Figure 3.7. This arrangement along with the appropriate control strategy provides the base for three possible configurations of blocks of the output voltage. The first option is to configure all four blocks in parallel; the second is to configure all four blocks in series. The third option is to configure block 1-block 2 and block 3-block 4 first in series and then in parallel, i.e.,  $(Out1+Out2) \parallel (Out3+Out4)$ . This way the output voltage can be

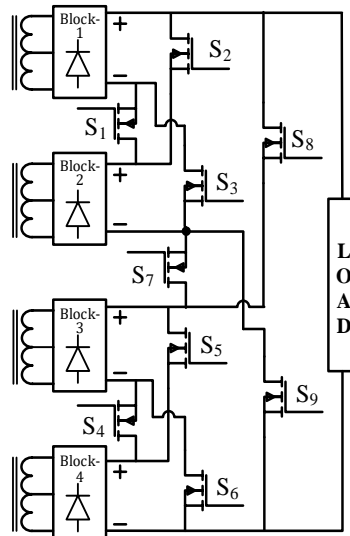


FIGURE 3.7 Proposed circuit for the extension of output voltage.

raised from base voltage  $X$  to  $2X$  and  $4X$ . Besides, the output voltage can further be adjusted in between these steps to meet the desired level.

### **3.8.5 Wide range isolated converter (WIRIC)**

By combining the previous four methods into a single entity, a novel isolated power converter with extended range of both input voltage and output voltage is developed, offering more flexibility than existing solutions. All the four sections have been implemented on a single printed circuit board. Low profile circuit elements such as power devices, transformers, inductors and capacitors have been selected to combine all sections on a single board. Furthermore, the transformers have been shaped in the form of a planar transformer structure. In order to implement the operational and features control, a simplified control method has been adopted as a proof of concept. A control strategy in combination with a digital signal processor and digital multiplexers has been employed. For the extended input section, pulse width modulated control is cloned on power devices by using four channels of multiplexers. Similarly, the extended range of the output voltage is achieved by the controlled signal provided on the gates of the active switches. The control strategy has been implemented on a separate printed circuit board, then the boards have been joined together by using a plug-in type connector. The complete concept of WIRIC is shown in Figure 3.8, which shows all the sections and the control. As shown in Figure 3.9, the concept is evaluated by designing a prototype. The components are assembled inside the module, so that the module could be kept cool by placing heat sinks on top and bottom side of the module.

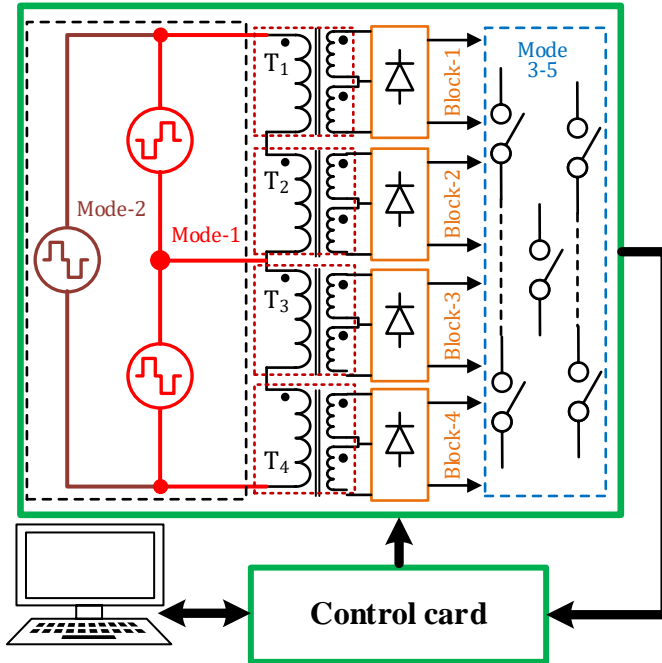


FIGURE 3.9 Diagram of the proposed wide range isolated converter, (WIRIC), showing inter-connection of all the four sections.

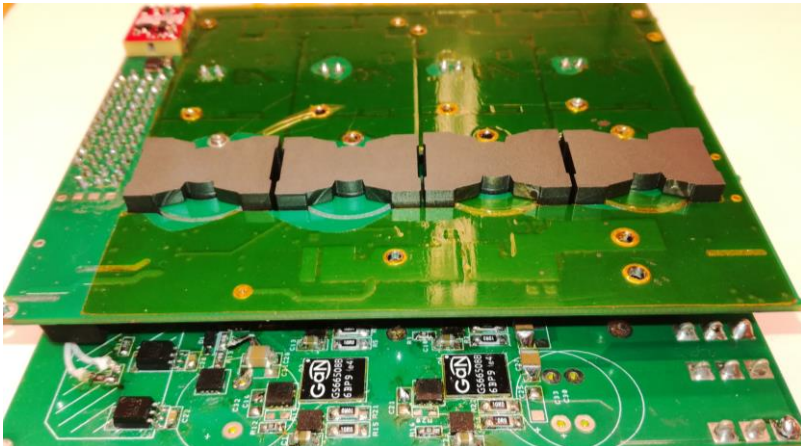
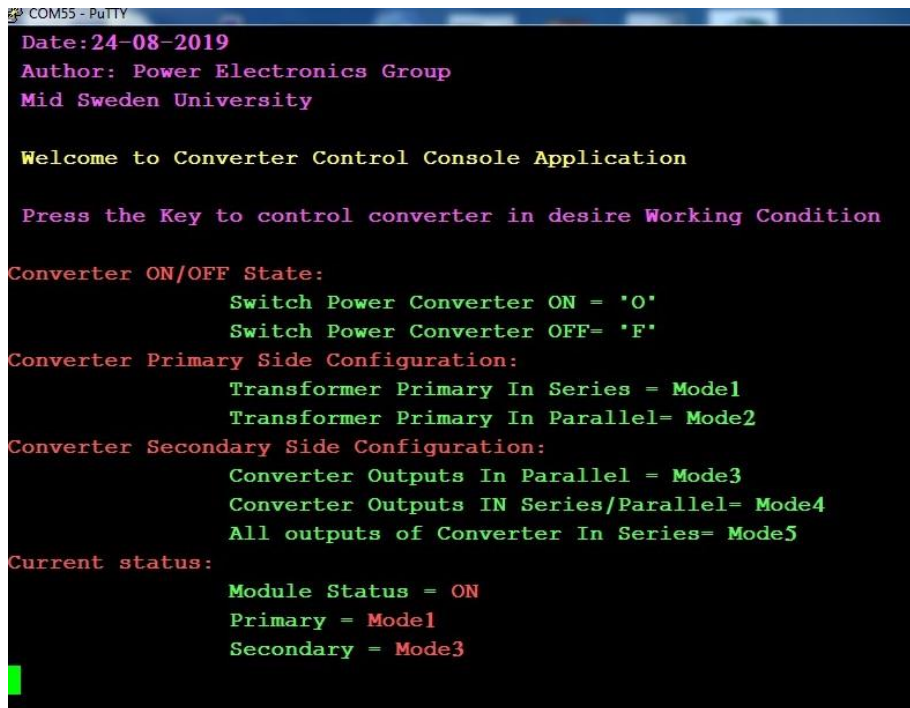


FIGURE 3.8 Picture of the power module, two separate boards have been joined together.

### Chapter 3: - Theory and Methods

In order to verify the proposed features of the converter, a PC based generalized user interface is implemented in the control board. All features of the converter have been characterised by using this user interface. A screen shot of the user interface is shown in Figure 3.10. It provides the flexibility to switch between different functionalities.



```
COM55 - PuTTY
Date:24-08-2019
Author: Power Electronics Group
Mid Sweden University

Welcome to Converter Control Console Application

Press the Key to control converter in desire Working Condition

Converter ON/OFF State:
    Switch Power Converter ON = 'O'
    Switch Power Converter OFF= 'F'
Converter Primary Side Configuration:
    Transformer Primary In Series = Mode1
    Transformer Primary In Parallel= Mode2
Converter Secondary Side Configuration:
    Converter Outputs In Parallel = Mode3
    Converter Outputs IN Series/Parallel= Mode4
    All outputs of Converter In Series= Mode5
Current status:
    Module Status = ON
    Primary = Mode1
    Secondary = Mode3
```

FIGURE 3.10 Screen shot of the graphical user interface (GUI) to verify the features of the proposed concept.

# 4 DISCUSSION

This chapter discusses the results based on the experimental/ simulation investigations. The whole research is characterised as a single stand-alone system. The concept is verified by using two different platforms. One is a modelling of the system on a SPICE-based simulation platform and the other is the experimental platform. The whole system is modelled for an example application of a dc-dc power converter, where the specifications are: input voltage = 100-400V<sub>dc</sub>, output voltage = 24-96V<sub>dc</sub>, and the load power = 1kW. Then each feature of the proposed converter is characterised both in a computer simulation and experimental work. The specifications of the prototype along with key circuit components are listed in Table 4.1.

**TABLE 4.1 Specifications and list of key components of the WIRIC**

SYMBOL	QUANTITY	VALUE
$V_{in}$	Input voltage	100-400V <sub>dc</sub>
$V_{out}$	Output voltage	24-96V <sub>dc</sub>
$P_{out}$	Load power	1kW
$f_s$	Switching frequency	200 kHz
$S_A-S_F$	Power devices	GS66508B
	Gate driver	LM5114
	Synchronous MOSFET	BSC350N20
	Synchronous controller	ZXGD3107
$DSP$	Microchip's dsPIC	Dspic33fj16gs
$Transformers$	Core shape/ size/ material	PQ 20/20/3C95
$L_p/L_s$	Primary/ secondary inductance	190/3μH
$L_{kp}/L_{ks}$	Primary/secondary leakage inductance	2.8/0.05μH
$R_{ac}$	Primary/ secondary winding ac resistance	120/10 mΩ
$N_p: N_s: N_s$	Primary to secondary turn ratio	2:1:1
$L_o$	Output filter inductor	4.7μH
$C_o$	Output filter capacitor	68μF
$S_1-S_9$	Output control switches	SIR872A

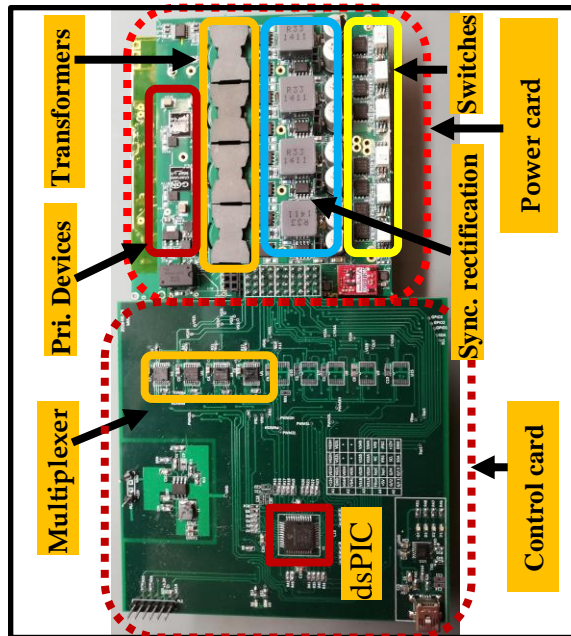


FIGURE 4.1 Component view of the converter showing both the power card and the control card.

#### 4.1 Gain of the converter

The proposed idea provides a unique one size fits all solution for the industry. The provision of reconfigurable features to extend the range of line voltage and output voltage makes it convenient to fit the solution in a wide range of applications. The reconfigurable structure controls the dc gain of the converter, which can be adopted according to the application. Two reconfigurable modes are available on the input side and three reconfigurable modes on the output side. Each mode sets the dc gain according to the configuration of circuit elements. The multiplication factor for the dc gain of the converter for each configuration of input/output modes is tabulated in Table 4.2. Here, the reference configuration of both the input side and the output side is mode-2/mode-3, where the gain is taken as unity. This configuration arranges all the transformers in series on the primary side and all blocks of the output voltage are parallel on the secondary side. Mode-4 arranges blocks of the output voltage both in series and parallel configuration,

whereas mode-5 configures all blocks in series. The dc gain can be made eight times high by configuring the converter to mode-1/mode-5.

**TABLE 4.2 Multiplication factors for calculation of the gain of the converter in each operational mode**

STATUS OF PRIMARY SECTION	STATUS OF OUTPUT CONTROL SECTION	GAIN MULTIPLE
MODE 2	Mode 3	1
	Mode 4	2
	Mode 5	4
MODE 1	Mode 3	2
	Mode 4	4
	Mode 5	8

## 4.2 Characterisation—input section

The availability of dual modes on the primary side of the converter extends the range of input voltage. This is accomplished by the switchover of operational modes of the converter in line with the level of input voltage. The switchover keeps the operational duty of the converter high, which allows an extension of the operational range without compromising the performance of the converter. In conventional power converters, the working of the converter with a low duty cycle at a higher level of operational input voltage results in more circulating current, which degrades the performance. A comparison of the conventional and the proposed converter’s length of flow of circulating current in a half-period of the cycle is shown in Figure 4.2. In the example application, the full range of the input voltage is divided into two operational modes, i.e., 100-200V mode-1/mode-3 and 200-400V to mode-2/mode-3. As seen, the switchover of modes in the proposed converter reduces the length of flow of the circulating current. For example, at the maximum level of input voltage  $V_{in} = 400V$ , the duration of the flow of circulation current is approximately 25% less compared to the duration in the conventional

converter. This is obtained because the proposed concept changes the effective gain of the converter. In mode-2/mode-3, the effective gain becomes half of the gain in mode-1/mode-3. Eventually, the duty cycle has to increase in order to maintain the operating conditions. Figure 4.3 demonstrates that the proposed converter keeps the operational duty cycle the same in both modes despite the wide variation in input voltage.

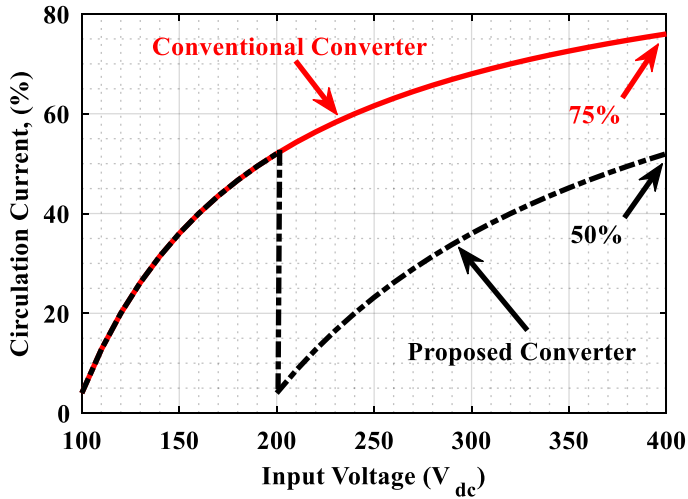


FIGURE 4.2 Comparison of the flow of circulating current in a half period of the switching cycle.

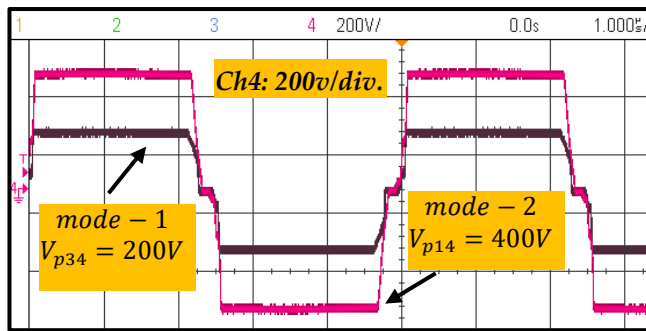
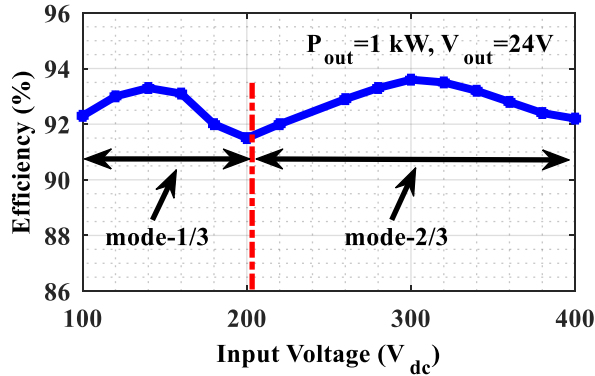


FIGURE 4.3 Demonstration of keeping the operational duty cycle high despite the 100% variation in line voltage, working modes are mode-1/mode-3 and mode-2/mode-3.

The figure shows the input voltage as the bridge voltage at the primary side of the converter; the operational duty of the converter remains constant even though the input voltage changes from 200V to 400V and vice versa. The operation of the converter with a higher duty cycle keeps the performance stable over the complete range of input voltage.

Figure 4.4 shows the performance of the example application of the converter for the variation in input voltage. As seen, the proposed converter maintains the efficiency stable for a wide range of input voltage. For  $V_{in}=100\text{--}200\text{V}$  the converter operates in mode-1/mode-3, as the input voltage increases, the efficiency drops because of the reduced duty cycle. For  $V_{in} > 200\text{V}$ , the converter reconfigures to mode-2/mode-3 and resets the duty ratio to high again, which results in improved efficiency. The specifications set in this example application can easily be modified to meet the requirements of other applications.



**FIGURE 4.4 Performance of the converter over the full range of line voltage.**

In addition to the stable performance over the wide range, the use of more than one transformer connected in series reduces the stress on each transformer by the number of transformers. This spreads the total transformer loss into number of transformers, which minimizes heat management efforts. The example application of the proposed converter consists of four transformers; this reduces the stress on each transformer by a factor of two in mode-1 and by a factor of four in mode-2. Figure 4.5 shows an example of a demonstration simulated in LTspice software during the operation of the converter in mode-2/mode-3. The primary windings of all four transformers  $T_1\text{--}T_4$  connected in series, and the input voltage to all transformers is

$V_{p14} = 400V$ . As seen, the stress on each transformer is reduced to  $V_{in}/4$ . This means that the voltage across each transformer is 100V.

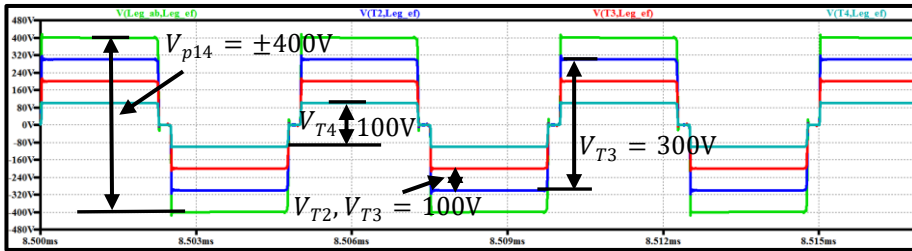


FIGURE 4.5 Demonstration of the voltage stress on each transformer.

### 4.3 Characterisation—output section

The output section of the proposed converter consists of three additional modes that are used to configure the isolated blocks of the output voltage in order to meet the requirements of a variety of applications, such as applications that require a low voltage/high current and applications that require a high voltage/low current. Here the modes are called mode-3, mode-4 and mode-5. As explained earlier, the example application contains four transformers providing four isolated blocks of the output voltage. In mode-3, all blocks are configured in parallel, mode-4 connects a pair of two blocks in series and then arranges them in parallel, and mode-5 arranges all four blocks in series. With the utilization of this arrangement, three steps of the output voltage can be obtained. In this case, the output voltage from the base voltage of 24V can be stepped up to 48V and 96V. The performance of the converter is recorded separately for both the input modes and for each configuration of the output control section. A performance comparison is shown in Figure 4.6. Each configuration reports similar performance. The efficiency of the converter remains stable when the output voltage switches between modes 3-5. The involvement of more devices in mode-1/mode-3 configuration show slightly higher losses than in mode-2/mode-3. Similarly, the use of more switches in mode-3 slightly reduces efficiency as compared to mode-4 and mode-5. A plot of efficiency over the full range of output voltage 24-96V<sub>dc</sub> has also been plotted in Figure 4.7. As seen the converter shows stable performance over the wide range of output voltage.

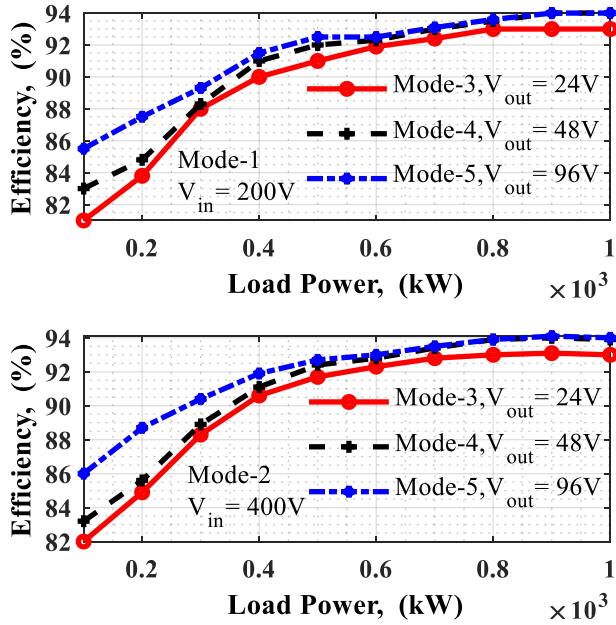


FIGURE 4.6 Performance of the converter for all three modes 3-5 of output voltage against both configurations of the primary side.

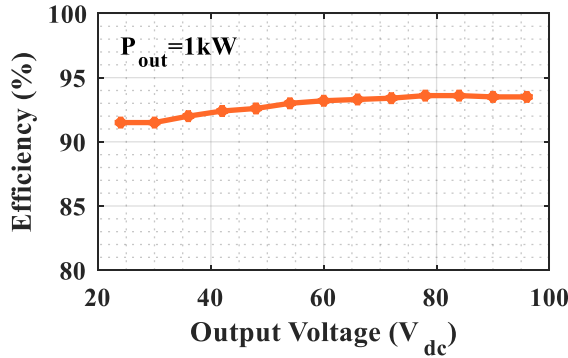


FIGURE 4.7 Performance characteristics of the converter over the full range of output voltage.

#### **4.4 Design considerations/ limitations**

There are a few considerations that need to be addressed in the design phase.

1. The multiple transformers in the proposed concept need to be installed carefully. A balanced flow of flux in each transformer is important to obtain the intended functionality. Although the primary windings of all transformers are connected in series, which ensures even flow of primary current through all transformers [63], an unbalanced air-gap can cause problems. The effect could be minimised by exerting equal pressure on the cores of each transformer during the assembly process to ensure that each transformer has the same air-gap.

2. Another important consideration is the switchover of modes. During the switchover of modes, most of the devices change status from OFF state to ON state. The risk of inrush current during the status switchover could destroy the device. The selection of device should be made by considering the possibility of occurring high voltage/current spikes.

3. The presented concept provides a one size fits all solution to the industry. There are two operational modes on the input side and three on the output side. Each mode has its own operational parameters. The effective circuit parameters also change in each mode. To accommodate all this, an intelligent control strategy is required, which can adapt the new control parameters according to the chosen mode of operation.

## **5 CONCLUSION AND FUTURE WORK**

The proposed concept has been successfully demonstrated in an example application of a power converter. It demonstrates stable performance over a wide range of input and output voltage. It keeps the operational duty cycle high for an extended range of the input voltage as compared to the traditional converter, which improves performance over a wide range of input voltage. By combining reconfigurable features of the proposal, the dc gain of the converter can be extended to 4 or 8. By using the flexible reconfigurable structure, the gain can be adjusted depending on loading conditions like high-voltage/ low-current and vice versa. Similar to stable performance for an extended range of input voltage, it also reports stable performance over an extended range of output voltage. The reconfigurable structure along with stable performance for the extended range of both the input side and the output side broadens the scope of the proposal for a variety of applications. Besides, the use of several transformers divides the load power among multiple elements on the secondary side, which allows the use of low profile elements and simplifies heat management. This can further help to build a low profile power converters to meet the requirements of the present space-conscious industry.

Although the concept shows satisfactory results, an intelligent control strategy is required before implementing it in a commercial application. As a part of future work, an adaptive control strategy is planned to make it commercial. After that, the approach will be extended in bi-directional applications. Additional investigations on how the gain of the converter can further be extended linearly could also be a part of future work.



## REFERENCES

- [1] I. Demirel and B. Erkmen, "A very low-profile dual output LLC resonant converter for LCD/LED TV applications," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3514–3524, 2014, doi: 10.1109/TPEL.2013.2278715.
- [2] C. D. Ward and C. W. Sohns, "Electronic component obsolescence," *IEEE Instrum. Meas. Mag.*, vol. 14, no. 6, pp. 8–12, 2011, doi: 10.1109/MIM.2011.6086892.
- [3] P. Corcoran, "Change and the Consumer Electronics Industry," *IEEE Consum. Electron. Mag.*, vol. 1, no. 4, pp. 3–16, 2012, doi: 10.1109/MCE.2012.2207509.
- [4] S. Ji, D. Reusch, and F. C. Lee, "High-frequency high power density 3-D integrated gallium-nitride-based point of load module design," *IEEE Trans. Power Electron.*, vol. 28, no. 9, pp. 4216–4226, 2013, doi: 10.1109/TPEL.2012.2235859.
- [5] D. Reusch, "High Frequency , High Power Density Integrated Point of Load and Bus Converters Electrical Engineering High Frequency , High Power Density Integrated Point of Load and Bus Converters," 2012.
- [6] B. Dc, D. C. Converter, W. Transformer, S. Jeon, and G. Cho, "A Zero-Voltage and Zero-Current Switching Full," vol. 16, no. 5, pp. 573–580, 2001.
- [7] J. Dudrik and J. Oetter, "High-frequency soft-switching DC-DC converters for voltage and current DC power sources," *Acta Polytech. Hungarica*, vol. 4, no. 2, pp. 29–46, 2007.
- [8] N. H. Kutkut, D. M. Divan, and R. W. Gascoigne, "Improved full-bridge zero-voltage switching PWM converter using a two-inductor rectifier," *IEEE Trans. Ind. Appl.*, vol. 31, no. 1, pp. 119–126, 1995, doi: 10.1109/28.363041.
- [9] X. Sun, X. Li, Y. Shen, B. Wang, and X. Guo, "Dual-Bridge LLC Resonant Converter With Fixed-Frequency PWM Control for Wide Input Applications," *IEEE Trans. Power Electron.*, vol. 32, no. 1, pp. 69–80, Jan. 2017, doi: 10.1109/TPEL.2016.2530748.
- [10] Q. Cao, Z. Li, and H. Wang, "Wide Voltage Gain Range LLC DC/DC Topologies: State-of-the-Art," in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, 2018, pp. 100–107, doi: 10.23919/IPEC.2018.8507899.
- [11] X. Sun, X. Li, Y. Shen, B. Wang, and X. Guo, "Dual-Bridge LLC Resonant Converter with Fixed-Frequency PWM Control for Wide Input Applications," *IEEE Trans. Power Electron.*, vol. 32, no. 1, pp. 69–80, 2017, doi: 10.1109/TPEL.2016.2530748.
- [12] H. Li, W. Zeng, L. Zhao, and S. Liu, "Dual mode modulation method for the full-bridge converter operating in a wide input voltage range," *Electron. Lett.*, vol. 52, no. 6, pp. 470–471, 2016, doi: 10.1049/el.2015.3655.
- [13] M. Kim, H. Jeong, B. Han, and S. Choi, "New Parallel Loaded Resonant Converter With Wide Output Voltage Range," *IEEE Trans. Power Electron.*, vol. 33, no. 4, pp. 3106–3114, Apr. 2018, doi: 10.1109/TPEL.2017.2706360.

- [14] Y. Lu, H. Wu, B. Tu, M. Li, Y. Xia, and Y. Xing, "Ultra-Wide Output Voltage Range Power Supply Based on Modular Switched-Converter Principle," *IEEE Trans. Power Electron.*, vol. 35, no. 1, pp. 94–106, Jan. 2020, doi: 10.1109/TPEL.2019.2912724.
- [15] H. Wang, M. Shang, and D. Shu, "Design Considerations of Efficiency Enhanced LLC PEV Charger Using Reconfigurable Transformer," *IEEE Trans. Veh. Technol.*, vol. 68, no. 9, pp. 8642–8651, Sep. 2019, doi: 10.1109/TVT.2019.2930551.
- [16] Z. Li, B. Xue, and H. Wang, "An Interleaved Secondary-Side Modulated LLC Resonant Converter for Wide Output Range Applications," *IEEE Trans. Ind. Electron.*, vol. 67, no. 2, pp. 1124–1135, Feb. 2020, doi: 10.1109/TIE.2019.2897507.
- [17] P. Sun, L. Zhou, and K. M. Smedley, "A reconfigurable structure DC-DC converter with wide output range and constant peak power," *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2925–2935, 2011, doi: 10.1109/TPEL.2011.2129576.
- [18] Bo Yang, Peng Xu, and F. C. Lee, "Range winding for wide input range front end DC/DC converter," in *APEC 2001. Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.01CH37181)*, 2002, vol. 1, pp. 476–479, doi: 10.1109/APEC.2001.911689.
- [19] D. Liu, Y. Wang, F. Deng, Q. Zhang, and Z. Chen, "Zero-Voltage Switching Full-Bridge T-Type DC/DC Converter with Wide Input Voltage Range and Balanced Switch Currents," *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10449–10466, 2018, doi: 10.1109/TPEL.2018.2800902.
- [20] R. Baranwal, G. F. Castelino, K. Iyer, K. Basu, and N. Mohan, "A Dual-Active-Bridge-Based Single-Phase AC to DC Power Electronic Transformer with Advanced Features," *IEEE Trans. Power Electron.*, vol. 33, no. 1, pp. 313–331, 2018, doi: 10.1109/TPEL.2017.2669148.
- [21] H. K. Yoon, S. K. Han, E. S. Choi, G. W. Moon, and M. J. Youn, "Zero-voltage switching and soft-commutating two-transformer full-bridge PWM converter using the voltage-ripple," *IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1478–1488, 2008, doi: 10.1109/TIE.2007.911923.
- [22] D. S. Wijeratne and G. Moschopoulos, "A ZVS-PWM full-bridge converter with reduced conduction losses," *IEEE Trans. Power Electron.*, vol. 29, no. 7, pp. 3501–3513, 2014, doi: 10.1109/TPEL.2013.2278695.
- [23] C.-Y. Lim, Y. Jeong, and G.-W. Moon, "Phase-Shifted Full-Bridge DC-DC Converter With High Efficiency and High Power Density Using Center-Tapped Clamp Circuit for Battery Charging in Electric Vehicles," *IEEE Trans. Power Electron.*, vol. 34, no. 11, pp. 10945–10959, Nov. 2019, doi: 10.1109/TPEL.2019.2899960.
- [24] Y. Jang and M. M. Jovanović, "A new PWM ZVS full-bridge converter," *IEEE Trans. Power Electron.*, vol. 22, no. 3, pp. 987–994, 2007, doi: 10.1109/TPEL.2007.897008.
- [25] X. Wu, X. Xie, C. Zhao, Z. Qian, and R. Zhao, "Low Voltage and Current Stress ZVZCS Full Bridge DC-DC Converter Using Center Tapped Rectifier Reset,"

- IEEE Trans. Ind. Electron.*, vol. 55, no. 3, pp. 1470–1477, Mar. 2008, doi: 10.1109/TIE.2007.911921.
- [26] Z. Guo, K. Sun, and L. Zhang, “Analysis and Evaluation of Dual Half-Bridge Cascaded Three-Level DC-DC Converter for Reducing Circulating Current Loss,” *IEEE J. Emerg. Sel. Top. Power Electron.*, vol. 5, no. 1, pp. 351–362, 2017, doi: 10.1109/JESTPE.2016.2604853.
- [27] K. D. Papastergiou and D. E. Macpherson, “An Airborne Radar Power Supply With Contactless Transfer of Energy—Part I: Rotating Transformer,” *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2874–2884, Oct. 2007, doi: 10.1109/TIE.2007.902044.
- [28] G.-B. Koo, G.-W. Moon, and M.-J. Youn, “Analysis and Design of Phase Shift Full Bridge Converter With Series-Connected Two Transformers,” *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 411–419, Mar. 2004, doi: 10.1109/TPEL.2003.823193.
- [29] R. Redl, N. O. Sokal, and L. Balogh, “A Novel Soft-Switching Full-Bridge DC/DC Converter: Analysis, Design Considerations, and Experimental Results at 1.5 kW, 100 kHz,” *IEEE Trans. Power Electron.*, vol. 6, no. 3, pp. 408–418, 1991, doi: 10.1109/63.85909.
- [30] Q. Chen *et al.*, “Phase-shifted full-bridge PWM converter with clamping diodes and current transformer,” *PESC Rec. - IEEE Annu. Power Electron. Spec. Conf.*, pp. 2403–2409, 2008, doi: 10.1109/PESC.2008.4592301.
- [31] Y. Shen, X. Sun, W. Li, X. Wu, and B. Wang, “A Modified Dual Active Bridge Converter with Hybrid Phase-Shift Control for Wide Input Voltage Range,” *IEEE Trans. Power Electron.*, vol. 31, no. 10, pp. 6884–6900, 2016, doi: 10.1109/TPEL.2015.2510033.
- [32] Bo-Yuan Chen and Yen-Shin Lai, “Switching Control Technique of Phase-Shift-Controlled Full-Bridge Converter to Improve Efficiency Under Light-Load and Standby Conditions Without Additional Auxiliary Components,” *IEEE Trans. Power Electron.*, vol. 25, no. 4, pp. 1001–1012, Apr. 2010, doi: 10.1109/TPEL.2009.2033069.
- [33] G.-B. Koo, G.-W. Moon, and M.-J. Youn, “New Zero-Voltage-Switching Phase-Shift Full-Bridge Converter With Low Conduction Losses,” *IEEE Trans. Ind. Electron.*, vol. 52, no. 1, pp. 228–235, Feb. 2005, doi: 10.1109/TIE.2004.841063.
- [34] E. S. Kim, J. Lee, Y. Heo, T. Marius, J. Ju, and Y. S. Kook, “LLC resonant converter with wide output voltage control characteristics according to operating mode transition,” *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 2018-March, pp. 2117–2123, 2018, doi: 10.1109/APEC.2018.8341309.
- [35] M. Shang and H. Wang, “LLC converter with reconfigurable voltage multiplier rectifier for high voltage and wide output range applications,” in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, pp. 1279–1285, doi: 10.1109/IECON.2017.8216218.
- [36] B. Axelrod, Y. Berkovich, and A. Ioinovici, “High Efficiency Parallel Post Regulator for,” *Proc. 2003 Int. Symp. Circuits Syst. 2003. ISCAS '03.*, vol. 3, no.

- 2, pp. 852–858, 2003.
- [37] H. Wu, L. Chen, and Y. Xing, “Secondary-Side Phase-Shift-Controlled Dual-Transformer-Based Asymmetrical Dual-Bridge Converter With Wide Voltage Gain,” *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5381–5392, 2015, doi: 10.1109/TPEL.2014.2371922.
- [38] S. Cetin and A. Astepe, “A phase shifted full bridge converter design for electrical vehicle battery charge applications based on wide output voltage range,” *Int. Conf. Appl. Electron.*, vol. 2016-Sept, pp. 51–56, 2016, doi: 10.1109/AE.2016.7577240.
- [39] H. Wu, X. Zhan, and Y. Xing, “Interleaved LLC Resonant Converter with Hybrid Rectifier and Variable-Frequency Plus Phase-Shift Control for Wide Output Voltage Range Applications,” *IEEE Trans. Power Electron.*, vol. 32, no. 6, pp. 4246–4257, 2017, doi: 10.1109/TPEL.2016.2602545.
- [40] H. Wu, L. Chen, and Y. Xing, “Secondary-Side Phase-Shift-Controlled Dual-Transformer-Based Asymmetrical Dual-Bridge Converter With Wide Voltage Gain,” *IEEE Trans. Power Electron.*, vol. 30, no. 10, pp. 5381–5392, 2015, doi: 10.1109/TPEL.2014.2371922.
- [41] B.-C. Kim, K.-B. Park, and G.-W. Moon, “Asymmetric PWM Control Scheme During Hold-Up Time for LLC Resonant Converter,” *IEEE Trans. Ind. Electron.*, vol. 59, no. 7, pp. 2992–2997, Jul. 2012, doi: 10.1109/TIE.2011.2166237.
- [42] Y. Jang, M. M. Jovanovic, and D. L. Dillman, “Hold-up time extension Circuit with integrated magnetics,” *IEEE Trans. Power Electron.*, vol. 21, no. 2, pp. 394–400, Mar. 2006, doi: 10.1109/TPEL.2005.869750.
- [43] I. H. Cho, K. M. Cho, J. W. Kim, and G. W. Moon, “A new phase-shifted full-bridge converter with maximum duty operation for server power system,” *IEEE Trans. Power Electron.*, vol. 26, no. 12, pp. 3491–3500, 2011, doi: 10.1109/TPEL.2011.2129532.
- [44] A. Chub, D. Vinnikov, R. Kosenko, and E. Liivik, “Wide Input Voltage Range Photovoltaic Microconverter With Reconfigurable Buck-Boost Switching Stage,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 7, pp. 5974–5983, Jul. 2017, doi: 10.1109/TIE.2016.2645891.
- [45] H. Wu, K. Sun, R. Chen, H. Hu, and Y. Xing, “Full-Bridge Three-Port Converters With Wide Input Voltage Range for Renewable Power Systems,” *IEEE Trans. Power Electron.*, vol. 27, no. 9, pp. 3965–3974, Sep. 2012, doi: 10.1109/TPEL.2012.2188105.
- [46] D. Liu, Y. Wang, F. Deng, Q. Zhang, and Z. Chen, “Zero-Voltage Switching Full-Bridge T-Type DC/DC Converter with Wide Input Voltage Range and Balanced Switch Currents,” *IEEE Trans. Power Electron.*, vol. 33, no. 12, pp. 10449–10466, Dec. 2018, doi: 10.1109/TPEL.2018.2800902.
- [47] Pengju Sun, Luwei Zhou, and K. M. Smedley, “A Reconfigurable Structure DC–DC Converter With Wide Output Range and Constant Peak Power,” *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2925–2935, Oct. 2011, doi: 10.1109/TPEL.2011.2129576.
- [48] A. Pressman and K. Billings, *Switching Power Supply Design - Pressman*, 2009.

- [49] V. Siliconix, "Zero-Voltage Switching Full-Bridge Converter: Operation, FOM, and Guidelines for MOSFET Selection System Application Note AN847 Zero-Voltage Switching Full-Bridge Converter:," pp. 1–6, 2014.
- [50] C. Series, "CoolMOS™ Benefits in both Hard and Soft Switching SMPS topologies Hard and Soft Switching topologies, applications and suitable CoolMOS™ families," *Infineon*, 2011.
- [51] Jo. Klein, "Design and Optimization of Soft Switched Power Converters for Low and Medium Power Applications," AN- 6005, *Fairchild Semiconductor*, 2014.
- [52] Maxim Integrated, "An Efficiency Primer for Switch-Mode, DC-DC Converter Power Supplies," *Power*, pp. 1–13, 2008.
- [53] N. Mohan and E. Persson, "Lecture Series on Soft-Switching in DC-DC Converters," *Soft-Switching*, 2002.
- [54] Voltech Instruments Ltd, "Measuring Leakage Inductance," *Notes*.
- [55] R. W. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, no. July. Boston, MA: Springer US, 2001, 2001.
- [56] W. G. Hurley and W. H. Wölfle, *Transformers and Inductors for Power Electronics*. 2013.
- [57] C. Basso, "AN1679 / D How to deal with Leakage Elements in Flyback Converters Prepared by: Christophe Basso," pp. 1–13, 2005.
- [58] R. Ayyanar and N. Mohan, "Novel soft-switching DC-DC converter with full ZVS-range and reduced filter requirement - Part II: Constant-input, variable-output applications," *IEEE Trans. Power Electron.*, vol. 16, no. 2, pp. 193–200, 2001, doi: 10.1109/63.911143.
- [59] J. Ferrell, J.-S. Lai, T. Nergaard, X. Huang, L. Zhu, and R. Davis, "The role of parasitic inductance in high-power planar transformer design and converter integration," *Ninet. Annu. IEEE Appl. Power Electron. Conf. Expo. 2004. APEC '04.*, vol. 1, no. C, pp. 510–515, 2004, doi: 10.1109/APEC.2004.1295855.
- [60] P. R. K. Chetty, "Resonant Power Supplies: Their History and Status," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 7, no. 4, pp. 23–29, 1992, doi: 10.1109/62.143195.
- [61] X. Ruan, "Soft - Switching PWM Full - Bridge Converters Presented by," 2012.
- [62] D. Incorporated, "Datasheet, Synchronous MOSFET Controller ZXGD3105N8," 2015. [Online]. Available: <https://www.diodes.com/assets/Datasheets/ZXGD3105N8.pdf>.
- [63] Y. Shen, W. Zhao, Z. Chen, and C. Cai, "Full-Bridge LLC Resonant Converter With Series-Parallel Connected Transformers for Electric Vehicle On-Board Charger," *IEEE Access*, vol. 6, pp. 13490–13500, 2018, doi: 10.1109/ACCESS.2018.2811760.



## Appendix – Papers Included