DESIGN AND DEVELOPMENT OF 200 WATTS BIDIRECTIONAL CLLC RESONANT CONVERTER FOR UNINTERRUPTIBLE POWER SUPPLY APPLICATIONS

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by

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
DAB	Dual Active Bridge
EMI	Electromagnetic Interference
FHA	Fundamental Harmonic Approximation
PWM	Pulse Width Modulation
PFM	Pulse Frequency Modulation
BPWM	Bipolar Pulse Width Modulation
UPWM	Unipolar Pulse Width Modulation
HPWM	Hybrid Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
MSPWM	Modified Sinusoidal Pulse Width Modulation
RS-HPWM	Random Switching Hybrid Pulse Width Modulation
THD	Total Harmonic Distortion
UPS	Uninterruptible Power Supply
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

LIST OF SYMBOLS

$S_1 - S_{10}$	Power switches
S_C	Control switch
L_r	Resonant inductance
L_m	Magnetizing inductance
L_{lkp}	Primary leakage inductance
L_{lks}	Secondary leakage inductance
L_{xm}	Transformer's magnetizing inductance
L_F	Filter inductor
L_C	Current limiting inductor
C_r	Resonant capacitor
C_{r1}	Primary resonant capacitor
C_{r2}	Secondary resonant capacitor
C_i	Input capacitor
C_o	Output capacitor
C_{dc}	DC-link capacitor
$C_{D1} - C_{D2}$	Voltage doubler capacitors
C_F	Filter inductor
C_H	Holding capacitor
C_{oss}	Equivalent parasitic capacitance of bridge switches
$R_{o.ac}$	Equivalent ac-load resistance
R_x	Effective resistive load
R_L	Load resistor
V_{ds}	DC source voltage

V_{dc}	DC-link voltage
V_{bat}	Battery voltage
$V_{o.rms}$	rms inverter output voltage
$V_{AC.rms}$	rms AC grid voltage
V_Z	Breakdown voltage for zener diode
v_{gs}	Gate to source voltage
v_{ds}	Drain to source voltage
v_{AC}	AC grid voltage
v_{AB}	Voltage across legs A - B
v_{CD}	Voltage across legs C - D
v_H	Holding capacitor voltage
v_m	Magnetizing voltage
I_{bat}	Battery current
i_M	Magnetizing current
i_P	Primary resonant current
i_S	Secondary resonant current
M	Voltage gain
$M_{forward}$	Voltage gain of forward mode
$M_{backward}$	Voltage gain of backward mode
Q	Quality factor
Z_o	Characteristic impedance
λ	Inductance ratio
σ	Capacitance ratio
f_n	Normalized switching frequency
f_r	Resonant frequency

f_s	Switching frequency
f_{si}	Inverter's switching frequency
f_p	Lower resonant frequency
f_o	Output frequency
f_c	Carrier frequency
f_{co}	Cut-off frequency
n_{Tr}	Transformer turns ratio
n_{CLLC}	CLLC transformer turn ratio
m_a	Modulation index
m_f	Frequency modulation index
A_r	Amplitude of reference signal
A_c	Amplitude of carrier signal
p	Number of pulses per half cycle
T_r	Transformer
s	Complex number
P_o	rms output power
t_{dead}	Dead time between upper and lower switches
T_S	Total time for one switching cycle
N_p	Number of primary turns
B_m	Flux density
A_N	Cross sectional area of transformer winding

REKA BENTUK DAN PEMBANGUNAN PENUKAR SALUN CLLC DWIARAH 200 WATTS UNTUK APLIKASI BEKALAN KUASA TANPA GANGGUAN

ABSTRAK

Bekalan kuasa tanpa gangguan (UPS) digunakan secara meluas untuk menyediakan kuasa yang boleh dipercayai dalam banyak aplikasi kritikal seperti komputer, pusat data, bilik bedah, dan peralatan telekomunikasi. Sistem UPS pada dasarnya terdiri daripada pengecas bateri, bateri, dan penyongsang. Secara konvensional, dua penukar satu arah (pengecas bateri dan penyongsang) sering dilaksanakan secara berasingan di mana setiap penukar akan memproses kuasa dalam satu arah. Walau bagaimanapun, dalam aplikasi tertentu, konfigurasi ini tidak optimum, oleh itu, penukar dwiarah adalah penyelesaiannya. Dalam UPS, konfigurasi penukar dwiarah membawa kepada pengurangan komponen perkakasan kerana pengecas bateri dan penyongsang boleh dibina dalam satu unit penukar. Dalam disertasi ini, reka bentuk terperinci dan pelaksanaan penukar salun CLLC dwiarah dan penyongsang berkecekapan tinggi baru untuk sistem UPS yang menyediakan aliran kuasa dua hala dibentangkan. Dalam topologi - topologi yang dicadangkan, penyongsang dua peringkat dilaksanakan di mana ia terdiri daripada penukar hadapan iaitu penukar salun CLLC dwiarah. Topologi pertama terdiri daripada penyongsang modulasi lebar denyut hibrid (HPWM) yang digabungkan dengan penukar salun dan dinamakan sebagai UPS 1. Topologi kedua terdiri daripada penyonsang gelombang sinus yang sangat efisien yang digabungkan dengan penukar salun dan dinamakan sebagai UPS 2. Topologi - topologi ini menawarkan beberapa kelebihan seperti prestasi pensuisan yang sangat baik, keupayaan operasi menurun/meningkat, dan kawalan pensuisan yang mudah. Keputusan simulasi dan eksperimen prototaip 200 W

dibentangkan untuk perbandingan, analisa, dan pengesahan. Keputusan yang dibentangkan menunjukkan bahawa penukar salun CLLC mencapai pensuisan voltan sifar (ZVS) untuk suis aktif dan pensuisan arus sifar (ZCS) untuk diod penerus sementara penyongsang menunjukkan bentuk gelombang keluaran yang berkualiti dengan kecekapan keseluruhan yang tinggi. Prestasi kecekapan menunjukkan bahawa UPS-UPS yang dicadangkan mampu menghasilkan kecekapan tinggi dalam mod ke hadapan dan mundur. Bagi UPS 1, kecekapan puncak adalah 88.08% dalam mod ke hadapan dan 92.24% dalam mod mundur. Bagi UPS 2, kecekapan puncak adalah 90.71% dalam mod ke hadapan dan 91.82% dalam mod mundur. Apabila dalam mod ke hadapan, kecekapan UPS 2 sedikit lebih tinggi daripada kecekapan UPS 1, tetapi dalam mod mundur, kecekapan UPS 1 sedikit lebih baik daripada kecekapan UPS 2.

DESIGN AND DEVELOPMENT OF 200 WATTS BIDIRECTIONAL CLLC RESONANT CONVERTER FOR UNINTERRUPTIBLE POWER SUPPLY APPLICATIONS

ABSTRACT

Uninterruptible power supply (UPS) is widely employed to provide reliable power in many critical applications such as computers, data centers, surgical rooms, and telecommunication equipment. UPS system essentially consists of a battery charger, battery, and inverter. Conventionally, two unidirectional converters (battery charger and inverter) are often implemented separately where each of the converters will process the power in one direction. However, in certain applications, this configuration is not optimal, hence, a bidirectional converter is the solution. In UPS, a bidirectional converter configuration leads to a reduction in hardware components because battery charger and inverter can be built in one converter unit. In this dissertation, a detailed design and implementation of bidirectional CLLC resonant converter and new high efficient inverter for UPS system that provide bilateral power flow are presented. In the proposed topologies, a two-stage inverter is implemented where it consists of a front-end converter namely bidirectional CLLC resonant converter. The first topology consists of hybrid pulse width modulation (HPWM) inverter combined with the resonant converter and named as UPS 1. The second topology consists of highly efficient sine-wave inverter combined with the resonant converter and named as UPS 2. These topologies offer several advantages such as excellent soft switching performance, buck/boost operation capability, and simple switching control. The simulation and experimental results of 200 W prototypes are presented for comparison, analysis, and validation. The presented results show that the CLLC resonant converter achieves zero voltage switching (ZVS) for active switches

and zero current switching (ZCS) for rectifier diodes, while the inverters show good quality output waveforms with high overall efficiency. The efficiency performance shows that the proposed UPSes were able to produce high efficiency in both forward and backward modes. For UPS 1, the peak efficiency was 88.08 % in forward mode and 92.24 % in backward mode. For UPS 2, the peak efficiency was 90.71 % in forward mode and 91.82 % in backward mode. When in forward mode, the efficiency of UPS 2 was slightly higher than the efficiency of UPS 1, but in backward mode, the efficiency of UPS 1 was slightly better than the efficiency of UPS 2.

CHAPTER ONE

INTRODUCTION

1.1 Background

With the increasing demand of critical applications such as servers, telecommunication systems, medical equipments, computers, and data centers, Uninterruptible Power Supply (UPS) has been widely used due to the fact of its ability to provide highly reliable power supply during power shortage [1]–[3]. UPS can improve the reliability, efficiency and safety of electronic systems. UPS has been extensively incorporated in the power system of hospital, ship, aircraft, satellite and space station. The growing need for this particular power electronic interface necessitates the research and innovation to develop converters with high power efficiency and high power density owing to the development demand in power supply technologies.

There are four major types of UPSes namely Standby UPS, Ferroresonant UPS, Line interactive UPS, and Online UPS. The Standby UPS or better known as Offline UPS is the most common type encountered on a daily basis. It is usually used in low power applications with power of no more than 2 kVA. It normally routes the input line voltage through surge suppressor, filter and transfer switch before finally being routed to the output of UPS device as shown in Figure 1.1. In the event of power failure, the system will switch over to battery backup power. The benefits of this type lie in its simplicity. The battery only starts supplying power when the main power fails, therefore it has high efficiency, robustness, and low cost.

The Ferroresonant UPS or Hybrid UPS is an extension from former Standby UPS design. The difference from the design standpoint is that the transfer switch that

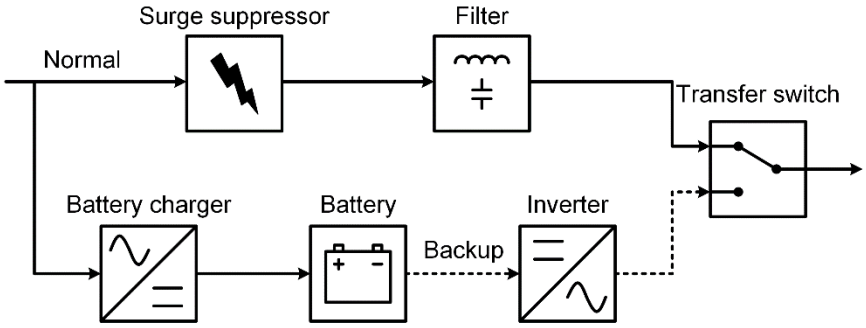

Figure 1.1: Simplified diagram of the Offline UPS [4].

selects between power sources has been replaced by a ferroresonant transformer as shown in Figure 1.2. The transformer has a metal core with two coils of wire wrapped around. When current is applied to one coil, the other coil will magnetically couple to the first coil and induce the current. The transformer consists of three windings with two act as inputs and one as output. The Ferroresonant UPS is usually available in a size range of up to 15 kVA.

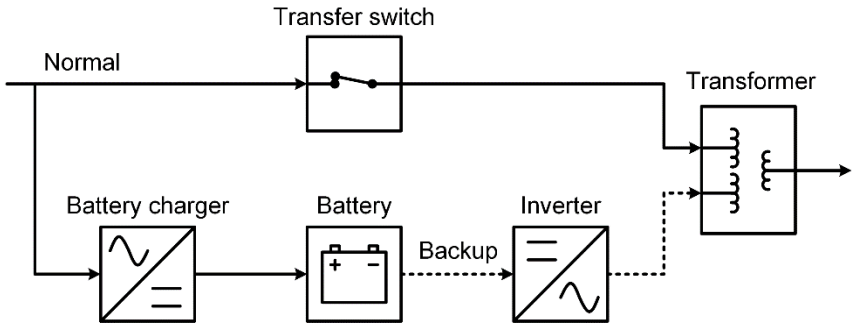

Figure 1.2: Simplified diagram of the Ferroresonant UPS [4].

The Line interactive UPS offers better performance as compared to the previous UPSes and normally served in low and medium power applications of up to 5 kVA. In this UPS, the internal mechanism only consists of an inverter/converter assembly and the transfer switch is located in line with input line voltage as shown in Figure 1.3. During the normal operation, the main power supplies directly to the load while the battery is charged through the inverter/converter. When the main power fails,

the transfer switch opens to disconnect the load from the main line and the backup power will take over and the battery maintains the continuity of power feed to the load through inverter/converter. The main advantage of this type is that the inverter/converter is permanently tied to the output. This allows the amount of times it takes to switch to backup power lesser compared to the previous types.

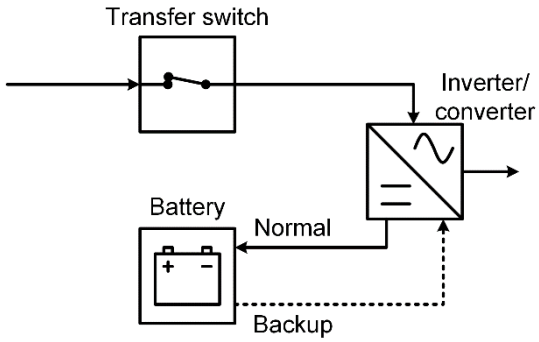

Figure 1.3: Simplified diagram of the Line interactive UPS [4].

The Online UPS has become dominant in high power which is above 10 kVA and high voltage applications in industrial and manufacturing plants. Its internal components are quite similar to the Standby UPS, however the way in which it operates is quite different. During normal condition, the input line voltage is not connected to the output. Instead, the input line voltage is routed to AC-DC converter where the power is used to charge the battery as shown in Figure 1.4. The battery then, discharge its power through inverter and supply power to the output through a transfer switch. The Online UPS will only use the line input power directly when the battery charger, battery or inverter fail. One of the advantage of this type of UPS is total isolation between the input line voltage and output voltage. Compared to the previous types, this UPS does not even require transition times from normal to backup power when main power fails. This allows the system to experience zero interruption when a power failure occurs.

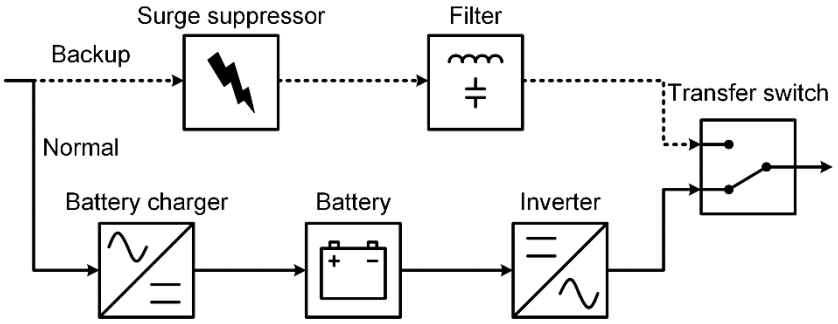

Figure 1.4: Simplified diagram of the Online UPS [4].

Generally, a typical UPS consists a battery charger, a battery bank, and an inverter. Although in some UPS system a single stage DC-AC inverter structure is used, in order to achieve high power efficiency it usually requires two stage structures which consist of DC-DC converter and DC-AC inverter. The two stage architecture which contains front-end DC-DC converter should has high efficiency and high power density performance over wide load condition. As for the DC-AC inverter part, a desirable PWM switching patterns are required in order to achieve lower harmonic contents and lesser ripples in the output waveform.

In this dissertation, a background description and review of the state-of-the-art DC-DC converters and DC-AC inverters are presented. New topologies and control schemes are proposed with the advantages of high efficiency, simple in design and low cost. The detailed design and operation are analyzed and described. A complete two stage architecture is investigated and developed. A simulation and laboratory prototype is tested and implemented and the contributions are discussed and presented in succeeding chapters.

1.2 Problem statement

In power electronic application such as UPS, the conversion of power generally requires two steps of exchange which are from main power source to backup power

source and then from backup power source to load when main power is interrupted. In conventional way, two unidirectional converters are often implemented where each of the converters processing the power in one direction [5]. Therefore, multiple converters are used in order to complete the system flow. This reduces the overall system efficiency up to 3 % and increases the cost of system hardware for the additional rectifier circuit that could cost around RM 10. Many conventional UPS designs utilize a separate battery charger and power inversion circuit as shown in Figure 1.5(a). The battery charger or rectifier circuit performs AC-DC inversion and charges the battery while grid power is connected. Whereas, the inverter converts the battery power from DC to AC and supplies to load when grid power fails. One limitation of this conventional topology is that it requires two separate power converters for rectification and charging as well as DC to AC inversion. In addition, the DC-link between inverter and rectifier requires higher voltage level than the battery voltage in order to obtain sufficient DC voltage level for the inverter. Therefore, a number of batteries are required to be connected in series. Hence, for applications that require low power to operate, this configuration is not optimal and economic.

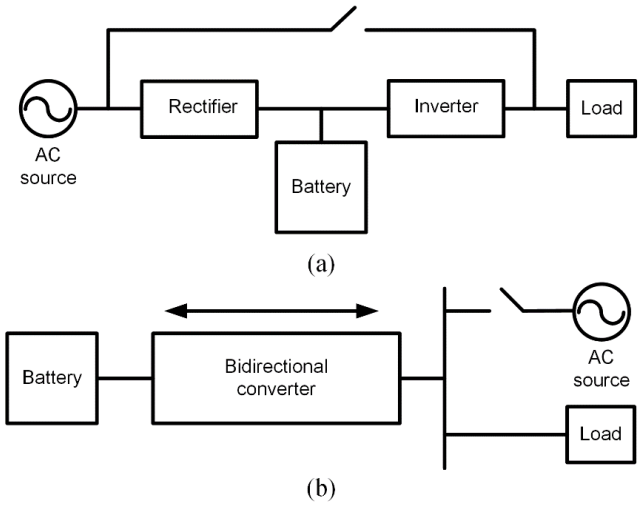

Figure 1.5: Simplified diagram of UPS. (a) Conventional UPS. (b) Bidirectional UPS [3].

Bidirectional DC-DC converter is an attractive research that has been developed in UPS system recently [6], [7]. Its characteristic feature that capable of bilateral power flow, provides the functionality of two unidirectional converters in a single converter as shown in Figure 1.5(b). Several bidirectional DC-DC converter topologies have been proposed in [6]–[13], focusing on decreasing number of switches, increasing in efficiency and power lost reduction. Bidirectional DC-DC converter topologies can be divided into two types i.e. non-isolated and isolated types. In applications which conversion ratio is not significant and galvanic isolation is not essential, non-isolated types are more preferable due to simplicity in their structure and control scheme. However, isolated types are more convenient for applications that require high voltage conversion ratio as it provides galvanic isolation, thus increases the reliability of the system. There are various isolated bidirectional DC-DC converter topologies which have been proposed in literature such as flyback [14], push-pull [15], dual active bridge, etc. The dual active bridge is the most popular used in isolated bidirectional converter topology [16], [17]. This is because its structure has high efficiency and capability to operate as rectifier or converter depending on the converter's mode. When in forward mode, it operates as converter and when in reverse mode, it operates as bridge rectifier.

In order to improve power density and reduce the size of magnetic component in isolated bidirectional DC-DC converter, high frequency operation is necessary. Unfortunately, high frequency operation exhibits high switching losses in semiconductor devices as was presented in [18] where a single switch that operates at 200 kHz switching frequency with operating voltage of 400 V and current at 4 A is estimated to have 3.46 W of switching losses. Due to this reason, soft switching is desired. Generally, soft switching can be achieved by either zero voltage switching

(ZVS) technique and/or zero current switching (ZCS) technique. In the case of isolated bidirectional DC-DC converter, these two techniques can be realized with snubber, active clamping, resonant switching, parasitic resonance, etc. In isolated unidirectional type UPS, the current topology normally requires around 12 to 18 semiconductor components in one complete system. However, isolated bidirectional type UPS can reduce the number of semiconductor components to only 10. Therefore, this thesis aims to contribute new topologies of isolated bidirectional resonant converter based UPS system. The proposed converters provide a bidirectional power flow control as well as soft switching features that minimize components counts and switching losses.

1.3 Research Objectives

The main aim of this research is to propose a new converter topology for UPS that capable of bilateral power flow. The specific objectives are:

- To design and develop a bidirectional CLLC resonant converter
- To design and develop a highly efficient single phase inverter for UPS system
- To evaluate the performance of the proposed topologies through simulations and experiments

1.4 Research Scope

The main focus of this research is to design and develop a two-stage converter for low power UPS system (< 1kVA) where it consists of two power converters namely bidirectional resonant DC-DC converter and a full-bridge inverter. A brief overview of different topologies for bidirectional DC-DC converter and full-bridge inverter are presented in literature review. Ultimately, research studies on various topologies come to a conclusion with two proposed topology systems for UPS. The topology systems are a new isolated bidirectional CLLC resonant converter with hybrid pulse width

modulation (HPWM) inverter and new isolated bidirectional CLLC resonant converter with a highly efficient sine-wave inverter. Different modes of operation in all stages are explained and the voltage gain of the resonant DC-DC converter is derived. Finally, the feasibility of the proposed converters is verified through computer simulation and experimental testing on laboratory prototypes.

1.5 Thesis Outline

The dissertation consists of six chapters, which are organized as follow.

Chapter 1 gives the detailed introduction of the research background based on general overview of UPS. The efficiency and reliability of bidirectional UPS system design is the main concern. Soft switching techniques and two-stage topologies are the main thesis contributions to improve efficiency and reliability. The research objectives are highlighted and the thesis outline is presented.

Chapter 2 reviews topologies that have been proposed by researchers regarding various bidirectional DC-DC converter topologies as well as various single phase full-bridge inverter topologies. Some latest topologies that have been proposed that related on isolated bidirectional DC-DC converter for UPS are presented. A brief review of basic resonant converter topologies and their DC gain characteristics are presented. The CLLC resonant converter is highlighted in more detail.

Chapter 3 proposes two topology systems for UPS. First, a new isolated bidirectional CLLC resonant converter with HPWM inverter is presented and discussed. An in-depth theory of the proposed bidirectional CLLC resonant converter is presented in detail. A brief topology description of HPWM inverter is presented. Secondly, a new isolated bidirectional CLLC resonant converter with a highly efficient

sine-wave inverter is presented and discussed. An in-depth description of a highly efficient sine-wave inverter is presented.

Chapter 4 discusses the design and implementations of the proposed overall systems. The components selection methods are presented which focus on design procedures for CLLC resonant tank and calculation of maximum voltage and current stress across main power components. Step by step to determine the appropriate values for CLLC resonant tank and filter components are presented. After that, the method for charging the battery is structured from the calculated CLLC resonant tank. Then, implementations for power circuit, control circuit, sensing circuit, and transformer are presented.

Chapter 5 discusses the simulation and experimental results of the proposed topology systems. Experiment measurements collected by using Agilent x1000 are shown to further validate the proposed topology systems. Converter operation constraints are also discussed. This chapter shows the performance evaluation for the proposed topology systems under various operating conditions of input battery voltage and load resistance.

Chapter 6 provides the conclusions of the thesis based on the research works that have been presented in previous chapters. It also makes recommendations for further research on this topic in the future.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

In this chapter, a background description and review of the state-of-the-art bidirectional DC-DC converters are discussed and presented. Then, some topologies of single phase inverter and their existing switching techniques are presented. Finally, a review on recent topologies of bidirectional inverter system is featured. A summary is given in order to highlight the advantages and deficiencies of each topology discussed.

2.2 Bidirectional DC-DC Converters

Based on terminology, bidirectional DC-DC converters operate in two modes of operation considering the difference of voltage amplitude on each side of the converter. For further clarification, the generic circuit structure of bidirectional DC-DC converter is illustrated in Figure 2.1. The converter can be characterized as a voltage fed or a current fed depending upon their energy source either voltage source or current source. The bidirectional DC-DC converter can be categorized into buck or boost type based on the placement of their auxiliary energy storage. The buck type is having energy storage placed on the high voltage side, while the boost type is having

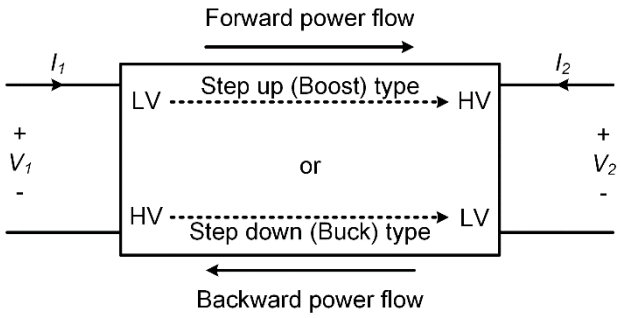

Figure 2.1: Basic structure of bidirectional DC-DC converter [19].

energy storage placed on the low voltage side. In order to realize the bilateral power flow in DC-DC converters, the power switches should be able to carry current on both direction. Therefore, unidirectional semiconductor power switch such as power MOSFET or IGBT in parallel with diode is implemented. So, for buck and boost type converters, the typical switch and diode are replaced by MOSFET/IGBT in parallel with diode. In literature, bidirectional DC-DC converter can be classified into two types which are non-isolated and isolated type. These two are developed based on their own merits in order to meet different application requirements.

2.2.1 Non-isolated Bidirectional DC-DC Converters

Non-isolated bidirectional DC-DC converters can be categorized into basic topologies such as buck-boost converter, cuk converter, SEPIC converter and derived topologies such as interleaved buck-boost converter, cascaded buck-boost converter and three level converter. Non-isolated bidirectional DC-DC converters have the advantages of simple structure, low cost, and high reliability. Among these converters, bidirectional buck-boost DC-DC converter shown in Figure 2.2 is the simplest and most widely used [20], [21]. Basically, bidirectional buck-boost DC-DC converter is the combination of a step-up stage and step-down stage connected in anti-parallel. The converter operates in step-down mode by turning off the switch S_2 and turning on switch S_1 with pulse width modulation (PWM) signal. It operates in step-up mode by turning off the switch S_1 and turning on switch S_2 with PWM signal.

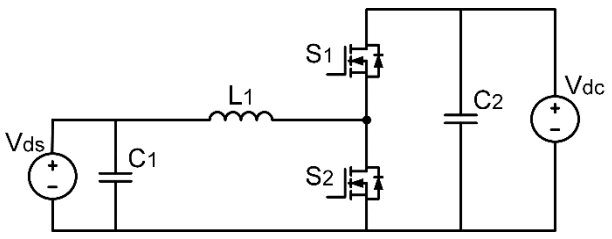

Figure 2.2: Bidirectional buck-boost DC-DC converter [20], [21].

Figure 2.3 shows a bidirectional cuk DC-DC converter [22], [23]. Figure 2.4 shows a bidirectional SEPIC DC-DC converter [24]. Both of these converters are transferring power bidirectionally by using two active switches S_1 and S_2 alternately.

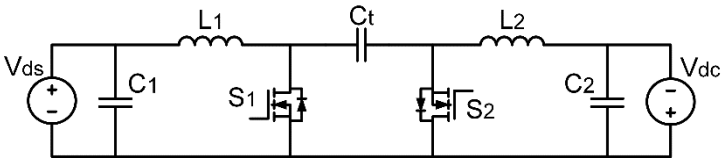

Figure 2.3: Bidirectional cuk DC-DC converter [22], [23].

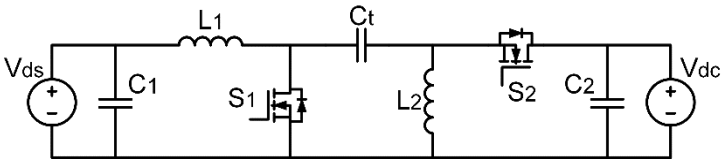

Figure 2.4: Bidirectional SEPIC DC-DC converter [24].

Bidirectional interleaved buck-boost converter is actually a combination of multiple basic bidirectional buck-boost DC-DC converter [25]. Figure 2.5 shows a bidirectional two-phase interleaved buck-boost converter. In this converter, there is 180˚ phase shift between the gate signal S_1 and S_3 in forward mode, and between the gate signal S_2 and S_4 in reverse mode. The interleaved buck-boost converter is typically used in high current applications. The higher number of interleaving in this converter results in lower output current ripple and smaller inductor can be used for faster dynamic responses.

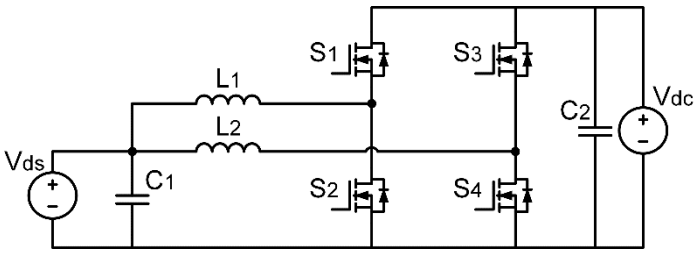

Figure 2.5: Bidirectional two-phase interleaved buck-boost DC-DC converter [25].

Bidirectional cascaded buck-boost converter which is shown in Figure 2.6 is also a derivation from basic bidirectional buck-boost DC-DC converter [26]. The key feature of this converter is that V_{ds} is not necessarily smaller than V_{dc}. It is normally used in application where the voltage on one side is either lower or higher than the voltage on the other side.

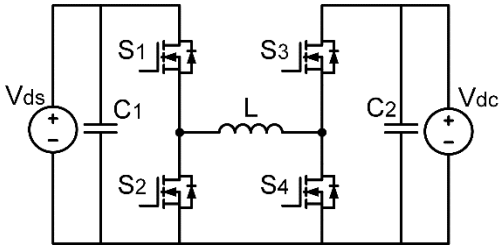

Figure 2.6: Bidirectional cascaded buck-boost DC-DC converter [26].

Another derived bidirectional DC-DC converter is the bidirectional multilevel converters [27]. Figure 2.7 shows an example of bidirectional three-level DC-DC converter. Basically, bidirectional multilevel DC-DC converters are developed for applications that have a high DC-link voltage.

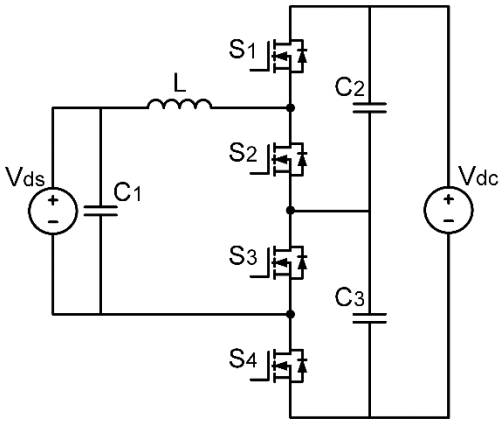

Figure 2.7: Bidirectional three-level DC-DC converter [27].

2.2.2 Isolated Bidirectional DC-DC Converters

In the bidirectional DC-DC converters, isolation is generally provided by a transformer. However, transformer basically adds extra size, costs and losses.

Nevertheless, since transformer can provide voltage isolation between two sources and give impedance matching between them, it gives advantages in many applications. The advantages of isolated bidirectional DC-DC converters include galvanic isolation, higher power density, high frequency soft switching with high efficiency, high step-up and step-down voltage ratio and low electromagnetic interference (EMI). Isolated bidirectional DC-DC converters can be divided into two types which are voltage-fed and current-fed. Current-fed isolated bidirectional DC-DC converters normally require switches with much higher voltage rating than the DC input and high voltage stress. Therefore, they are normally suitable for low voltage high current applications [28]. One important characteristic of a voltage-fed isolated bidirectional DC-DC converters is that the output voltage waveform is not affected by the load parameters. The other advantage of voltage-fed isolated bidirectional DC-DC converters is that the voltage sources are commonly available such as battery, DC power supply, or rectified AC bus. Hence, they are easier to be implemented in industrial applications. For the isolated bidirectional DC-DC converters, the sub-topology can be a combination of half-bridge, full-bridge, push-pull and their derivations.

One of the most widely used topologies is the combination of current-fed and voltage-fed full-bridge/ half-bridge/ push-pull and its derivations. Figure 2.8 shows the basic topology structure of this type of converter [29] with a full-bridge structure. The front-end full-bridge is connected to current source or DC inductor, and the other end full-bridge is connected to voltage source or DC capacitor. This topology was proposed for application with low voltage battery and high voltage DC-link. This topology however suffer from several drawbacks due to transformer's non-ideality. This results in leakage inductance and leakage energy stored in the transformer. The

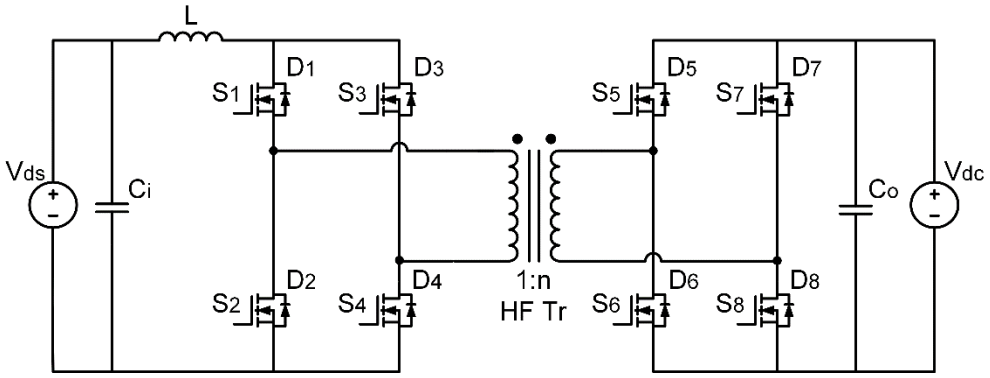

Figure 2.8: Isolated bidirectional DC-DC converter based on a current-fed full-bridge and a voltage-fed full-bridge [29].

leakage energy causes high voltage spikes on switches in current-fed side during switching.

Figure 2.9 shows the improvement made based on earlier topology. A RCD snubber circuit is added into the current-fed side full-bridge to alleviate voltage stress on the switches [30]. A similar approach was employed in [31], to reduce the voltage stress on the switches in current-fed side but lossless snubber was used as shown in Figure 2.10. Based on similar structure, authors in [32]–[34] , added an active clamp snubber circuit S_c and C_c on the current-fed side full-bridge as shown in Figure 2.11. The addition of active clamp result in ZVS in all switches on current-fed side, and ZVS

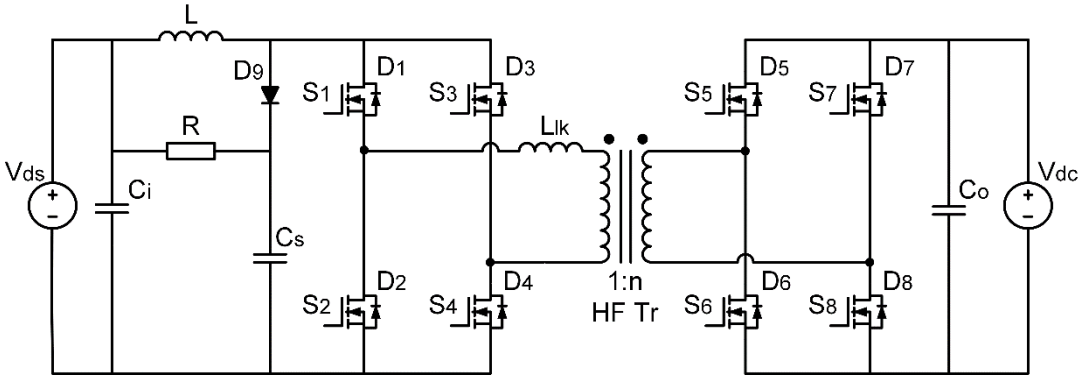

Figure 2.9: Isolated bidirectional DC-DC converter based on a current-fed full-bridge and a voltage-fed full-bridge with RCD snubber [30].

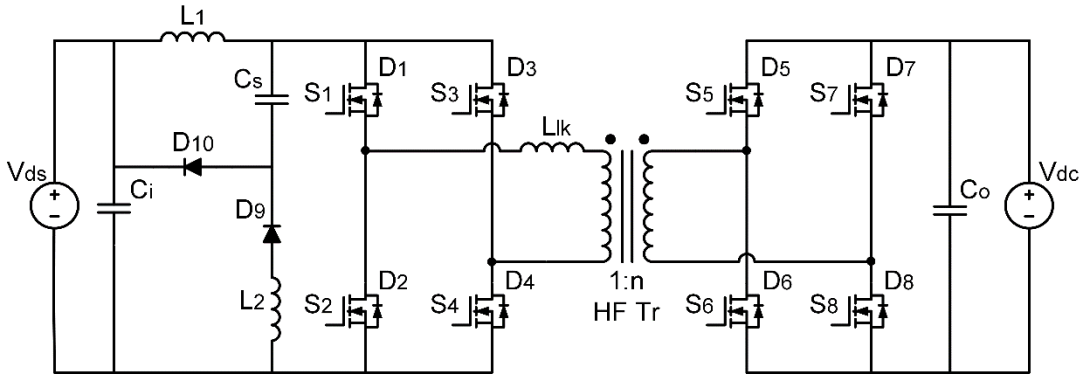

Figure 2.10: Isolated bidirectional DC-DC converter based on a current-fed full-bridge and a voltage-fed full-bridge with lossless snubber [31].

or ZCS achieved in all switches on voltage-fed side. Another derivation of this type of topology was reported in [35], where a half-bridge structure was employed on the voltage-fed side instead of a full-bridge as shown in Figure 2.12. One of the advantages of half-bridge structure is that it can double the voltage when operates as half-bridge rectifier (voltage doubler), thus greatly reduce the number of turns in transformer secondary winding.

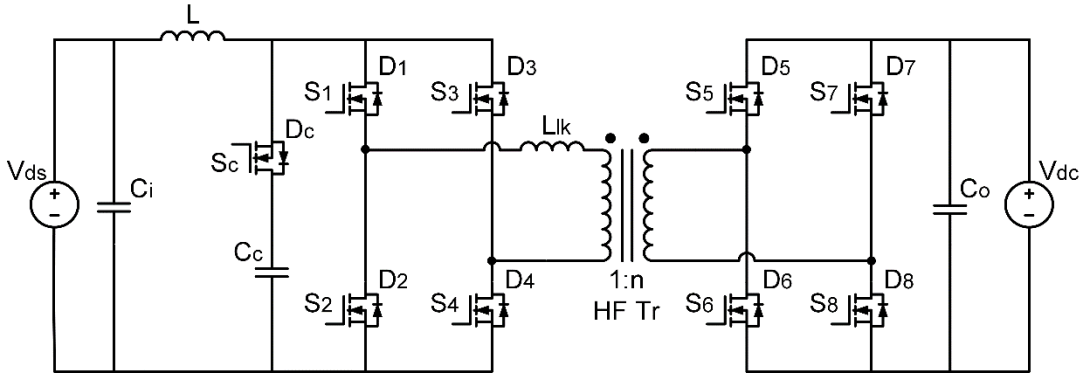

Figure 2.11: Isolated bidirectional DC-DC converter based on a current-fed full-bridge and a voltage-fed full-bridge with active clamp snubber [32].

As shown in Figure 2.13, a half-bridge was employed on both voltage-fed and current-fed side [36]. The advantage of this topology is that it does not require any snubber circuit because S_1 can act as an active clamp switch. Another type of structure

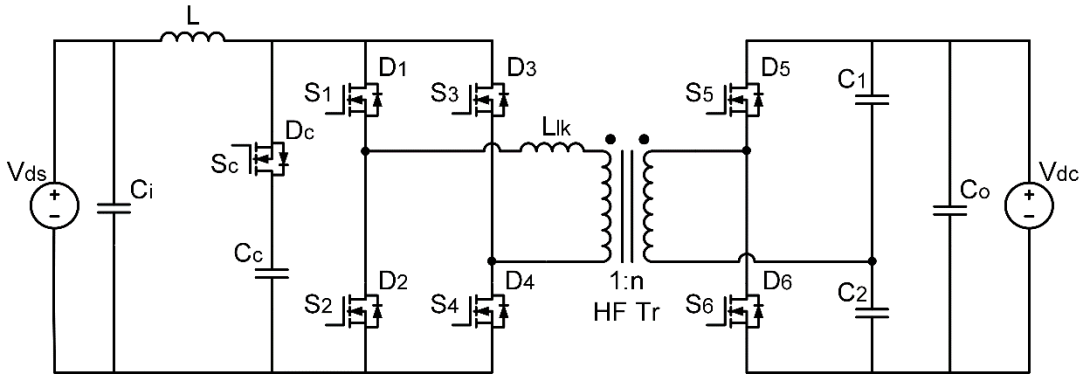

Figure 2.12: Isolated bidirectional DC-DC converter based on a current-fed full-bridge and a voltage-fed half-bridge with active clamp snubber [35].

which does not require any snubber is shown in Figure 2.14 which was reported in [37]. In this topology, a push-pull was employed on current-fed side and half-bridge was employed on voltage-fed side. However, half-bridge topology and push-pull topology require double in input current, resulting double in switch's current stress compared to the full-bridge topology for the same input power. Therefore, these topologies are better for low power applications.

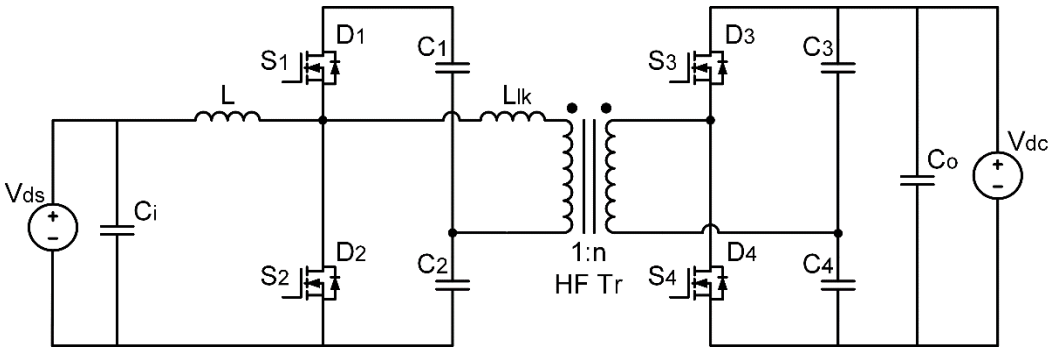

Figure 2.13: Isolated bidirectional DC-DC converter based on a current-fed half-bridge and a voltage-fed half-bridge [36].

The most popular and widely used topology for isolated bidirectional DC-DC converter is dual active bridge (DAB). A typical DAB isolated bidirectional DC-DC converter is shown in Figure 2.15. It utilizes the leakage inductance of the transformer

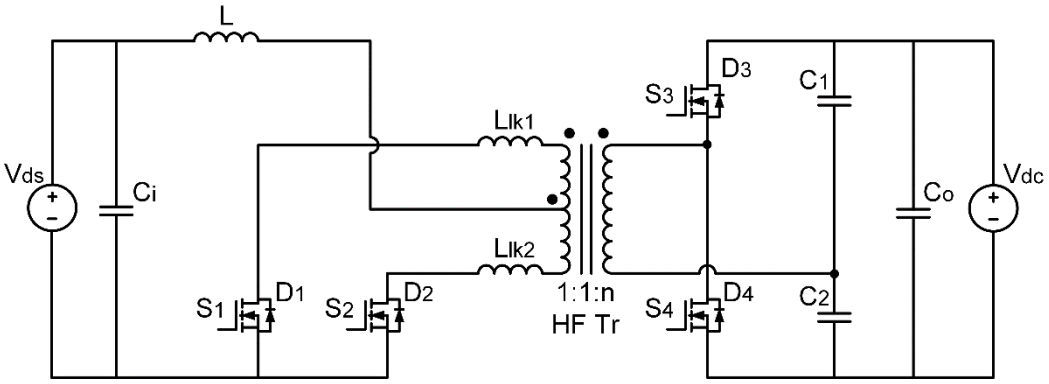

Figure 2.14: Isolated bidirectional DC-DC converter based on a current-fed push-pull and a voltage-fed half-bridge [37].

as the main energy storage and as transfer element to deliver the bidirectional power [38]–[41]. The DAB isolated bidirectional DC-DC converter is a voltage-fed on each side of the isolation transformer. The control of DAB is very simple and straightforward. The control sequence can be either one bridge is phase-shift controlled and the other is uncontrolled (only antiparallel diodes conduct) or both bridges output a square voltage waveforms and the phase between the two voltages square waveform can be controlled. DAB features several advantages such as ZVS can be achieved for switches in both bridges, lower voltage stress on switches compared to current-fed type, and high efficiency.

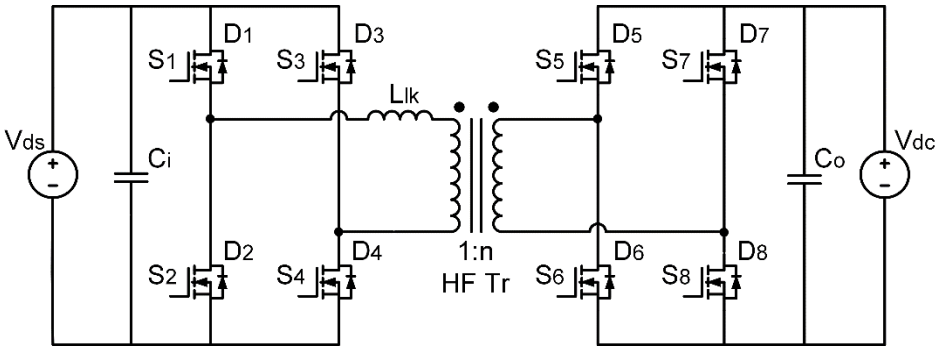

Figure 2.15: Isolated bidirectional DC-DC converter based on two voltage-fed full-bridges [38].

DAB also has few topology derivation, such as the combination of voltage-fed half-bridge and a voltage-fed full-bridge as shown in Figure 2.16 [42], and the combination of two voltage-fed half bridges as shown in Figure 2.17 [43]. This topology however suffers from several drawbacks such as limited voltage range due to limited ZVS range operation, and high turn-off losses. Moreover, at light load conditions, DAB may suffer from hard switching due to energy stored in the leakage inductance may not be large enough to discharge the drain-source capacitances of the switches, thus negating the ZVS feature.

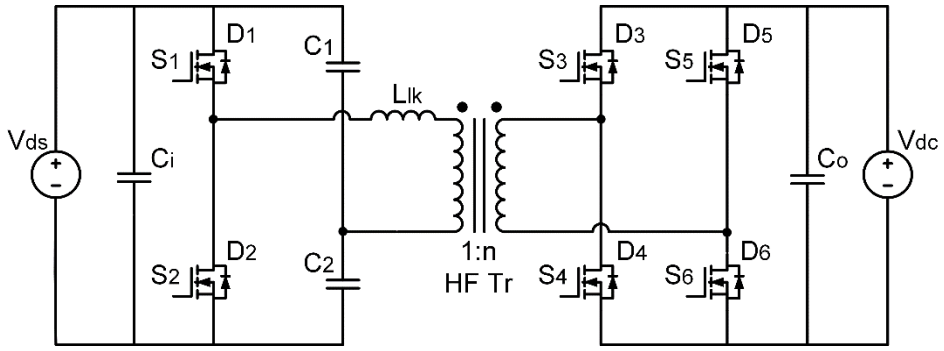

Figure 2.16: Isolated bidirectional DC-DC converter based on a voltage-fed half-bridge and a voltage-fed full-bridge [42].

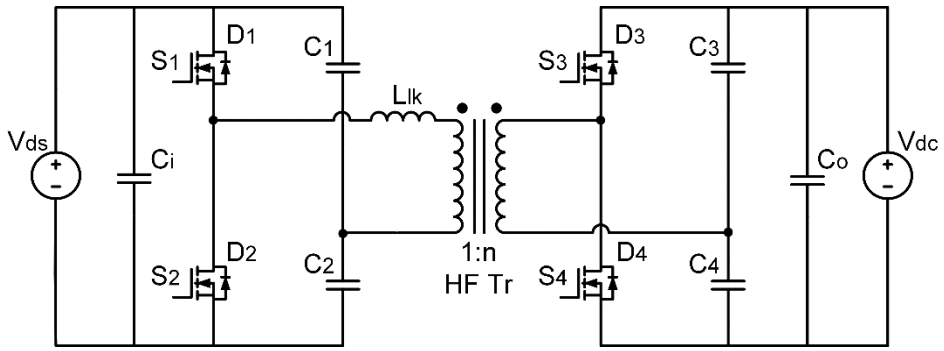

Figure 2.17: Isolated bidirectional DC-DC converter based on two voltage-fed half-bridges [43].

Another popular variant of DAB isolated bidirectional DC-DC converter is bidirectional series resonant DC-DC converter which was reported in [44]–[46] as

shown in Figure 2.18. It consists of two voltage-fed full-bridges and a set of LC resonant tank i.e. capacitor and inductor connected in series. By forming a LC resonant network, a nearly sinusoidal current is obtained which enables low turn-on and turn-off current. Similar to previous design, the control sequence of phase shift angle between the primary and secondary switching-bridges can be employed. Figure 2.19 shows the DC voltage gain characteristic of the series resonant converter where the voltage gain is always less than one. The impedance of the resonant tank changes when the switching frequency changes. The minimum impedance occurs at resonant frequency, so when the switching frequency is equal to resonant frequency, the DC voltage gain of the converter is equal to one. When the switching frequency is above resonant frequency, ZVS is achieved and when the switching frequency is below resonant frequency, ZCS is achieved. The drawback of this converter is wide switching frequency variation range in order to regulate the output voltage especially at light load condition (smaller quality factor, *Q*). Therefore, as the switching frequency drifts away from resonant frequency, the impedance increases, thus more energy circulates in the resonant tank resulting in higher conduction losses. Besides, when it increases the phase shift angles, it produces high turn-off losses and high circulating current.

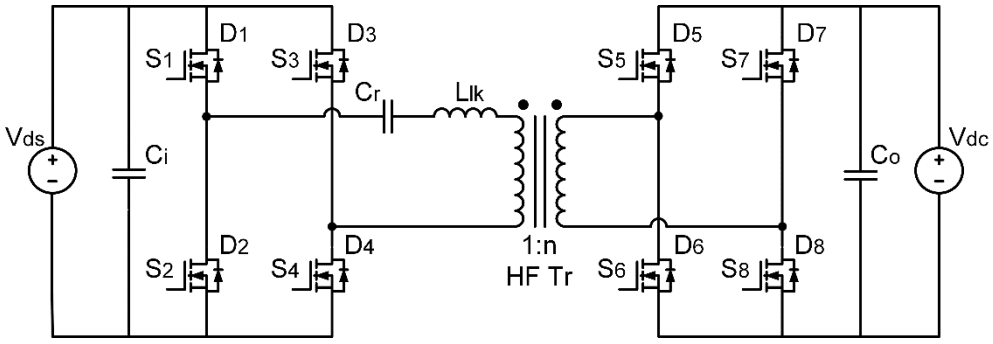

Figure 2.18: Isolated bidirectional DC-DC converter based on two voltage-fed full-bridges with a series resonant network [45].

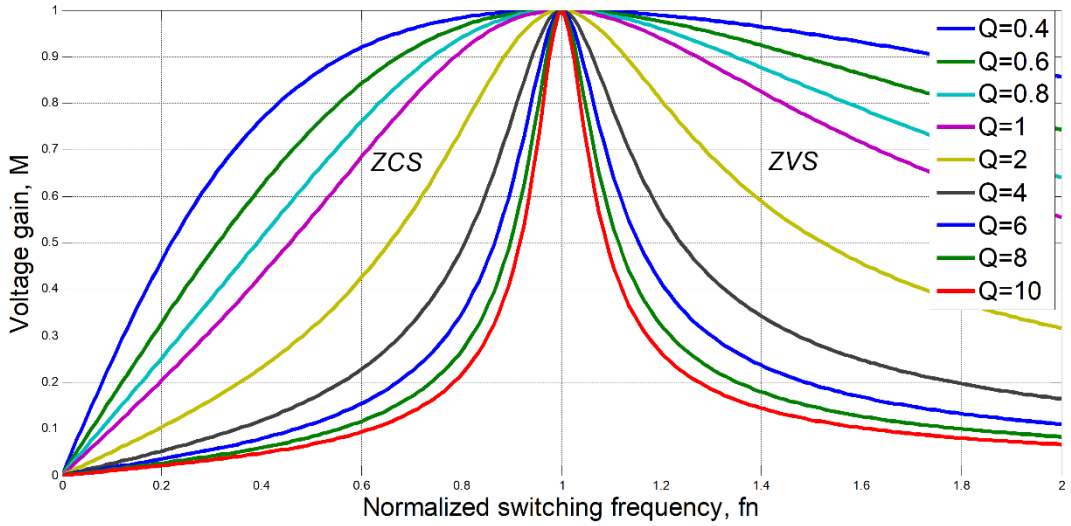

Figure 2.19: DC characteristic of full-bridge series resonant converter [47].

Furthermore, this converter can only operate under buck mode, which is not suitable for wide input and output range applications.

In order to attain wider and higher voltage conversion ratio, improved resonant network with three elements such as LLC resonant network were introduced and among the family of resonant converters, the LLC resonant converter has superiority in performance. This includes buck/boost operation capability, narrow switching frequency variation range and excellent soft switching performance: zero voltage switching (ZVS) of primary active switches and zero current switching (ZCS) of secondary rectifier diodes [48]–[58]. It offers soft switching in all its switches without additional circuitry such as snubber or active clamp. Therefore, a very high frequency switching is possible. Because of this feature, LLC resonant converter is having high efficiency that is always more than 90 %, high power density that is up to 5 kW and smaller hardware components (require only one component for resonant tank).

In the LLC resonant converter, the control sequence only applied to the primary switching-bridge where a fix switching signal with duty ratio of 0.5 is delivered to

bridge's switches. The operation of the bridge switches is similar to the operation of voltage source inverter where the upper switch of one leg is complementary to the lower switch of the other leg of the bridge in which one complementary will be conducting for the first half cycle and the other one will be conducting for the second half cycle. The output voltage regulation of the converter is controlled by the pulse frequency modulation (PFM) technique due to its voltage gain is related with the switching frequency, f_s. The voltage gain, M of the conventional LLC resonant converter can be described as follow [48], [49], [51], [52]:

$$M = \frac{1}{\sqrt{(1+\lambda-\frac{\lambda}{f_n^{\,2}})^2 + Q^2(f_n - \frac{1}{f_n})^2}} \tag{2.1}$$

The inductance ratio, λ is defined as below where L_r is resonant inductance and L_m is magnetizing inductance:

$$\lambda = \frac{L_r}{L_m} \tag{2.2}$$

The characteristic impedance, Z_o is defined as below where C_r is resonant capacitor:

$$Z_o = \sqrt{\frac{L_r}{C_r}} \tag{2.3}$$

The resonant frequency, f_r of the converter is:

$$f_r = \frac{1}{2\pi\sqrt{L_r.C_r}} \tag{2.4}$$

The lower resonant frequency, f_p of the converter is:

$$f_p = \frac{1}{2\pi\sqrt{(L_m + L_r).C_r}} \tag{2.5}$$

The normalized switching frequency, f_n is defined as ratio between switching frequency divided with resonant frequency, where f_s is the switching frequency:

$$f_n = \frac{f_s}{f_r} \tag{2.6}$$

The quality factor, Q is defined as below where $R_{o.ac}$ is the equivalent ac-load resistance and n is the transformer turns ratio:

$$Q = \frac{Z_o}{n^2 R_{o.ac}} \tag{2.7}$$

As shown in Figure 2.20, the DC voltage gain characteristic of the conventional LLC resonant converter can be divided into three regions [50]. Region I is when the switching frequency, f_s of the converter is higher than the resonant frequency, f_r. In this region, the voltage gain is always less than one, and the gain continues to drop as the switching frequency become higher. During operation under this region, the ZVS is achieved on the primary switches. For the Region II, the switching frequency is between two resonant frequencies f_p and f_r. In this region, the voltage gain is higher than one and ZVS is achieved on the primary switches. For region III, the ZCS is achievable for the primary switches while ZVS is not achievable. Therefore, for a converter that is controlled with MOSFET, it should be prevented from entering this region.

There are many researches on LLC resonant converter have been reported in the literature [48], [49], [50]– [59]. However, most of them are designed for unidirectional power transfer. In order to realize bidirectional power flow in LLC resonant DC-DC converter, author in [60] proposed isolated bidirectional LLC resonant DC-DC converter as shown in Figure 2.21. This topology is similar to conventional unidirectional LLC converter and having identical performance. However, the converter has lost its LLC feature: ZCS is no longer achieved on the

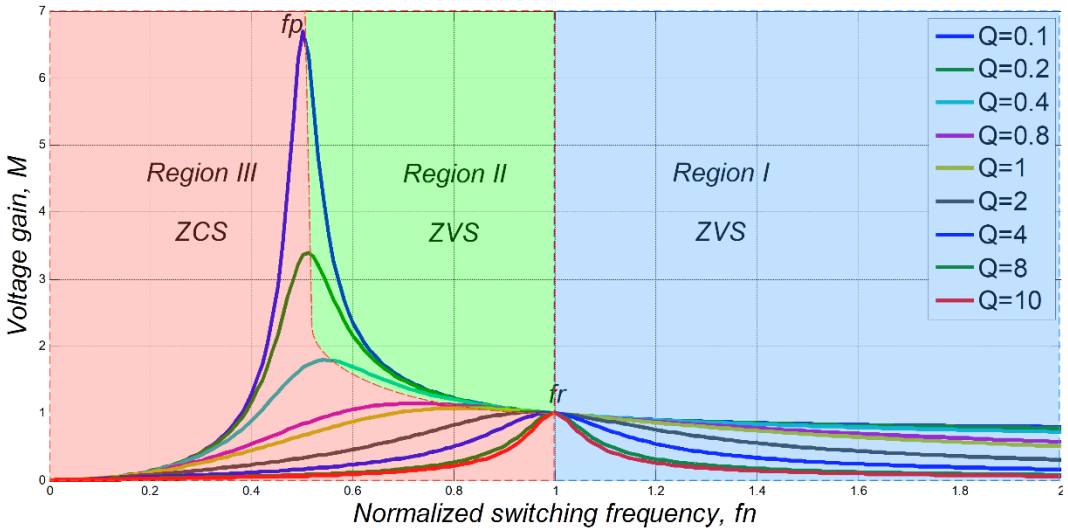

Figure 2.20: DC characteristic of conventional full-bridge LLC resonant converter [50].

rectifier side when operating in reverse way. Moreover, during the reverse power flow, the magnetizing inductance, L_m is in parallel with the bridge voltage causing it to no longer participates in resonant network, thus converting the topology into a series resonant DC-DC converter. The efficiency of the converter drops considerably as the switching frequency operates far away from the series resonant frequency, making it unsuitable for wide input and output range applications.

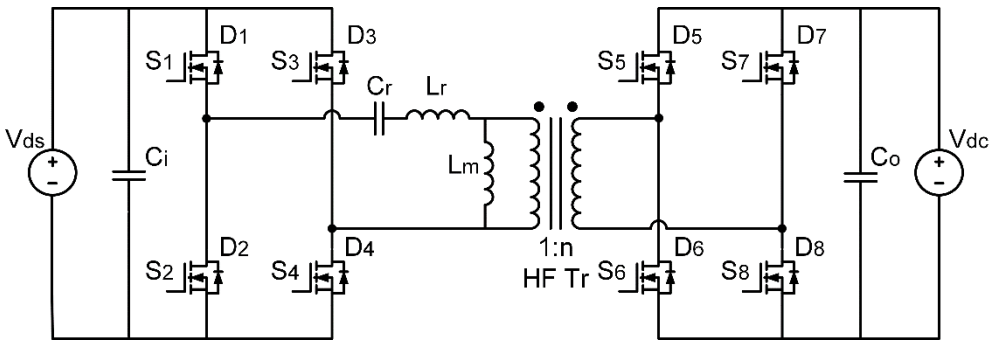

Figure 2.21: Isolated bidirectional DC-DC converter based on two voltage-fed full-bridges with a LLC resonant tank [60].