

HIGHER ORDER SERIES RESONANT DC-DC CONVERTER FOR HIGH VOLTAGE APPLICATIONS

ASIM AMIR

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**HIGHER ORDER SERIES RESONANT DC-DC CONVERTER FOR HIGH
VOLTAGE APPLICATIONS**

by

ASIM AMIR

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requirement for the degree
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TABLE OF CONTENTS

	Page
ACKNOWLEDGEMENTS	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	vii
LIST OF FIGURES	viii
LIST OF ABBREVIATION	xiv
LIST OF SYMBOLS	xv
ABSTRAK	xvi
ABSTRACT	xvii
CHAPTER 1: INTRODUCTION	
1.1 Background	1
1.2 Statement of Problem and Motivation	3
1.3 Research Scope	4
1.4 Research Objectives	5
1.5 Thesis Outline	5
CHAPTER 2: LITERATURE REVIEW	
2.1 Overview	7
2.2 Conventional HV DC Power Supplies	7
2.3 Switch Mode Converter Based HV Power Supplies	8
2.3.1 PWM Inverter Based HV DC Power Supply	8
2.3.2 Voltage Multiplier Based HV DC Power Supply	10

2.4	Resonant Converter Based HV DC-DC Power Supplies	12
2.4.1	Series Resonant Based HV DC-DC Converter	15
2.4.2	Parallel Resonant Based HV DC-DC Converter	19
2.4.3	Series Parallel Based Resonant HV DC-DC Converter	21
2.5	Higher Order Based Resonant HV DC-DC Converters	23
2.6	Comparison between Resonant Based HV DC-DC Converters	25
2.7	Control Techniques for Resonant Converters	27
2.7.1	Pulse Frequency Modulation	27
2.7.2	Pulse Amplitude Modulation	30
2.7.3	Phase Shift Modulation	31
CHAPTER 3: METHODOLOGY		
3.1	Overview	33
3.2	LCCL Series Resonant HV DC-DC Converter Controlled by Switching Frequency	33
3.2.1	Description of the Circuit	34
3.2.2	Control of Output Voltage by Switching Frequency	37
3.2.3	Steady-State Analysis of the Circuit	38
3.2.4	Modes of Operation	39
3.2.5	Frequency Response of the Proposed LCCL Series Resonant HV DC-DC Converter	42
3.3	LCCL Series Resonant HV DC-DC Converter Controlled by Linear Variable Inductor Control	46
3.3.1	Description of the Circuit	46
3.3.2	Control of Output Voltage by Linear Variable Inductor	47

3.4	LCCL Series Resonant Voltage Multiplier Based HV DC-DC Converter	49
3.4.1	Description of the Circuit	49
3.4.2	Steady-State Analysis	50
3.4.3	Modes of Operation	51
3.4.4	Frequency Response of the Proposed LCCL Series Resonant Voltage Multiplier Based HV DC-DC Converter	53

CHAPTER 4: DESIGN AND IMPLEMENTATION

4.1	Overview	56
4.2	Full Bridge Inverter/ Gate Drive Circuit and Control Signal Generation Circuit Design for the Proposed Converters	56
4.2.1	Design of Control Signal Generation Circuit	57
4.2.2	Design of Full Bridge Inverter and Drive Circuit	59
4.2.3	Determination of Voltage and Current Ratings of Power Switches and Selection of Power IGBTs for the Full Bridge Inverter	61
4.3	Design of High Voltage Transformer	62
4.3.1	Selection of Core	63
4.3.2	Determination of Wire Size	63
4.3.3	Determination of Number of Turns	64
4.3.4	Determination of Leakage Inductance	65
4.4	Design of Linear Variable Inductor	65
4.5	Design of LCCL Series Resonant Tank	67
4.6	Design of High Voltage Full Bridge Diode Rectifier	69

CHAPTER 5: RESULTS AND DISCUSSION

5.1	Overview	71
5.2	Proposed LCCL Series Resonant HV DC-DC Converter	71
5.2.1	Simulation Results	71
5.2.2	Experimental Results	76
5.2.2.1	Linear Variable Inductor Control	78
5.2.2.2	Switching Frequency Control	88
5.3	Proposed LCCL series resonant VM based HV DC-DC converter	97

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1	Conclusion	104
6.2	Future Work	105
	REFERENCES	106
	APPENDICES	114
	LIST OF PUBLICATIONS	115

LIST OF TABLES

	Page
Table 2.1 Comparison of series, parallel and series parallel resonant converters	27
Table 5.1 Parameters for simulation	72
Table 5.2 Parameters for laboratory Experiment for Linear Variable Control	77
Table 5.3 Results for linear variable inductor controlling of inductance value	78
Table 5.4 Parameters for laboratory Experiment for Switching Frequency Control	89
Table 5.4 Parameters for simulation	98

LIST OF FIGURES

		Page
Figure 1.1	Block diagram of dc-dc converter	2
Figure 2.1	Auto-transformer based HV DC power supply	8
Figure 2.2	Conventional PWM HV power supply	10
Figure 2.3	Operation of two stage Cockcroft-Walton multiplier	11
Figure 2.4	Voltage Multiplier based High Voltage power supply	12
Figure 2.5	Resonant converter based High Voltage power supplies	13
Figure 2.6	Equivalent circuit of HV transformer	14
Figure 2.7	Series resonant HV dc-dc converter	16
Figure 2.8	Half bridge dual series resonant DC-DC converter HV power supply	17
Figure 2.9	Multi series resonant DC-DC converter HV power supply	18
Figure 2.10	Two full bridge inverters with dual series resonant DC-DC Converter HV power supply	19
Figure 2.11	Parallel resonant HV DC-DC converter	21
Figure 2.12	Series parallel resonant based HV DC-DC converter	22
Figure 2.13	Third order resonant HV DC-DC converter	25
Figure 2.14	Fourth order resonant HV DC-DC converter	25
Figure 2.15	Wave forms for pulse frequency modulation control	30
Figure 2.16	Wave forms for pulse amplitude modulation control	31

Figure 2.17	Wave forms for phase shift modulation control	32
Figure 3.1	Schematic diagrams of the proposed LCCL series resonant HV DC-DC converter controlled by switching frequency	35
Figure 3.2	Control of output voltage by switching frequency	38
Figure 3.3	Steady-state waveform of the proposed system	39
Figure 3.4	Operating mode-1 of proposed series resonant converter	40
Figure 3.5	Operating mode-2 of proposed series resonant converter	40
Figure 3.6	Operating mode-3 of proposed series resonant converter	40
Figure 3.7	Operating mode-4 of proposed series resonant converter	41
Figure 3.8	AC equivalent circuits for proposed LCCL series resonant HV DC-DC converters	43
Figure 3.9	Schematic diagram of the proposed LCCL series resonant HV DC-DC converter-controlled by linear variable inductor	47
Figure 3.10	Control of output voltage by linear variable inductor	48
Figure 3.11	Schematic diagram of the proposed series resonant LCCL voltage multiplier based HV DC-DC converter	51
Figure 3.12	Operating mode-1 of proposed series resonant converter	52
Figure 3.13	Operating mode-2 of proposed series resonant converter	52
Figure 3.14	Operating mode-3 of proposed series resonant converter	53
Figure 3.15	Operating mode-4 of proposed series resonant converter	53
Figure 4.1	Full bridge inverter circuit with inverter drive circuit and control signal generation circuit	57
Figure 4.2:	Control signal generation TL494 microchip based circuit	59

Figure 4.3:	Full-bridge inverter isolation and drive circuit	61
Figure 4.4	Power switch (IGBT-IRGP4062DPbF)	62
Figure 4.5:	HV transformer design used in laboratory prototype	62
Figure 4.6:	Selected E-core for the HV transformer design	63
Figure 4.7:	Design of linear variable inductor	65
Figure 4.8:	Inductor control circuit	66
Figure 4.9:	Linear variable inductor design used in the laboratory prototype	67
Figure 4.10:	Proposed series resonant tank circuit	68
Figure 4.11:	Proposed LCCL series resonant tank design used in laboratory prototype	69
Figure 4.12:	Full bridge diode rectifier with capacitive filter design (a) circuit (b) prototype	70
Figure 5.1:	Simulation schematic diagram of proposed LCCL series resonant HV DC-DC converter	73
Figure 5.2:	Simulation results for variable inductor value at 10uH	74
Figure 5.3:	Simulation results for variable inductor value at 80uH	75
Figure 5.4:	Output voltage at various inductor values	76
Figure 5.5:	Gating signals for the inverter switches CH1 is S_1, S_4 and CH2 is S_2, S_3	79

Figure 5.6:	Experimental results for LVI-control at 7 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	80
Figure 5.7:	Experimental results for LVI-control at 15 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	81
Figure 5.8:	Experimental results for LVI-control at 20 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	82
Figure 5.9:	Experimental results for LVI-control at 25 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	83
Figure 5.10:	Experimental results for LVI-control at 28 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	84
Figure 5.11:	Experimental results for LVI-control at 30 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	84
Figure 5.12:	Experimental results for LVI-control at 33 μ H and constant	85

	switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	
Figure 5.13:	Experimental results for LVI-control at 36 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	86
Figure 5.14:	Experimental results for LVI-control at 44 μ H and constant switching at 80 kHz frequency (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant tank current. (b) CH1 is output voltage and CH2 is resonant current.	87
Figure 5.15:	Efficiency with respect to output power of the proposed LCCL series resonant HV DC-DC converter	88
Figure 5.16:	Gating signal (a) CH1 is for inverter switches S1,S4 and CH2 is resonant current at $F_s=80$ kHz. (b) CH1 is output voltage and CH2 is resonant current	90
Figure 5.17:	Gating signal (a) CH1 is for inverter switches S1,S4 and CH2 is resonant current at $F_s=86$ kHz. (b) CH1 is output voltage and CH2 is resonant current	91
Figure 5.18:	Gating signal (a) CH1 is for inverter switches S1,S4 and CH2 is resonant current at $F_s=90$ kHz. (b) CH1 is output voltage and CH2 is resonant current	92

Figure 5.19:	Gating signal (a) CH1 is for inverter switches S1,S4 and CH2 is resonant current at $F_S=96$ kHz. (b) CH1 is output voltage and CH2 is resonant current	93
Figure 5.20:	Gating signal (a) CH1 is for inverter switches S1,S4and CH2 is resonant current at $F_S=100$ kHz. (b) CH1 is output voltage and CH2 is resonant current	94
Figure 5.21:	Gating signal (a) CH1 is for inverter switches S1,S4 and CH2 is resonant current at $F_S=106$ kHz. (b) CH1 is output voltage and CH2 is resonant current	94
Figure 5.22:	Gating signal (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant current at $F_S=121$ kHz.(b) CH1 is output voltage and CH2 is resonant current	95
Figure 5.23:	Gating signal (a) CH1 is gating signal for inverter switches S1,S4 and CH2 is resonant current at $F_S=131$ kHz (b) CH1 is output voltage and CH2 is resonant current	96
Figure 5.24:	Efficiency with respect to output power of the proposed LCCL series resonant HV DC-DC converter for switching frequency control	97
Figure 5.25	Simulation schematic diagram for proposed series resonant VM based DC-DC converter	99
Figure 5.26:	Simulation results for variable inductor value at 10uH	100
Figure 5.27:	Simulation results for variable inductor value at 80 μ H	101
Figure 5.28:	Output voltage at various inductor values	102

LIST OF ABBREVIATIONS

AC	Alternating current
AC-DC	Alternating current to direct current
CCM	Continuous conduction mode
DC	Direct current
DC-DC	Direct current to direct current
DCM	Discontinuous conduction mode
HV	High-voltage
IGBT	Insulated gate bipolar transistor
MOSFET	Metal-oxide-semiconductor field-effect transistor
OP-AMP	Operational amplifier
PFM	Pulse frequency modulation
PSM	Phase shift modulation
PWM	Pulse width modulation
VM	Voltage multiplier
ZCS	Zero current switching
ZVS	Zero voltage switching
LVI	Linear variable inductor

LIST OF SYMBOLS

A_c	Cross sectional area of ferrite core
B_m	Magnetic flux density
C	Resonant tank capacitor
C_p	Parallel capacitor
C_s	Series capacitor
C_1, C_2, C_3, C_4	1 st , 2 nd , 3 rd , 4 th bootstrap capacitor
D_1, D_2, D_3, D_4	1 st , 2 nd , 3 rd , 4 th antiparallel diode of power switches
D_1, D_2, D_3, D_4	1 st , 2 nd , 3 rd , 4 th bootstrap diode
$D_{Z1}, D_{Z2}, D_{Z3}, D_{Z4}$	1 st , 2 nd , 3 rd , 4 th zener diode
f_r	Resonant frequency
$f_{r(p)}$	Parallel resonant frequency
$f_{r(s)}$	Series resonant frequency
f_s	Switching frequency
f_{start}	Switching frequency during start-up
L_s	Leakage inductance of high-voltage transformer
n	Turns ratio of high-voltage transformer
N_p	Primary turns of high-voltage transformer
R_L	Load resistor
S_1, S_2, S_3, S_4	1 st , 2 nd , 3 rd , 4 th power switch (IGBT)
V_{in}	Input voltage
V_o	Output voltage
Z	Impedance
ω_r	Angular resonant frequency

PENUKAR AT-AT SALUNAN SIRI PERINGKAT TERTINGGI UNTUK PENGUNAAN VOLTAN TINGGI

ABSTRAK

Bekalan kuasa penukar AT-AT bervoltan tinggi (HV) salunan siri konvensional mampu menyerap kebocoran aruh daripada pengubah HV, lalu memberikan tekanan rendah kepada komponen dan menghalang pengubah HV daripada tepu, tetapi mempunyai batasan seperti kebolehpayaan kawalan yang lemah pada beban ringan, dan kecekapan yang rendah. Untuk mengatasi masalah tersebut, kajian ini mencadangkan topologi salunan berperingkat tinggi bagi penukar AT-AT HV salunan siri serta dua strategi kawalan voltan output yang berbeza. Salunan siri peringkat keempat LCCL bagi penukar AT-AT HV direka yang terdiri daripada empat elemen penyimpanan; kapasitor disambung secara selari dengan pengaruh bolehubah linear (LVI) dan induktans bocor pengubah HV secara siri. Dua strategi kawalan dicadangkan untuk mengawal voltan keluaran penukar AT-AT HV salunan siri LCCL. Strategi kawalan yang pertama adalah berdasarkan kawalan frekuensi pensuisan sementara mengekalkan frekuensi salunan malar. Dalam strategi kawalan kedua, frekuensi pensuisan dimalarkan manakala kawalan voltan output dicapai dengan mengubah kearuhan salunan. Ini dapat dicapai dengan menggunakan LVI dalam litar tangki. Dua strategi kawalan ini yang mengawal voltan keluaran bagi penukar AT-AT HV salunan siri LCCL beroperasi dalam mod pengaliran berterusan. Dua skim kawalan digunakan ke salunan siri LCCL berasaskan AT-AT HV menunjukkan keupayaan menghasilkan voltan keluaran tinggi pada kecekapan 75% untuk kuasa masukan 18W. Keputusan di sahkan oleh simulasi dan juga rekabentuk makmal.

HIGHER ORDER SERIES RESONANT DC-DC CONVERTER FOR HIGH VOLTAGE APPLICATIONS

ABSTRACT

The conventional series resonant High Voltage (HV) DC-DC converter power supply is able to absorb the leakage inductance of the HV transformer, provides lower component stress and prevents the HV transformer from being saturated but poses poor controllability at light load and lower efficiency. To overcome these problems, this research work proposes higher order resonant topologies of series resonant HV DC-DC converter with two different output voltage control strategies. A fourth order LCCL series resonant HV DC-DC converter was designed consisting of four storage elements; a capacitor connected in parallel with a linear variable inductor (LVI) and the leakage inductance of the HV transformer in series. Two control strategies are proposed to regulate the output voltage of the LCCL series resonant HV DC-DC converter. First control strategy, is based on varying the switching frequency while keeping the resonant frequency constant. In the second control strategy, the switching frequency is kept constant while the output voltage control is achieved by varying the resonant inductance. This is accomplished by using a LVI in the tank circuit. Operation of the converter is carried out in continuous conduction mode. Both control schemes which are implemented to the LCCL series resonant based HV DC-DC converter show the capability to produce high output voltage at 75% efficiency for input power of 18 W. The result is verified for both simulation and experimental setup.

CHAPTER 1

INTRODUCTION

1.1 Background

Consumption of energy is increasing rapidly around the globe these days. Therefore requirement of green energy sources have become a part of the future energy system. The thought that invokes the idea for a change from ground to hall on energy sources to green and renewable energy sources is all based and biased today on the platform of power electronics; where power converter systems gain special status for day in and day out demands.

Immense amount of work is done by researchers in the past years to improve the power converter technologies. Power converters are employed to provide regulated voltage to drive the internal circuit of a particular application, the power range of one of these HV power supplies can be from several watts, up to hundreds of kilowatts. Typical applications of power converters include computer power supplies, house appliance power supplies, battery chargers, welding machines, telecommunication power supplies, dc motor drives, etc [1, 2].

Figure 1.1 presents the basic block diagram of a resonant based converter power supply for HV applications. This power supply is divided into six portions [3]-[5]. A full bridge inverter is employed with four power switches IGBTs or MOSFETs. The inverter requires a controller circuit which triggers the switches between ON-OFF conditions. Various types of modulation techniques can be applied to control the inverter switches for example PF pulse frequency or PA pulse

amplitude modulation control techniques [6]-[10]. A resonant tank circuit with a combination of a capacitor and an inductor in series, parallel or series parallel arrangement [11]-[13]. The core component stands to be the high voltage transformer with a capability to boost the voltage. Finally a full bridge diode rectifier is required with a filter capacitor.

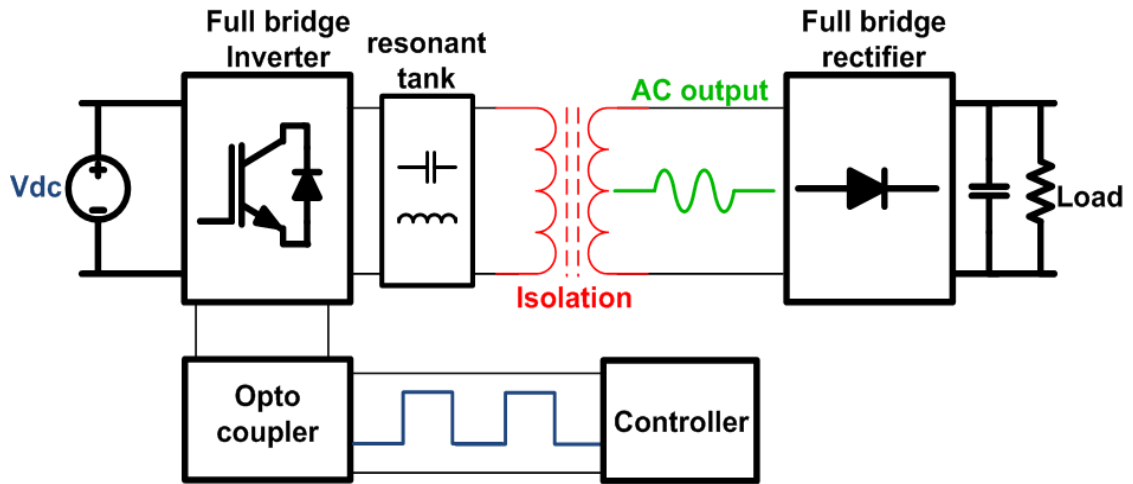


Figure 1.1: Block diagram of DC-DC converter

The functionality of the HV power supply comes into its focal operation by utilizing the invention of gate controlled switching devices (power switches), IGBTs or MOSFETs. Since these power switches come with higher power, voltage and current ratings, they provide loss less switching and make possibility of designing high voltage power supplies in kilo volt range. High voltage DC power supplies are utilized in various applications such as X-ray power supplies, lasers, accelerators and many more.

Many researchers have developed power supplies for various applications worldwide over the years until recent, but still problems associated with HV DC power supplies demand certain amount of novelty work to improve the power supply

technique. Therefore, the need for development of DC power supplies in higher voltage range still remains a difficult task to be accomplished.

1.2 Statement of Problems and Motivation

The core component used in the design of any HV power supply is the HV transformer, used to boost the voltage. The HV transformer exacerbates non-idealities such as leakage inductance and winding capacitance due to the reason that it requires large turn's ratio (500-800) depending on the application. The performance of the DC-DC converter is largely affected by these non-idealities. These non-idealities inherent problems like voltage current spikes in the output voltage and increase switching losses.

To eliminate the problems associated with the HV transformer, resonant based DC-DC converter topologies have been proposed such as series, parallel and series-parallel resonant. However, each resonant topology has its merits and demerits dependent on the bases of their individual performance [14, 15].

The series resonant HV DC-DC converter is used in the design of HV power supply for its capability to absorb the leakage inductance of the HV transformer. Moreover switching losses are minimum, there is no saturation of HV transformer and provides inherent over load protection since it behaves as a current source. And it provides good control when operated at heavy loads. It is also able to control the output voltage over a wide range since the resonance is in series with the load. The converter requires a capacitive filter at the output to eliminate the voltage ripples. However, series resonant HV DC-DC converter has poor controlling capability

when operated on light loads or no load. It requires high frequency or some other control method to overcome this problem [16]-[17].

If problems associated with the series resonant HV DC-DC converter, like controllability at light loads and efficiency could be increased. The performance of HV DC-DC converter for high voltage application can be made better.

Therefore, this thesis proposes new topologies of series resonant HV DC-DC converter to overcome these problems.

1.3 Research Scope

The scope of this research focuses on the method to design and implement novel higher order series resonant DC-DC converter topologies for high voltage applications. It begins by a brief literature review on various converter topologies for HV applications. Research then proposes two novel higher order series resonant topologies for HV applications namely a LCCL series resonant HV DC-DC converter topology and a LCCL series resonant voltage multiplier-based HV DC-DC converter topology.

The design of the power circuits and their implementations on laboratory prototypes are included in this research. Finally, the feasibility of proposed converters is tested. Verification is done by simulation performed on OrCAD PSpice software and it is tested by laboratory experiments. The performances of the proposed converters are justified by the results from simulation and experiment results.

1.4 Research Objectives

The main objectives of this research are:

- (a) To propose a LCCL series resonant HV DC-DC converter.
- (b) To design and evaluate the performance of the proposed LCCL series resonant HV DC-DC converter.
- (c) To control the output voltage over a wide range by switching frequency control scheme.
- (d) To control the output voltage over a wide range by linear variable inductor control scheme.

1.5 Thesis Outline

Chapter 1: Thoroughly discusses the general discussion on energy consumption, HV power supplies and their applications, after that addresses related problems associated with the design of conventional series resonant converter topology. The objective of the thesis is presented.

Chapter 2: Presents a brief review of the literature for the HV DC-DC converter power supply topologies. The topologies that have been proposed by researchers worldwide up to date are discussed. The three conventional resonant series, parallel, and series-parallel HV DC-DC converter topologies have been reviewed, advantages and disadvantages of each resonant topology are presented and compared. Higher order resonant topologies and the control techniques for the resonant converters have been presented.

Chapter 3: This chapter describes the proposed two novel topologies for HV power supplies. First, the LCCL series resonant HV DC-DC converter and then the LCCL series resonant voltage multiplier based HV DC-DC. The explanation includes its circuit operation, steady state analysis and frequency response analysis. Furthermore two control schemes are presented to control the converters output voltage.

Chapter 4: Discusses the designs associated to all components of the proposed converters. Implemented laboratory prototype is also presented.

Chapter 5: Simulation and experimental results are discussed for the proposed converters. Based on the respective simulation and experimental results the performances of both HV DC-DC converter topologies have been evaluated. Output voltage control range and efficiency is given and presented for each of the converter.

Chapter 6: Research findings are concluded in this chapter. Achievements of the research objective, quality of the proposed converters for high voltage applications and observations are presented. Finally, advancement in the future for continuing this work has been suggested.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter presents the literature review on the HV DC power supply topologies starting with the earliest conventional HV DC power supply designs which is autotransformer based. After that switch mode converter based HV DC power supplies are presented in which PWM inverter and Cockcroft-Walton voltage multiplier based HV DC power supplies are discussed. This chapter will also discuss the resonant converter based HV DC-DC converter topologies in which series, parallel, and series parallel resonant DC-DC converters are included. Higher order resonant DC-DC converters are given. The control techniques for resonant converters are presented. Finally a brief comparison is presented on these topologies on the bases of their individual performance as high voltage power supplies.

2.2 Conventional HV DC Power Supplies

Autotransformer Based HV DC Power Supply

The auto-transformers firstly used in HV DC power supplies are constructed from a single winding and single core, portion of which is primary and portion secondary. AC voltage is applied across two of the primary terminals, and the secondary voltage taken from one common terminal and one variable tap connected to the control

panel which adjusts the variable tap varied according to the load requirements. A high voltage transformer is preferred to step-up the voltage, finally DC voltage is supplied to the load by a full bridge diode rectifier, and this topology is shown in Figure 2.1 [18]. Although this topology is efficient to control the voltage at the output over a wide range, by varying a tap between the autotransformer winding, it lacks to provide smooth output voltage when varied due to the fact that variation on the autotransformer voltage is varied in steps. Due to low operating frequency around 60Hz, since this converter is fed from AC line the output DC voltage results in high percentage of voltage ripples, and that affects the performance of the high voltage transformer.

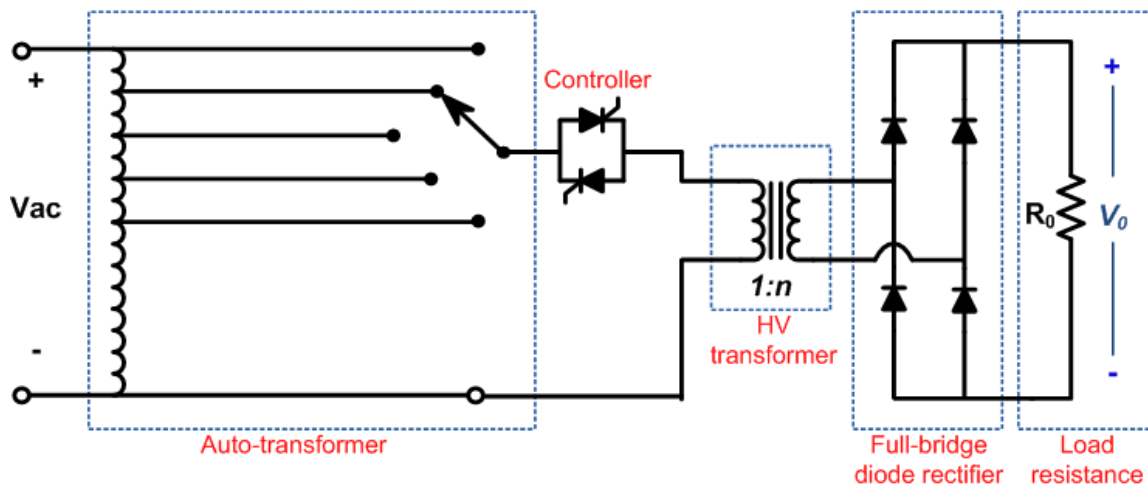


Figure 2.1: Auto-transformer Based HV DC power supply.

2.3 Switch Mode Converter Based HV Power Supplies

2.3.1 PWM Inverter Based HV DC Power Supply

The conventional PWM inverter based HV DC power supply is constructed from a low frequency diode rectifier with a low pass filter capacitor, a full bridge

inverter, a HV transformer and full bridge diode rectifier with high frequency diode rectifier. AC line voltage with 60Hz of frequency is supplied at the input. The action of input rectifier is to convert the AC line voltage to a more stable DC voltage. The full bridge inverter converts the DC voltage into AC voltage with a frequency exactly equal to the PWM drive frequency. AC output voltage from the full bridge inverter is stepped up using a HV transformer with high turns ratio built according to voltage required as per application. Full bridge diode rectifier is employed to convert secondary AC high voltage into DC high voltage and supplied to the load after filtering through a filter capacitor in order to remove voltage ripples as shown in Figure 2.2[19].

By varying the pulse width of the power switches the output voltage could be controlled. Power transfer to the load depends on the duty cycle, when the switches are turned ON power is transferred, whereas no power can be transfer occurs if the switches are OFF. In this topology the duty cycle is set less than 50%.

However the power switches in this topology are turned ON and OFF over hard switching, which can cause switching losses. Moreover high voltage transformer due to high insulation requirements between the primary and secondary windings causes non-idealities such as parasitic capacitances and leakage inductances. These non-idealities result into voltage ripples and current spikes are produced at the output. In addition, due to leakage inductance the inductive reactance increases in the primary side which will slow down the flow of current through the power switches which affects the power transfer [20, 21].

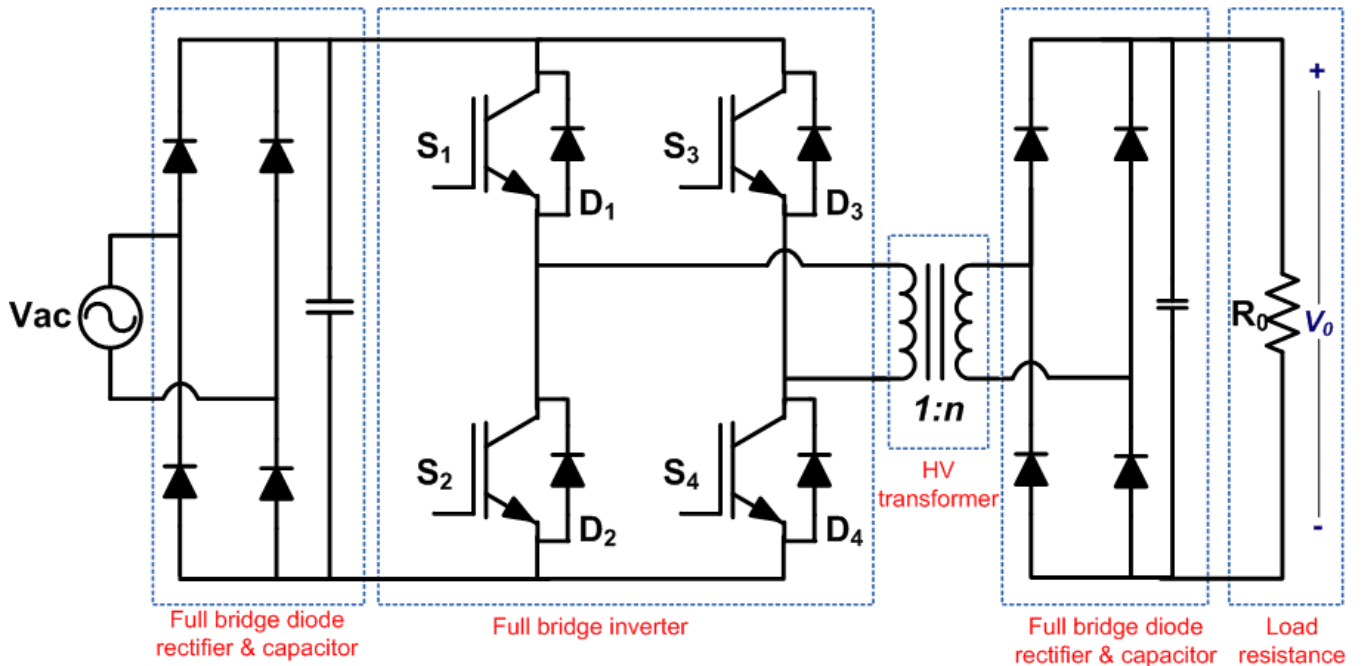


Figure 2.2: Conventional PWM HV power supply.

2.3.2 Voltage Multiplier Based HV DC Power Supply

Voltage multiplier circuit is a combination of high voltage capacitors and high voltage power diodes constructed in order to convert AC electrical power from a lower potential to a higher DC potential as it passes through the stages of the multiplier. The voltage boosting capability depends on the number of stages. Multiplier circuit was named after John Douglas Cockcroft, a British physicist and Ernest Thomas Sinton Walton an Irish physicist in 1932. Today Cockcroft-Walton circuits are being used in accelerators, high voltage power supplies, x-ray machines, television sets, and photocopiers [22] [23].

Figure 2.3 shows the operation of a two stage multiplier circuit, capacitor (C_2 and C_4) are smoothing capacitors and capacitors (C_1 and C_3) are coupling capacitors, while

(D_1, D_2, D_3, D_4) are a series connected diode rectifier. The number of stages is equal to the number of smoothing capacitors between ground and output voltage, in this case there are two.

The input voltage is rectified and increases as it passes through each stage of the multiplier circuit depending on the stages involved. During the negative or the lowest peak, capacitor C_1 is charging through D_1 diode. After the capacitor C_1 is charged up to X the potential of capacitor C_1 adds with the source during positive peak and charges capacitor C_2 up to twice the potential of C_1 up to $2X$ through diode D_2 .

Again during the second negative cycle the potential across C_1 falls to $0V$, thus permitting C_3 to charge up to $2X$ through D_3 . Over the second positive peak again the potential across C_1 increases up to $2X$, simultaneously C_4 is charging up to $2X$. During this the output voltage becomes the sum of the potential difference across C_1 and C_4 which rises up to $4X$. Here X is the potential difference between the capacitor.

As the multiplier circuit performs with two diodes and two capacitors at each additional stage increases the voltage at the output by twice the peak AC voltage of the supply.

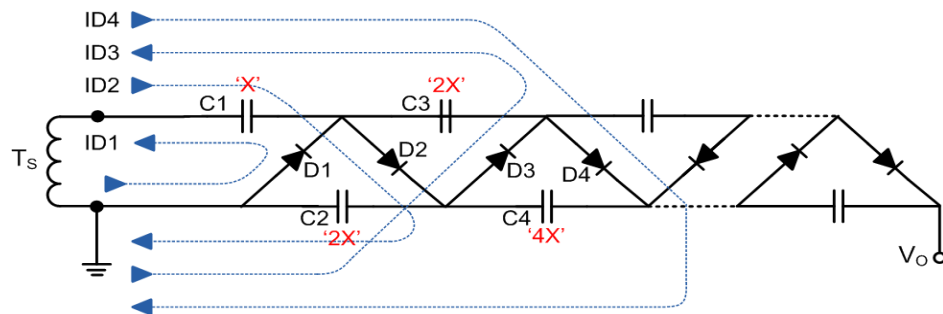


Figure 2.3: Operation of two stage Cockcroft-Walton multiplier.

The multiplier circuit is useful in high voltage power supplies when connected at the secondary side of the transformer so as to increase the output voltage and decreases the parasitic elements associated with the transformer.

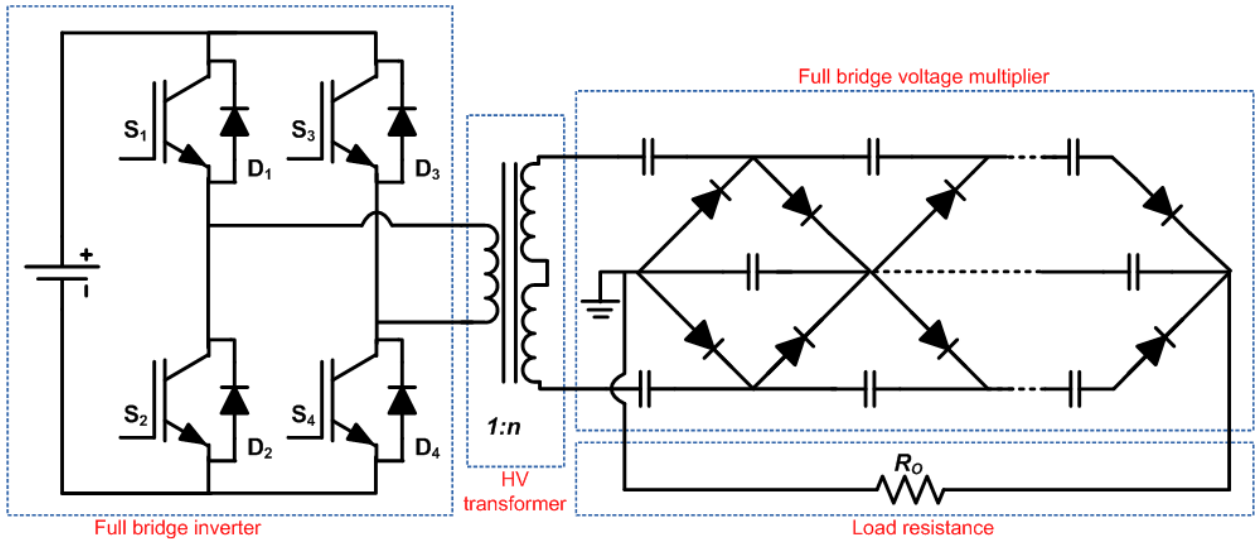


Figure 2.4: Voltage multiplier based high voltage power supply.

2.4 Resonant Converter Based HV DC-DC Power Supplies

Switching can rather be made soft in conventional PWM converters by introducing an inductor and a capacitor as a resonant tank connected between the inverter and primary side of HV transformer. Addition of LC resonant components introduces an under-damped behavior in the circuit and resonant current becomes approximately sinusoidal. Soft switching also minimizes the conduction losses in the components. Furthermore, by controlling the difference between the resonant frequency and the switching frequency, control of power flow to the load can be achieved.

In these converters the load is considered as a part of the resonant tank to assist zero-current switching and zero-voltage switching conditions between the inverter switches. Zero voltage switching condition can be achieved if the switching frequency is made more than the resonant frequency on the other hand zero current switching is accomplished by making the switching frequency less than the resonant frequency.

Figure 2.6 shows the topology of the resonant converter based HV DC-DC power supply which was constructed similar to the conventional PWM inverter based HV DC power supply but a resonant tank circuit consisting of a capacitor and inductor is connected between the full bridge inverter and the high voltage transformer.

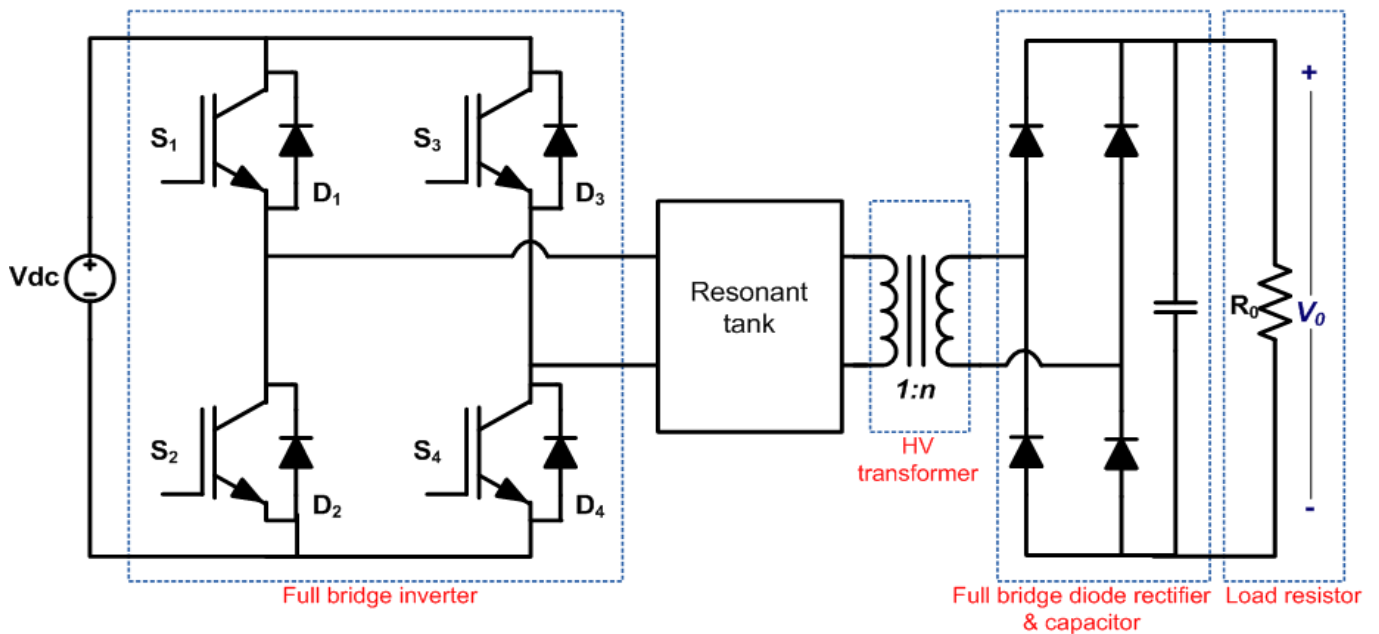


Figure 2.5: Resonant converter based high voltage power supplies

The HV transformer requires higher turns ratio and insulation requirements between the primary and secondary of the HV transformer, result into magnifying non-idealities such as parasitic capacitance and leakage inductance as shown in equivalent

circuit of HV transformer in Figure 2.6. Increased voltage and current spikes are observed at the output of the converter. To overcome these non-idealities several types of resonant converters are proposed by researchers such as series, parallel, and series-parallel [24].

In the series resonant topology, load is connected in series with the resonant inductor and the capacitor, where the leakage inductance can be absorbed from the HV transformer with the assistance of the series connected capacitor. In the parallel resonant topology, load is connected in parallel with the capacitor. This arrangement is able to absorb the leakage inductance and parasitic capacitance of the high voltage transformer. LC arrangement in the parallel resonant tank is according to the non-idealities of the high voltage transformer. Series-parallel resonant tank is a combination of both aforementioned tank circuits. This arrangement has the ability to absorb leakage inductance and parasitic capacitance of the high voltage transformer with an additional assistance from an extra capacitor connected in series [25-26].

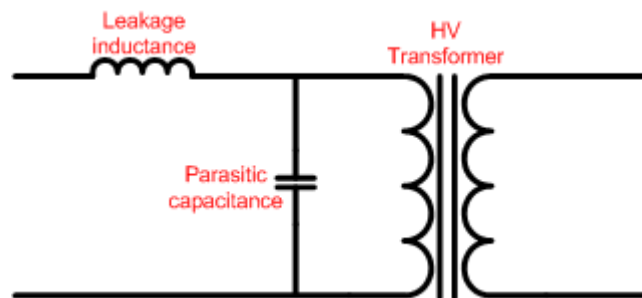


Figure 2.6: Equivalent circuit of HV transformer.

2.4.1 Series Resonant Based HV DC-DC Converter

Figure 2.7 shows the schematic diagram of a full bridge series resonant DC-DC converter. In the series resonant converter the load is connected in series with the resonant tank and resonant tank is made up of an inductor and a capacitor. Impedance of the resonant tank is changed by varying the switching frequency. When the switching frequency is set lower than the resonant frequency the converter operates in zero current switching ZCS condition. On the other hand when the switching frequency is higher in comparison with the resonant frequency, the converter operates under zero voltage switching ZVS condition. Whereas if the switching frequency is made equal to the resonant frequency, the impedance of the resonant tank can be decreased to minimum, allowing maximum input power flow to the load. Moreover, as switching frequency increases, the impedance of the resonant tank increases resulting in blocking the path for the input power flow to the load by creating oscillations in the primary side. So for series resonant converter, the maximum gain happens at resonant frequency [26]-[28]. However it has a poor performance at light loads and no load, in order to regulate the output voltage at light loads the switching frequency needs to be increased or decreased greatly [29, 30].

Capacitor connected in the series resonant topology is able to absorb the leakage inductance of the high voltage transformer and avoids the transformer from being saturated [24, 26]. This topology behaves as a current source which provides inherent over-load protection. Moreover it provides high efficiency over a wide range of loads and has an ability to produce high output load current [28].

Moreover the resonant current decreases as the load on the output is reduced due to series connection with the load. Therefore this topology is able to maintain high efficiency for a wide load range [31, 32].

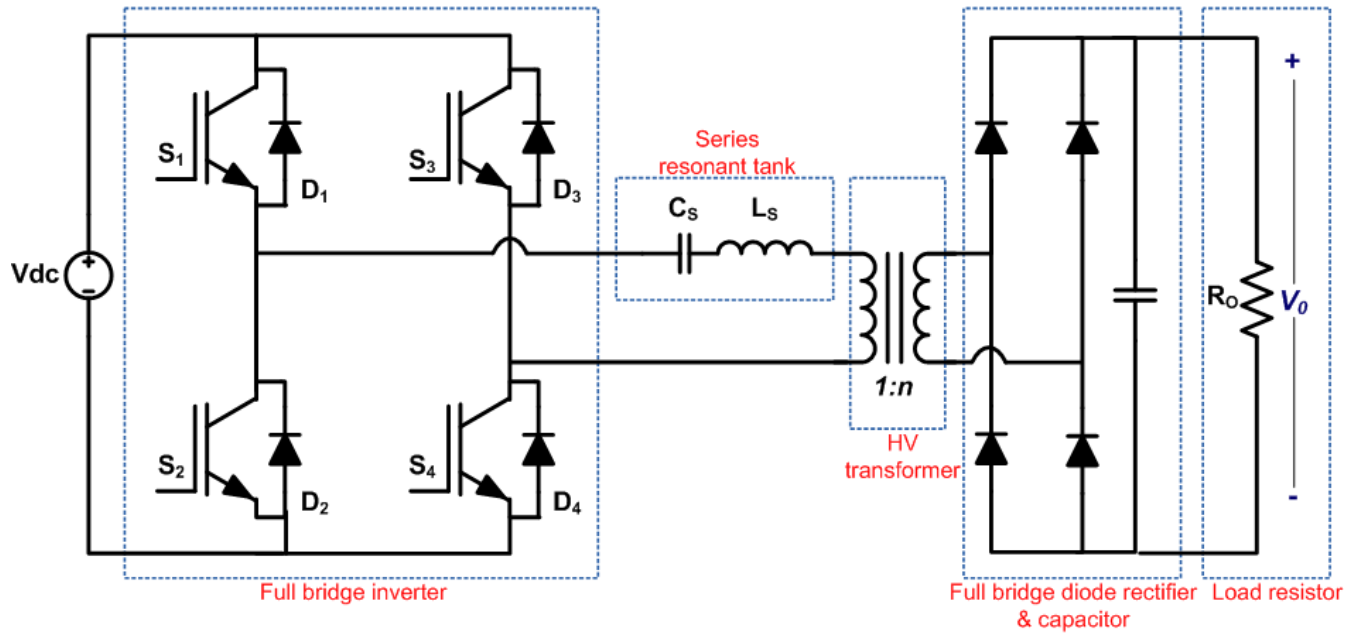


Figure 2.7: Series resonant HV DC-DC converter

Lee et.al in [33] have proposed a novel ZCS series resonant topology for high voltage applications which consists of two series resonant tanks connected to two high voltage transformers this topology is shown in Figure 2.8. The operation is carried in discontinuous conduction mode, and inverter switches are turned ON and OFF at ZCS condition therefore switching loss are minimized. However this converter has two transformers therefore it consists of more transformer non-idealities.

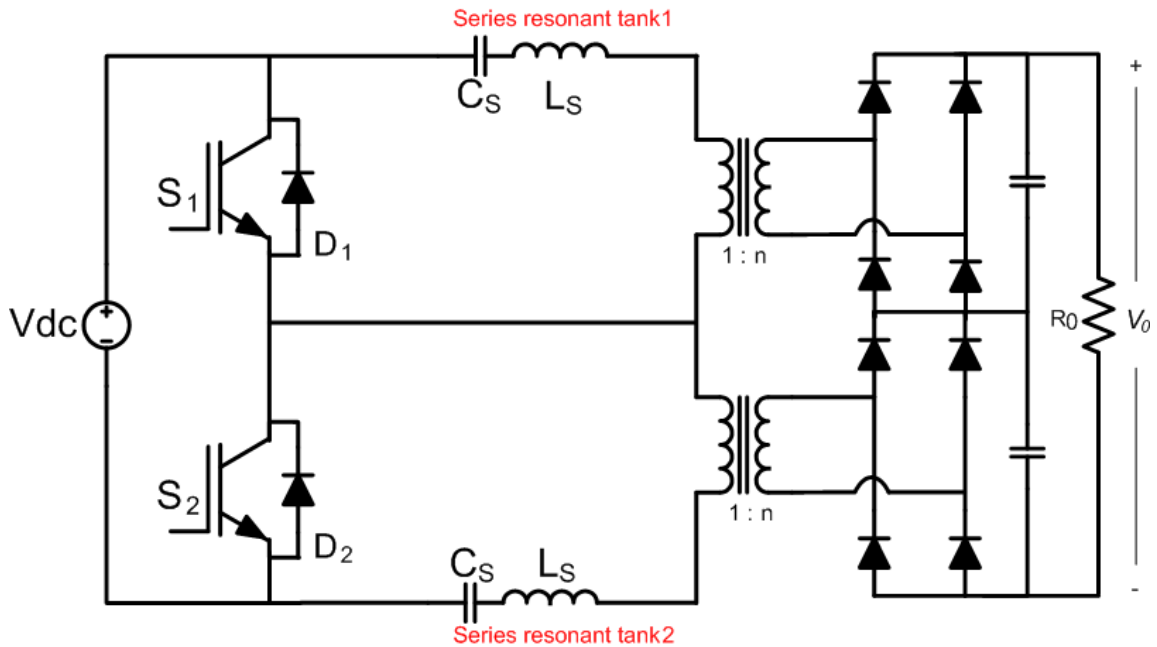


Figure 2.8 Half bridge dual series resonant DC-DC converter high voltage power supply.

Lee et.al in [34] has proposed a ZCS series resonant high voltage DC-DC converter for X-ray power supply shown in Figure2.9. This topology has five resonant capacitors with increasing value form one another with a relay switches to turn ON and OFF. It is operated in DCM and the inverter switches are turned ON and OFF at ZCS. The output voltage is controlled by the five capacitors in the series resonant tank. One of the five capacitors is default which is present in the tank always while other four are included or excluded from the tank via four relay switches. As the capacitance of the resonant tank increases the output power increases and output power decreases as the capacitance decreases.

This topology is able to absorb the leakage inductance of the high voltage transformer as it consists of several capacitors of different value at the primary side of the transformer.

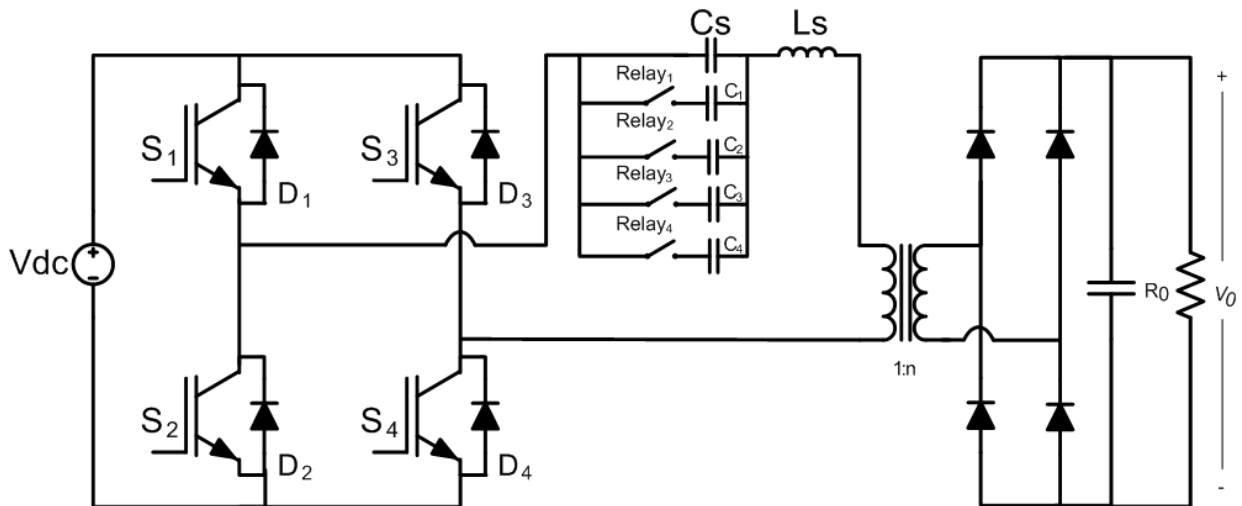


Figure 2.9 Multi series resonant DC-DC converter HV power supply.

Figure 2.10 shows a new series resonant DC-DC converter topology for high voltage applications. This topology is proposed by Iqbal et.al in [35]. Two full bridge inverters are employed and two series resonant tanks are connected to the inverters individually. Output voltage from these two series resonant tanks is boosted by two high voltage transformers and then rectified through a voltage multiplier. Control of the output voltage is achieved by controlling the phase shift of the output voltage of both inverters. However is this topology soft switching is not achieved. This topology has a lot of switches which makes it difficult to control.

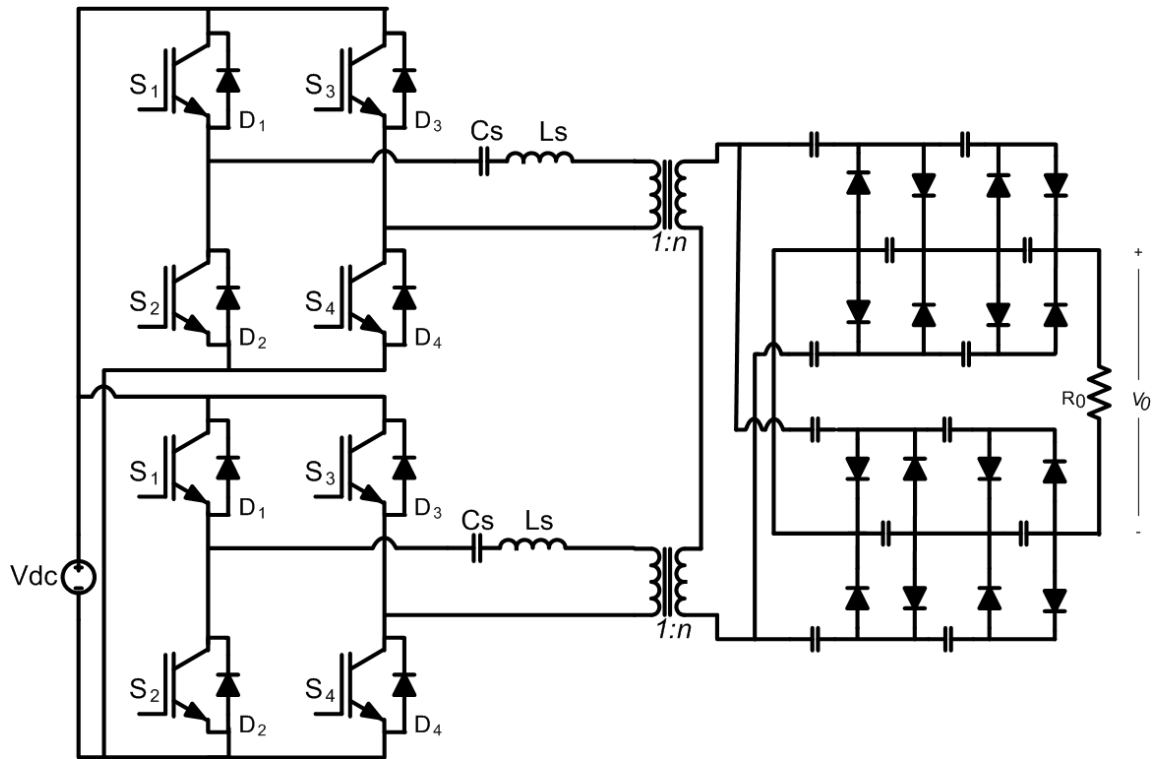


Figure 2.10: Two full bridge inverters with dual series resonant DC-DC converter HV power supply.

2.4.2 Parallel Resonant Based HV DC-DC Converter

In parallel resonant converter, the resonant tank consists of an inductor and a capacitor. Where the capacitor is connected in parallel with the load but the inductor still behaves in series with the load. In this converter a LC filter is preferable at the load to compensate the parallel connected capacitor at the primary side [36, 37].

Figure 2.11 shows the schematic diagram of a full bridge parallel resonant DC-DC converter. Parallel resonant converter has an advantage over the series resonant converter, where it is able to control the output voltage at light load without having a need to vary the switching frequency over a wide range [38]-[40].

In parallel combination when the switching frequency is made higher than the resonant converter, the circuit becomes inductive and the power switches turn ON and OFF at ZVS condition. This will reduce the impedance of resonant tank; hence the flow of input power to the output is maximum. In contrast, when the switching frequency is set lower than half of the resonant frequency, the circuit becomes capacitive which increases the impedance of the resonant tank, and the power switches turn ON and OFF at ZCS condition thus the flow of input power to the output reduces to minimum. A third condition occurs when the switching frequency is equal to the resonant frequency in this condition resonant tank impedance is minimum, during this condition the circuit behaves as a closed circuit, therefore the output voltage is maximum. The parallel resonant converter should not be operated below the resonant frequency condition. Optimal results are possible when the converter is operated above resonant frequency [41].

Parallel resonant converter topology can utilize the leakage inductance and parasitic capacitance of the high voltage transformer as its arrangement of the resonant elements is same as transformer parasitic elements [24], [26]. In addition, this topology is unable to prevent transformer from being saturated [42]. Moreover, the resonant current remains constantly high even though the load on the output is reduced. This is because the resonant tank is connected in parallel with the load. This topology has low efficiency if output load is light [36].

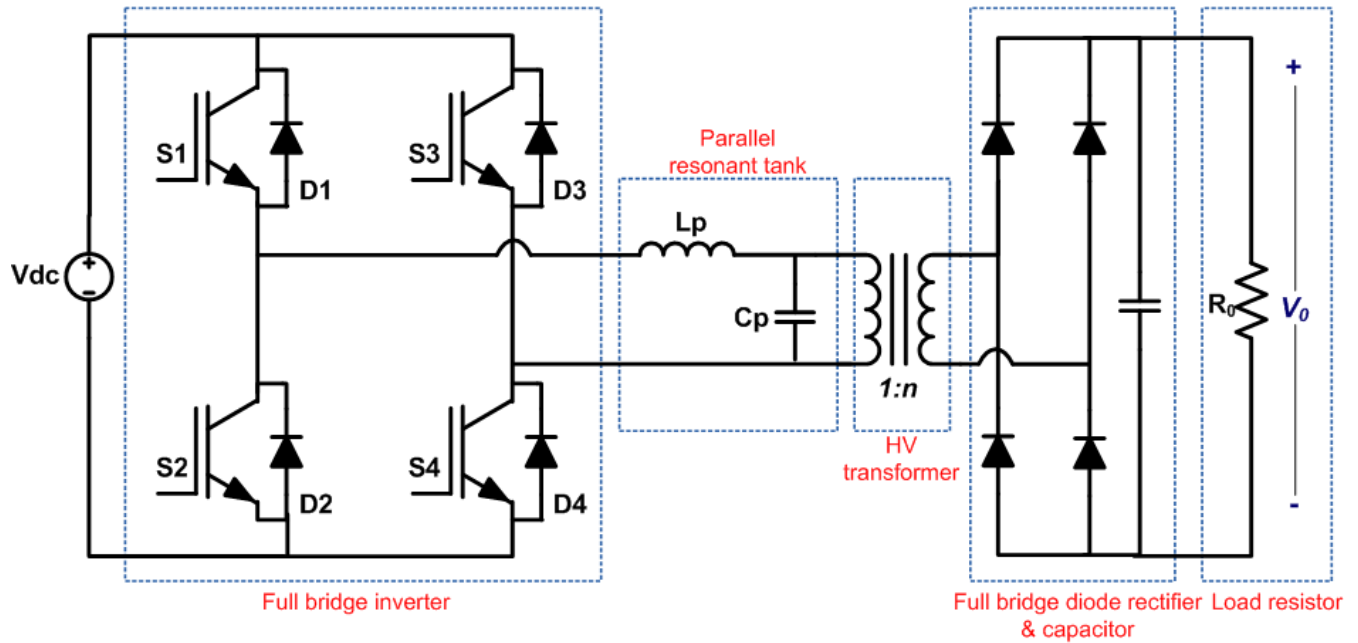


Figure 2.11: Parallel resonant HV DC-DC converter.

2.4.3 Series Parallel Resonant Based HV DC-DC Converter

Series parallel resonant converter is a combination of series and parallel resonant converter. It is constructed of three storage elements an inductor L_s and capacitor C_s connected in series and a capacitor C_p connected in parallel with the load as shown in Figure 2.12. This topology is also known as LCC resonant converter.

In this converter dual properties of series and parallel converter can be observed. It is able to control the output voltage at light loads like parallel resonant converter. However the efficiency is lower compared to series resonant converter [43]-[47].

Series Parallel resonant converter topology can utilize the leakage inductance and parasitic capacitance of the high voltage transformer as its arrangement of the

resonant elements is same as transformer parasitic elements and also it consists of an extra capacitor in series. This extra series capacitor avoids the high voltage transformer from going into saturation [24]-[26], [48], [49].

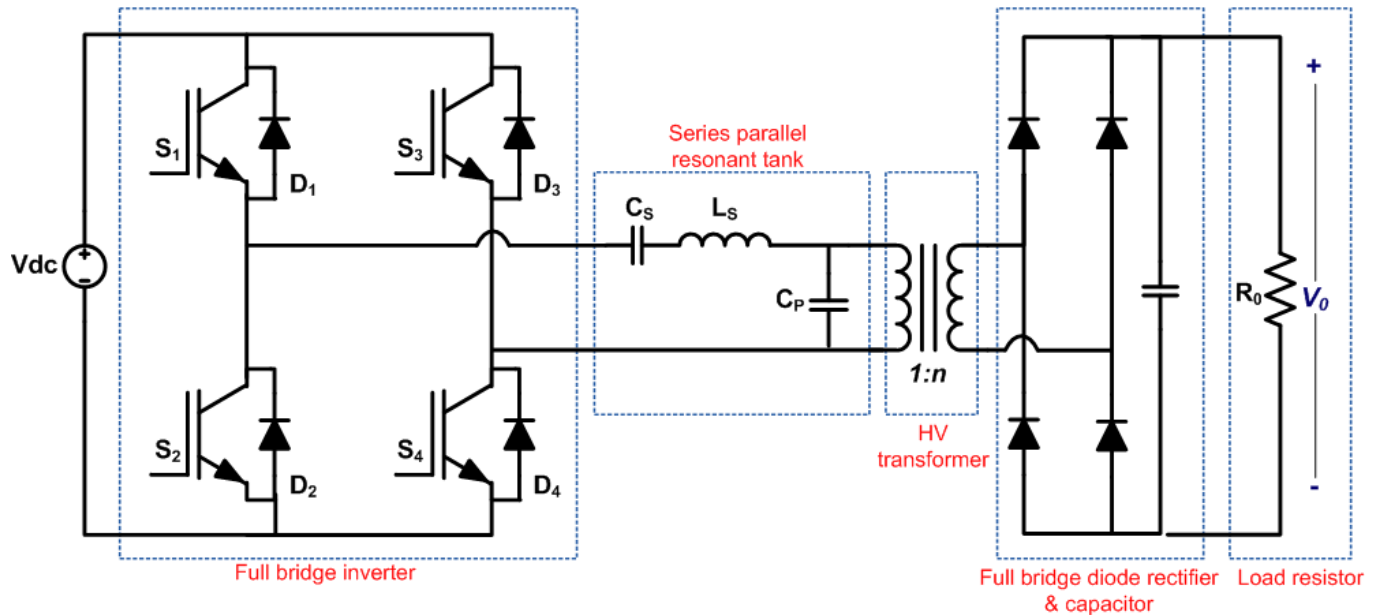


Figure 2.12: Series parallel resonant based HV DC-DC converter.

The main advantage of the parallel resonant converter is that the output DC filter capacitor does not carry high ripple currents. This is because in the parallel resonant converter, output diodes rectify the voltage (not current as in the case of series converter). This feature makes it possible to use a LC output filter in which the inductor limits the ripple current of the output capacitor. Steigerwald in [26] has used an inductive filter in series-parallel resonant converter. Also capacitive filter has been used by Bhat in [50], [51]. Capacitive filter is used for applications that require high voltage.

It is difficult to control the resonant frequency of the series-parallel resonant converter because it changes with the change in load. At heavy loads, it takes the properties of the series resonant converter, while it behaves as the parallel resonant converter if the load is light [52].

2.5 Higher Order Resonant DC-DC Converters

Before the invention of resonant converters, power from source to load was transferred directly and controlled by the operating frequency of the power switches, conventional PWM converters is an example. First order resonant converters are zero voltage and zero current switch converters; this type provides loss less switching. Second and third order resonant converters are the conventional SRC, PRC, and SPRC that have features like zero voltage switching (ZVS), zero current switching (ZCS), high frequency operation, high efficiency, small size, low electromagnetic interference (EMI) and the ability to control the output voltage over a wide range [26]. Considering the number of storage elements various different combinations of resonant tanks can be formed, but not all possible combinations result in a useful manner. The high voltage transformer is most problematic in the DC-DC converter power supply design, since it produces parasitic elements such as leakage inductance and parasitic capacitance, by increasing the number of storage elements in the resonant tank, gives a better capability to absorb these parasitic elements. Moreover output voltage can be control over a wide load range, without having a need to vary the switching frequency if the load is varied [53].

However, with three, four or more energy storage elements in the resonant tank it is difficult to control the resonant frequency, if the tank consists of series and parallel combinations, since both have entirely different behavior with the load. Therefore precise values of the resonant elements have to be set for optimal results.

Oeder in [54] and Liu et.al in [55] have proposed a third order series parallel resonant converter. Figure 2.13 shows this topology, in which the parallel capacitor is connected on the secondary side of the high voltage transformer and primary side consists of leakage inductance of the transformer and a capacitor in series. Though this arrangement of three resonant elements the parasitic capacitances and the leakage inductance of the transformer are absorbed in the resonant tank.

Bhat et.al in [56] have proposed a resonant converter with four elements as shown in Figure 2.14, two separate resonant tanks. $L_S C_S$ series resonant tank and $L_P C_P$ parallel tank. As noted previously this circuit is multi-resonant. This topology has both advantages of series and parallel resonant converters. It has high efficiency even at light loads like the series topology as an inductor and capacitor are connected in series.

Resonant elements used as parallel L_P and C_P , if these parallel resonant elements are placed on the secondary side, the leakage inductances of the HF transformer can also be used as part of resonating inductance. If parallel resonant elements L_P and C_P are placed on the primary side the leakage inductance is acting as two leakage inductances L_S and L_P .

Proposed converter utilizes a capacitive filter as it is implied to high voltage output applications.