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Mathematical Modeling, Design and Analysis of LLC-T Series Parallel Resonant Converter

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ABSTRACT: - *This paper represents a modified LCL-T (inductor inductor capacitor) series parallel resonant converter (SPRC) has been mathematically modeled and validated. The limitations of two element resonant topologies have been removed by adding a third reactive element. The study indicates the mathematical modeling and design of LCL-T SPRC. The proposed approach is expected to provide better voltage regulation for dynamic load conditions. The analysis shows that the output of converter is free from the ripples, and has constant current, regulated output voltage.*
The analysis is carried out using the state space approach. The study indicates the superiority of SPRC over series or parallel resonant converter. The results show that the output of converter is free from the ripples, constant current, regulated output voltage and these converters can be used for many airborne applications.
Key-Words: - *Resonant Converter, ZVS, ZCS, Power Electronics, State Space Analysis.*

I.INTRODUCTION

RESONANT converters (RCs) feature zero-voltage switching (ZVS), zero-current switching, high-frequency operation, high efficiency, small size, and low electromagnetic interference. RCs have been successfully applied to many applications including constant-voltage (CV) dc power supplies, constant-current (CC) power supplies, high-frequency ac power supplies for induction heating, power factor correction, and discharge lamp ballast. An important area of application of RCs is high-voltage (HV) power supplies. The design of a high voltage (HV) power converter is complex because of high leakage inductance and winding capacitance associated with the transformer. Since these parasitic components can easily be integrated as a part of resonant network, RCs are popularly applied for these applications. [1]
Aims to develop a fast and efficient power supply using an LCL type resonant converter configuration. For ease of use, the entire system is monitored by a microcontroller which controls the power output and monitors the power supply.
In recent years the design and development of various DC-DC Resonant Converters (RC) have been focused for electrical, electronics, telecommunication and aerospace applications. It has been found that these converters experience high switching losses, reduced reliability, electromagnetic interference (EMI) and acoustic noise at high frequencies. The Series Parallel Resonant Converters (SPRC) is found to be suitable, due to various inherent advantages. The series and parallel Resonant Converter (SRC and PRC respectively) circuits are the basic resonant converter topologies with two reactive elements. The merits of SRC include better load efficiency and inherent dc blocking of the isolation transformer due to the series capacitor in the resonant network. However, the load regulation is poor and output-voltage regulation at no load is not possible by switching frequency variations. On the other hand, PRC offers no-load regulation but suffers from poor load efficiency and lack of dc blocking for the isolation transformer. It has been suggested to design Resonant Converter with three reactive components for better regulation.[8], [9]

II.PROPOSED LCL-T SERIES PARALLEL RESONANT CONVERTER

LCL-T SPRC is expected the speed of response, voltage regulation and better load independent operation. Keep the above facts in view, the LCL-T SPRC has been module and analysised for estimating various responses. The closed loop state space module has been derived and simulate using MAT LAB/Simulink for comparing the performance with existing converter. [1], [2], [3]

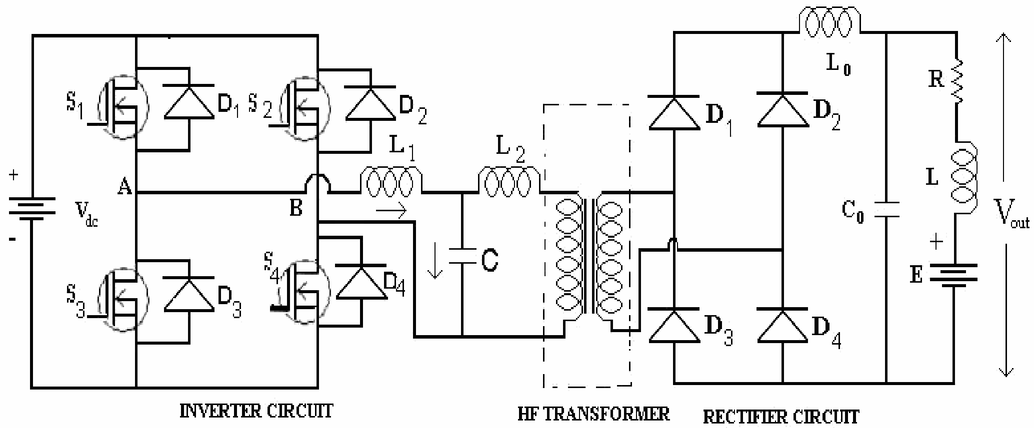

Figure 1: LCL-T Series Parallel Resonant Converter

LCL-T RC is an attractive alternative for HV power supplies due to its own merits.
Many applications of Resonant Converters are as: HV pulsed load application. HV dc power supply for medical application like X-ray generator is popularly developed using PRC. SRC with voltage multiplier. HV ac power supply in corona discharge process for rendering affinity of polyethylene film to ink or glue using transformer leakage inductance and electrode capacitors. HV power supply for electrical discharge machining. High-power electrostatic precipitators using LCC RC. Ozone generation using LCC RC. The use of third-order resonant tank for megahertz range HV-ac power supply for low temperature plasma generation. The high-power industrial application of CO2 laser also needs HV power supply.

III.MATHEMATICAL MODELING

3.1 Assumptions in State Space Analysis

Mathematical modeling of proposed converter was done using state space analysis.[1]
The following assumptions are made in the state spare analysis of the LCL Resonant Full Bridge Converter.
1) The switches, diodes, inductors, and capacitors used are ideal.
2) The effect of snubber capacitors is neglected.
3) Losses in the tank circuit are neglected.
4) DC supply used is smooth.
5) Only fundamental components of the waveforms are used in the analysis.
6) Ideal High Frequency transformer with turns ratio n =1.

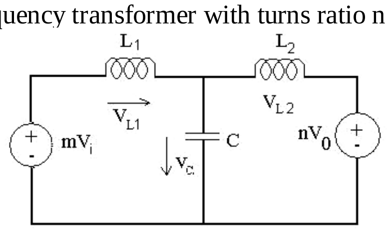

Figure 2: Equivalent Circuit Model of LCL –T SPRC.
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The equivalent circuit shown in Figure 1 is used for the analysis. The vector space equation for the converter is:

$$\dot{X} = AX + BU \qquad (1)$$

$$Y = CX + DU$$

Where,

$$\dot{X} = \frac{d}{dt}\begin{bmatrix} i_{L1} \\ V_c \\ i_{L2} \end{bmatrix}, \quad X = \begin{bmatrix} i_{L1} \\ V_c \\ i_{L2} \end{bmatrix}, \quad U = \begin{bmatrix} V_i \\ V_o \end{bmatrix}$$

The state space equation for LCL-T SPRC converter is obtained from Fig.1

$$\frac{di_{L1}}{dt} = \frac{mV_i}{L_1} - \frac{V_C}{L_1} \qquad (2)$$

$$\frac{dV_c}{dt} = \frac{1}{C}(i_{L1} - i_{L2})$$

$$\frac{di_{L2}}{dt} = \frac{-nV_o}{L_2} + \frac{V_C}{L_2}$$

$$\frac{d}{dt}\begin{bmatrix} i_{L1} \\ V_c \\ i_{L2} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L_1} & 0 \\ \frac{1}{C} & 0 & \frac{-1}{C} \\ 0 & \frac{1}{L_2} & 0 \end{bmatrix}\begin{bmatrix} i_{L1}(t) \\ V_C(t) \\ i_{L2}(t) \end{bmatrix} + \begin{bmatrix} \frac{m}{L_1} & 0 \\ 0 & 0 \\ 0 & \frac{-n}{L_2} \end{bmatrix}\begin{bmatrix} V_i \\ V_O \end{bmatrix} \quad (3)$$

$$A = \begin{bmatrix} 0 & \frac{-1}{L_1} & 0 \\ \frac{1}{C} & 0 & \frac{-1}{C} \\ 0 & \frac{1}{L_2} & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} \frac{m}{L_1} & 0 \\ 0 & 0 \\ 0 & \frac{-n}{L_2} \end{bmatrix}$$

The sum of the zero input response and the zero state response for LCL-T SPRC is given by

$$X(t) = [\emptyset(t)[X(0)]] + L^{-1}[\emptyset(s)B[U(s)]] \quad (4)$$

Solving equation (4), the current and voltage components can be related as

$i_{L1}(t) = i_{L1}(t - t_{P-1})\left[cos\omega(t - t_{P-1}) + \frac{1}{CL_2\omega^2}[1 - cos\omega(t - t_{P-1})]\right]I_1 + [V_C(t -$
$tP-1-1L1\omega sin\omega t-tP-1I2+1CL1\omega 21-cos\omega t-tP-1iL1t-tP-1I3$
(5)

$V_C(t) = i_{L1}(t - t_{P-1})\left[\frac{1}{C\omega}sin\omega(t - t_{P-1})\right]I_1 + [V_C(t - t_{P-1})][cos\omega t]I_2 + [i_{L2}(t -$
$tP-1-1C\omega sin\omega t-tP-1I3$
(6)

$i_{L2}(t) = i_{L1}(t - t_{P-1})\left[\frac{1}{CL_2\omega^2}[1 - cos\omega t]\right]I_1 + [V_C(t - t_{P-1})]\left[\frac{1}{L_2\omega}sin\omega t\right]I_2 +$
$[i_{L2}(t - t_{P-1})]\left[cos\omega t + \frac{1}{CL_1\omega^2}[1 - cos\omega t]\right]I_3$
(7)

The voltage can be estimated from equations (5), (6) and (7).

IV. PROPOSED CIRCUIT DESCRIPTIONS

Above power circuit uses Power MOSFET's. ON & OFF time of Power MOSFET's are small as compared to that of BJT. Power MOSFET is a faster device than BJT. Also we are using Power MOSFET of higher rating than of required because its forward conduction drop will be less for the same value of current as compared to MOSFET of the required rating. Power MOSFET's are chosen because they are work at higher voltage with fewer losses.

The dv/dt stress across Power MOSFET will be low & provision of snubber circuit is not necessary.

Here the small DC link capacitor C1 (unlike large filters capacitor used in a conventional rectifier.) is used to filter the switching frequency components entering the line and to draw the line current for the most of the parts 50 Hz cycle. S_1, S_2, S_3 & S_4 are four MOSFET's switches. The resonant tank circuit is formed by the resonant inductors L_1, L_2 and capacitor C. For the constant dc output voltage Vout at the load, a large capacitor filter C_0 is used to filter voltage ripple i.e. transfer from the input section to the output section. The inductor filter L_0 is used to filter the HF switching frequency current ripple.

The value of resonant inductor and the capacitor is chosen according to the decided resonant frequency. The gauge of the wire used for winding the inductor is such that it is capable of carrying a current more than 5 A. the ferrite core is chosen such that it is capable of handling 500W power. The 1-26-38 EE core can handle up to 1500 W power. Also the window area is sufficient to accommodate the required number of windings of required gauge.

At standard value of capacitor is chosen as the resonant capacitor. The resonating frequency is about 20 kHz to 50 kHz.

4.1 Control Circuit:

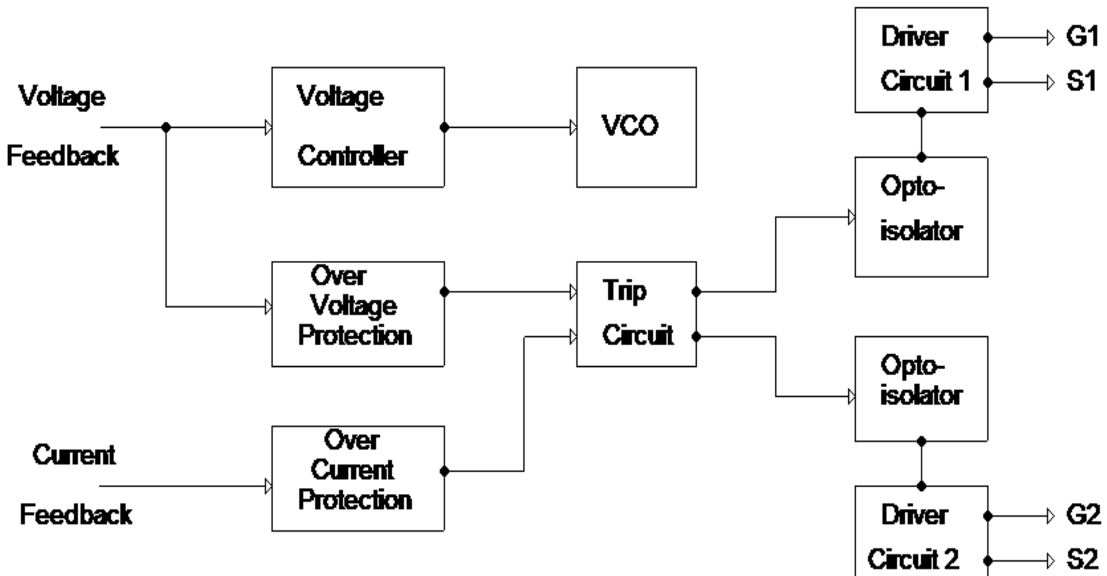


Fig. 3 Block diagram of Control Circuit

Fig. 3 shows control card or circuit of voltage controller, over voltage protection & over current protection.

4.2 SMPS:

This SMPS power supply generates a voltage of 12 V. It has SMPS IC multiplied transformer as its main components. SMPS IC TOP SWITCH 101 is responsible for regulating the output voltage to a desired value. Transformer has multiplied secondary winding, to generate the separate output voltage isolate from each other. Turns ratio between primary and secondary are adjusted so as to obtain +12 V and -12 V which is given to different IC's used in the control card and to the driver card and all supply are isolated from each other.

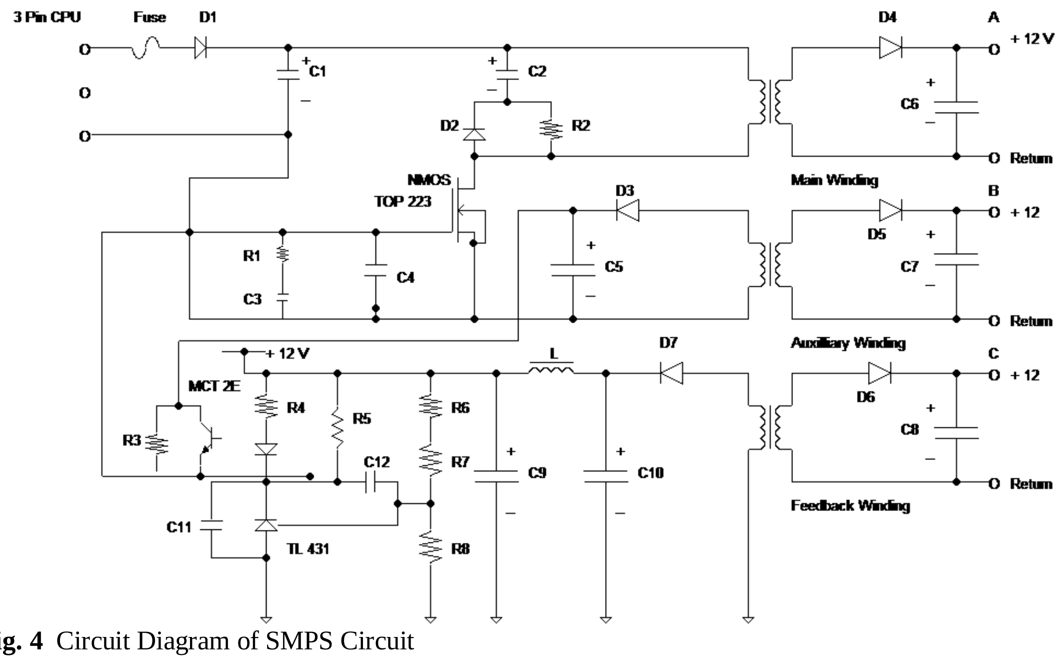


Fig. 4 Circuit Diagram of SMPS Circuit

This circuit is highly accurate 12 V, 3 V secondary regulated fly back power supply. That will operate from 70 V to 130 V input. High voltage supply is applied to the primary winding of transformer. The other side of the transformer is driven by the integrated high voltage MOSFET transistor within the TOP 100 (V1). The circuit operates at a switching frequency near about 25 kHz set by the internal oscillator.

A TL 431 shunt regulator directly senses and accurately regulates the output voltage. The effective voltage can be fine turned by adjusting the resistor divider formed by R5, R6 & R7.

4.3 Driver Circuit:

Output of the VCO is applied to the power devices via NOT gates, optocoupler and the pulse amplifier circuit. TLP 250 is used for driver circuit. The VCO output is given to the inverter such that there is a delay in the firing pulses for the two arms. Thus the unit avoids the cross conduction of MOSFET. Power supply given to the two optocoupler should be isolated from each other.

4.4 Current Feedback by using C**.T.:**

Current transformer is used to transfer the current from primary to secondary side to measure high circulating current in the resonant circuit we use current transformer. Current transformer's primary is connecting in series with the resonant circuit and it; secondary sides are never left open. The turn ratio of the transformer is 1:400; it reduces the secondary current by a factor of 400. This is then converting to the corresponding voltage by connecting a resistor of suitable value as a load. The voltage across this load is given to the over current protection circuit of the control card circuit.

4.5 Voltage Feedback:

The part of the output voltage is sampled and given the voltage controller and over voltage protection card. There negative feedback is used so as to operate the circuit above the resonant frequency.

4.6 Rectifier and Filter:

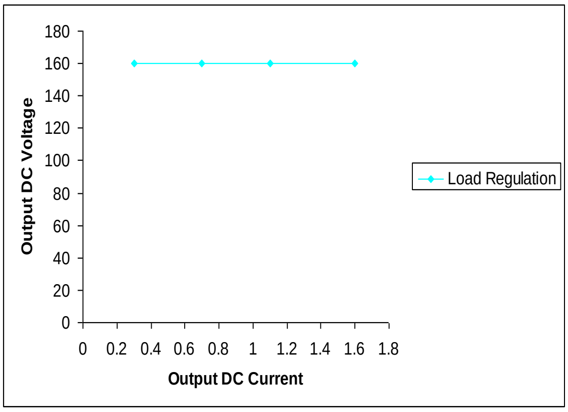
High frequency sine wave is applied to the bridge rectifier. The diodes of bridge rectifier must be fast recovering diodes. The rectified voltage is then filtered by LC type filter. The inductor is wound on a ferrite since the ripple frequency is very high. A core is selected such that it can handle 500 W powers. This output is given to lamp load.

V. EXPERIMENTAL RESULTS

Observation Table 1:- Load Regulation:

Sr. No.	Input A.C. Voltage (Volts)	Output D.C. Voltage (Volts)	Output D.C. current (Amps)
1	45 V	160 V	0.3 A
2	56 V	160 V	0.7 A
3	70 V	160 V	1.1 A
4	87 V	160 V	1.6 A

Output DC Current Vs Output DC Voltage



From above graph it is observe that for varying load condition the power supply maintain its output voltage 160 V. i.e. within closed tolerance. Also the power supply gives protection against line born disturbances such as over load protection, short circuit protection etc.

Observation Table 2:- Efficiency:

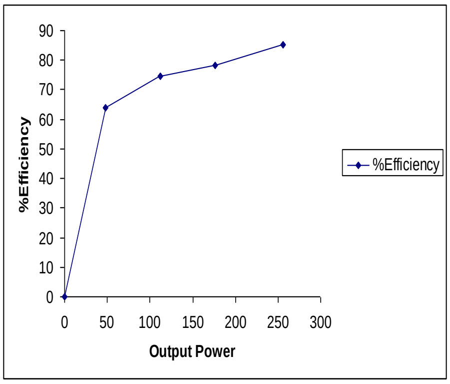
Sr. No.	Input A.C. Power (Watts)	Output D.C. Power (Watts)	Efficiency η%
1	75 W	48W	64 %
2	150 W	112 W	74.66 %
3	225W	176 W	78.22%

4	300W	256 W	85.33%

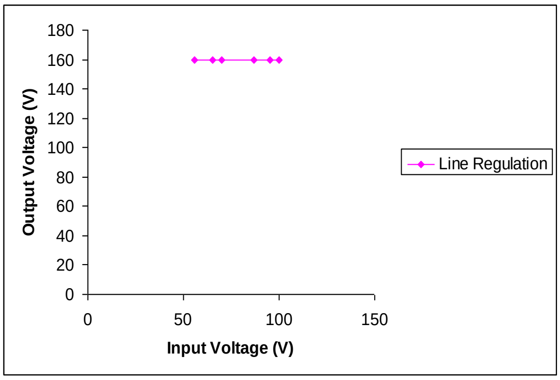
From above graph it is observe that efficiency of the power supply goes on increasing up to 85% to 90% which is the basic requirement of the power supply.

Observation Table 3:- Line Regulation :

Load Conditions	Input A.C. Voltage (Volts)	Output D.C. Voltage (Volts)	Output D.C. current (Amps)
One half Load	56 V 65 V 70 V	160 V 160 V 160 V	0.7 A 0.7 A 0.7 A
Full Load	87 V 95 V 100 V	160 V 160 V 160 V	1.6 A 1.6 A 1.6 A



Input Voltage Vs Output Voltage :



VI.CONCLUSION

A detailed analysis of the LCL-T RC is presented in this paper for its application as a constant voltage (CV) power supply. It is seen that the converter exhibits load-independent voltage and current gain at certain operating frequencies, the latter being useful for a CV power supply. The condition for converter design optimized for minimum size of resonant network is derived. Various methods for the control of output voltage over a wide conversion range and against variation in input dc voltage are discussed.

This CV power supply reduces the filtering requirement. If sufficient number of modules is connected in parallel, the additional filter can be eliminated. The leakage inductance of the transformer can be advantageously integrated into the LCL-T resonant network. Part-load efficiency is better due to lower circulating currents.

An experimental result on the prototype converter validates the merits of the converter topology. These merits make the topology applicable as a CV power supply in various applications.

DC power converters have been described which are capable of operating in the hundreds of kilohertz range and which employ a resonant circuit. The advantages of the Series Parallel resonant dc-dc converters which are verified by a developed setup as follows-

1. Low power MOSFET stresses due to lossless snubber operation.
2. Switching frequencies in the hundreds of kilohertz range to reduce size, weight and cost of the power supply.
3. Switching losses i.e. turn-on & turn-off losses; are reduced by zero voltage and zero current switching.
4. Ability to step the input voltage either up or down.

REFERENCES

[1] C. Nagarajan and M. Madheswaran, "Performance Analysis of LCL-T Resonant Converter with Fuzzy/PID Controller using State Space Analysis", *International Journal of Electronic Engineering Research, ISSN 0975 - 6450 Volume 2 Number 1* (2010) pp. 51–70

[2] Deepak S. Gautam and Ashoka K. S. Bhat,"A Comparison of Soft-Switched DC-to-DC Converters for Electrolyzer Application", *IEEE Transactions On Power Electronics*, Vol. 28, No. 1, January 2013

[3] G.S.N.Raju and Seshagirirao Doradla, "An LCL Resonant converter with PWM Control Analysis, simulation, and Implementation", *IEEE Transactions On Power Electronics*, vol.10, No.2 March 1995.

[4] Bin Gu, Jih-Sheng Lai, Nathan Kees and Cong Zheng, "Hybrid-Switching Full-Bridge DC–DC Converter With Minimal Voltage Stress of Bridge Rectifier, Reduced Circulating Losses, and Filter Requirement for Electric Vehicle Battery Chargers", *IEEE Transactions On Power Electronics*, Vol. 28, No. 3, March 2013

[5] S. Selvaperumal, C. Christober Asir Rajan, and S. Muralidharan, "Stability and Performance Investigation of a Fuzzy-Controlled LCL Resonant Converter in an RTOS Environment", *IEEE Transactions On Power Electronics*, Vol. 28, No. 4, April 2013

[6] A.K.S.Bhat, .Analysis and Design of LCL-Type Series Resonant Converter,. *IEEE INTELEC*, pp172-178, (1994).

[7] Vijayakumar Belaguli, and Ashoka K. S. Bhat, "Series-Parallel Resonant Converter Operating in Discontinuous Current Mode—Analysis, Design, Simulation, and Experimental Results," *IEEE Transactions on Circuits and* System—I: Fundamental Theory and Applications, vol. 47, no. 4, April 2000

[8] Mangesh Borage, Sunil Tiwari, and Swarna Kotaiah, "LCL-T Resonant Converter With Clamp Diodes:A Novel Constant-Current Power Supply With Inherent Constant-Voltage Limit" IEEE *Transactions On Industrial Electronics*, vol. 54, no. 2, april 2007.

[9] Mangesh Borage, Sunil Tiwari, and Swarna Kotaiah, "Analysis and Design of an LCL-T Resonant Converter as a Constant-Current Power Supply", *IEEE Transactions on Industrial Electronics*, vol. 52, no. 6, December 2005.

[10] Gregory Ivensky, Svetlana Bronstein and Sam Ben-Yaakov, "Approximate Analysis Of The Resonant LCL DC-DC Converter", *23rd IEEE Israel Convention*, pp. 44-48, Tel-Aviv, 2004.

[11] Michael J. Ryan, William E. Brumsickle, Deepak M. Divan, "A New ZVS LCL- Resonant Push–Pull DC–DC Converter Topology", *IEEE Transactions On Industry Applications*, Vol. 34, No. 5, September/October 1998.

[12] Robert L. Steigerwald, "High-frequency Resonant Transistor DC-DC converters", *IEEE Tran. On Industrial Electronics*. Vol. IE-31, No.2, May 1984.

[13] Pravin K. Jain, Wen Kang, Harry Soin, and Youhao Xi, "Analysis and Design Consideration of a Load and Line Independent Zero Voltage Switching Full Bridge DC/DC converter Topology", *IEEE Tran. On Power Electronics*. Vol.17, No.5 September 2002.

[14] Robert L Steigerwald, "A Comparision of Half-bridge Resonant Converter Topologies", *IEEE Tran. On Power Electronics*. Vol.3, No.2, April 1988.

[15] Ashoka K. S. Bhat, " Analysis and Design of a Series-Parallel Resonant Converter with Capacitive Output Filter", *IEEE Tran. On Industrial Applications*. Vol.27, No.3, May/June 1991.

[16] M. Prabhakar and V. Kamraj, "Analysis and implementation of LCC resonant DC-DC converter for Automative Application", *IETE Journal of Research*. Vol.56, issue 4, July-Aug 2010.