

Experimental Study and Steady State Stability Analysis of CLL-T Series Parallel Resonant Converter with Fuzzy Controller using State Space Analysis

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Abstract: This paper presents a Closed Loop control of CLL-T (Capacitor Inductor Inductor). Series Parallel Resonant Converter (SPRC) has been simulated and the performance is analysed. A three element CLL-T SPRC working under load independent operation (voltage type and current type load) is presented in this paper. The Steady State Stability Analysis of CLL-T SPRC has been developed using State Space Technique and the regulation of output voltage is done by using Fuzzy controller. The simulation study indicates the superiority of fuzzy control over the conventional control methods. The proposed approach is expected to provide better voltage regulation for dynamic load conditions. A prototype 300 W, 100 kHz converter is designed and built to experimentally demonstrate, dynamic and steady state performance for the CLL-T SPRC are compared from the simulation studies.

Keywords: Control System, Fuzzy logic, MATLAB, Power Electronics, Resonant Converter.

1 Introduction

The developments of the DC-DC Resonant Converters are increasing now a day due its performance. A DC-DC Resonant Converter (RC) are used in telecommunication and aerospace application, at high frequency these converters experience high switching losses, reduced reliability, electromagnetic interference (EMI) and acoustic noise. To overcome these drawbacks, the 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. The LCL tank circuit based DC-DC SPRC has been experimentally demonstrated and reported by many researchers [1-4]. Mangesh B. Borage et al [5] have demonstrated the characteristics of LCL-T Resonant converter using Asymmetrical duty cycle (ADC). The converter operated at fixed resonant frequency and its analysed using state space approach. Later, Mangesh Borage et al [6] have demonstrated an LCL-T half bridge resonant converter with clamp diodes. The output current or voltage is sensed for every change in load because the output voltage or constant current increases linearly. The feedback control circuit has not been provided. LCL-T RC with constant current supply operated at resonant frequency is presented [7].

Vijayakumar Belaguli et al [8] have experimentally demonstrated with independent load when operated at resonant frequency, making it attractive for application as a constant voltage (CV) power supply. It has been found from the literature that the LCL tank circuit connected in series-parallel with the load and operated in above resonant frequency improves the load efficiency and independent operation. Chew L et al [9] have demonstrated LCC SPRC using robust control method, this method used to varying the converter gain, the gain was derived by using state plan analysis. The voltage and current type load was presented with

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variable load condition. The closed loop operation was presented using PI controller with load independent operation as obtained. Lakshminarasamma N. et al [10] have demonstrated active clamp ZVS DC-DC converter. The steady state stability analysis was presented for ZVS Buck converter. There is no possible of load independent operation. The converter operates at duty cycle >0.5 , above its operation the converter fails to instability. Later, Martin P.Foster et al [11] have demonstrated CLL half bridge Resonant Converter with open loop operation. The ac equivalent circuit analysis and fundamental mode approximation (FMA) analysis was derived used to the modeling the converter and compared.

Paolo Mattavelli et al [12] have demonstrated different approaches which offer the fuzzy logic control (FLC). This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. The FLC approach with same control rules can be applied to several dc-dc converters. The author utilized the proposed control technique for Buck-Boost converter and demonstrated. J.M. Correa et al [13] have demonstrated a DC/AC series resonant converter with fixed load value considering two control approaches.

Later T. S. Sivakumaran et al [14] have demonstrated a CLC SPRC using FLC for load regulation and line regulation. The performance of controller has been evaluated and found that the load independent operation may not be possible. C.Nagarajan et al [15] have simulated an LCL-T SPRC using FLC and PID controller. The performance of controller has been found to be better when the fuzzy controller has been considered. The Harmonic Spectrum and dynamic analysis for RLE load are presented. M.Prabhakar et al [16] have simulated an LCC RC. The closed form expressions are derived for different resonant topologies. The Voltage gain expression for these topologies are obtained and plotted.

It is clear from the above literatures that the output voltage regulation of the converter against load and supply voltage fluctuations have important role in designing high-density power supplies. A CLL-T SPRC is expected the speed of response, voltage regulation and better load independent operation. Keep the above facts in view, the CLL-T SPRC has been model and analysed for estimating various responses. The closed loop state space model and AC analysis has been derived and simulate using MATLAB/Simulink. A prototype 300 W, 100 kHz the CLL-T SPRC is implemented and the experiment results are compared with the simulation results. The simulation results agree with the experimental results.

2 Proposed CLL-T Series Parallel Resonant Converter with Fuzzy Controller

The resonant tank consisting of three reactive energy storage elements (CLL-T) has overcome the

conventional resonant converter that has only two reactive energy storage elements. The first stage converts a DC voltage to a high frequency ac voltage. The second stage of the converter is to convert the AC power to DC power by suitable high frequency rectifier and filter circuit. Power from the resonant circuit is taken either through a transformer in series with the resonant circuit or series in the capacitor comprising the resonant circuit as shown in Fig. 1. In both cases the high frequency feature of the link allows the use of a high frequency transformer to provide voltage transformation and ohmic isolation between the DC source and the load.

In CLL-T SPRC the load voltage can be controlled by varying the switching frequency or by varying the phase difference between the two inverts where the switching frequency of each is fixed to the resonant frequency. The phase domain control scheme is suitable for wide variation of load condition because the output voltage is independent of load. The DC current is absent in the primary side of the transformer, there is no possibility of current balancing. Another advantage of this circuit is that the device currents are proportional to load current. This increases the efficiency of the converter at light loads to some extent because the device losses also decrease with the load current. If the load gets short at this condition, very large current would flow through the circuit. This may damage the switching devices. To make the circuit short circuit proof, the operating frequency should be changed.

A schematic diagram of full-bridge CLL-T SPRC is shown in Fig. 2. The resonant circuit consist of series inductance L_1 , parallel capacitor C and series inductance L_2 . S_1 - S_4 is switching devices having base /gate turn-on and turn-off capability. D_1 to D_4 are anti-parallel diodes across these switching devices. The MOSFET (S_1) and its anti parallel diode (D_1) act as a bidirectional switch. The gate pulses for S_1 and S_2 are in phase but 180 degree out of phase with the gate pulses for S_3 and S_4 . The positive portion of switch current flows through the MOSFET and negative portion flows through the anti-parallel diode. The RLE load is connected across bridge rectifier via L_0 and C_0 . The voltage across the point AB is rectified and fed to RLE load through L_0 and C_0 . For the analysis it is assumed that the converter operates in the continuous conduction mode and the semiconductors have ideal characteristics.

3 Steady State Stability Analysis for the Proposed Converter

3.1 Mathematical Modeling using State Space Technique

The equivalent circuit of CLL-T SPRC is shown in Fig. 3. The mathematical modeling using state space technique can be obtained assuming all the components to be ideal. The state space equation for CLL-T SPRC converter is:

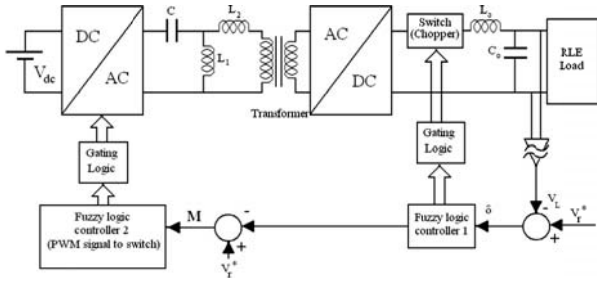


Fig. 1 Block Diagram of CLL-T Series Parallel Resonant Converter.

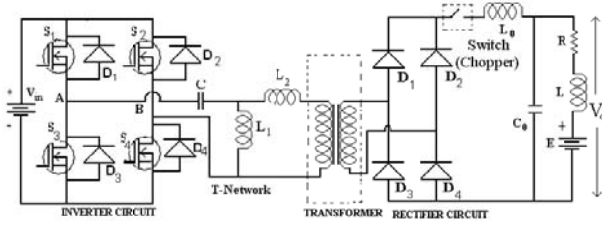


Fig. 2 Circuit diagram of CLL-T SPRC.

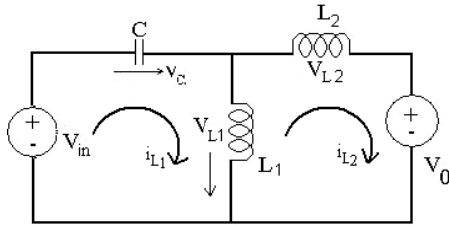


Fig. 3 Equivalent Circuit Model of CLL-T SPRC.

$$\frac{di_{L1}}{dt} = \frac{V_c}{L_1} - \frac{V_{in}}{L_1}, \quad (1)$$

$$\frac{di_{L2}}{dt} = \frac{V_c}{L_2} - \frac{V_{in}}{L_1} - \frac{V_o}{L_2}, \quad (2)$$

$$\frac{dV_c}{dt} = \frac{i_{L1}}{C} + \frac{i_{L2}}{C} \quad (3)$$

The state-space model for CLL-T SPRC:

$$\frac{d}{dt} \begin{bmatrix} i_{L1} \\ i_{L2} \\ V_c \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L1} \\ 0 & 0 & \frac{1}{L2} \\ \frac{1}{C} & \frac{1}{C} & 0 \end{bmatrix} \begin{bmatrix} i_{L1}(t) \\ i_{L2}(t) \\ V_c(t) \end{bmatrix} + \begin{bmatrix} -\frac{1}{L1} & 0 \\ -\frac{1}{L1} & -\frac{1}{L2} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{in} \\ V_o \end{bmatrix} \quad (4)$$

3.2 AC Analysis for the Proposed Converter

The converter is operated only in the lagging power factor mode, AC sinusoidal analysis has been carried out to bring out the important features of the network. Also, in the AC analysis, the output rectifier and filter are replaced by the equivalent ac resistance and the square-wave input voltage source is replaced by its fundamental sinusoidal equivalent. The power transfer from input to output is assumed to be only via the fundamental component and the contribution of all the harmonics is neglected. Without losing generality, the turn's ratio (N_1/N_2) of the isolation transformer is assumed to be unity. The equivalent AC resistance for the rectifier with capacitive filter is given by

$$R_{ac} = \frac{8}{\pi^2} R_o \quad (5)$$

The resonant frequency and the normalized switching frequency are defined as

$$\omega_r = \frac{1}{\sqrt{LC}}, \quad f_r = \frac{1}{2\pi\sqrt{LC}}, \quad \omega_n = \frac{\omega_s}{\omega_r}, \quad f_n = \frac{f_s}{f_r} \quad (6)$$

The characteristics impedance and Q of the resonant network are

$$Z = \sqrt{\frac{L}{C}} \quad \text{and} \quad Q = \frac{\omega_r L}{R_o} = \frac{Z}{R_o} \quad (7)$$

The ratio of inductance is defined as

$$\delta = \frac{L_2}{L_1} \quad (8)$$

The voltage and current gain are defined as

$$M = \frac{V_o}{V_{in}} \quad \text{and} \quad H = \frac{I_o}{\left(\frac{V_{in}}{Z}\right)} \quad (9)$$

Voltage gain for the converter topology is computed by using Eq. (9), from the voltage gain expression, a characteristics plot is obtained. This is compared with the desired characteristics plot to decide upon the suitability for automotive application.

$$M = \frac{V_o}{V_{in}} = \frac{1}{\left(1 - \frac{1}{\omega_n}\right) + j\frac{\pi^2}{8}Q\left(\delta\omega_n - \frac{1}{\omega_n}(1+\delta)\right)} \quad (10)$$

$$H = \frac{1}{Q\left(1 - \frac{1}{\omega_n}\right) + j\frac{\pi^2}{8}\left(\delta\omega_n - \frac{1}{\omega_n}(1+\delta)\right)} \quad (11)$$

4 Results and Discussion

4.1 Design Parameters of the Converter

For the design of CLL-T SPRC [5], the design specifications are: minimum and maximum value of DC voltage, maximum output current (I_o), corresponding to the full-load condition and switching frequency (f_s). It is desired to design the converter with the following specifications as shown in Table 1. These values were obtained using a design procedure to assure the resonance for almost all power range (load-independent

design) and also to limit the current and voltage peak values. To prove the wide load range operation and also to show that the fuzzy controller used is robust to parameter variations.

4.2 Fuzzy Logic Control (FLC)

Fuzzy control involves three stages: fuzzification, inference or rule evaluation and defuzzification. The SPRC are modeled using MATLAB software. Fuzzy control is developed using the fuzzy toolbox. The fuzzy variables ‘e’, ‘ce’ and ‘Δu’ are described by triangular membership functions. Five triangular membership functions are chosen for simplicity. Table 2 shows the fuzzy rule base created in the present work based on intuitive reasoning and experience. Fuzzy memberships NB, NS, Z, PS, PB are defined as Negative Big, Negative Small, Zero, Positive Small, and Positive Big.

It can be inferred that the output voltage is far from the reference value, then the change of switching frequency (Δu) must be large so as to bring the output to the reference value quickly. The output voltage approaches the reference value, and then a small change of switching frequency is necessary and if the output voltage is near the reference value and is approaching it rapidly, then the frequency must be kept constant so as to prevent overshoot.

At every sampling interval, the reference voltage and load voltage are used to calculate the error (e) and change in error (ce) signals that act as the input to the FLC. The stage of fuzzification, fuzzy inference and defuzzification are then performed as given flowchart shown in Fig. 4.

$$e = V_r - V_L \quad (12)$$

$$ce = e - pe$$

where Vr is the reference or the desired output voltage, VL is the actual output voltage and pe is previous error. The duty ratio of the converter can be determined by the fuzzy inference. For instance, if the output voltage continues to increase gradually while the current is low during the charging process the fuzzy controller will maintain increase in voltage to reach the set point.

A drop in the output voltage level triggers the fuzzy controller to increase the output voltage of the converter by modifying the Modulation Index (MI) of the

Table 1 Design Parameters.

S.no	Parameter	Value
1	Power output	300W
2	Minimum input voltage	100V
3	Minimum output voltage	100V
4	Maximum load current	3A
5	Transformer Turns ratio	1
6	Switching frequency (fs)	100KHz
7	Series Inductance L1, L2	39.18 μH
8	Parallel Capacitance (C)	66 nF
9	Load Inductance (Lo)	1mH
10	Load Capacitance (Co)	650μF

converter. The resolution of fuzzy logic control system relies on the fuzziness of the control variables while the fuzziness of the control variables depends on the fuzziness of their membership functions.

Table 2 Fuzzy Rules.

Error (e)		NB	NS	Z	PS	PB
Change in error (ce)	NB	NB	NB	NB	NM	Z
	NS	NB	NM	NS	Z	PM
	Z	NB	NS	Z	PS	PB
	PS	NM	Z	PS	PM	PB
	PB	Z	PM	PB	PB	PB

4.3 Simulation Results

The Closed loop simulation using FLC is carried out using MATLAB/Simulink software. Depending on error and the change in error, the value of change of switching frequency is calculated. The Fuzzy set parameters instruction and function blocks available in MATLAB are used to update the new switching frequency of the pulse generators. The entire system is simulated with a switching frequency of 100 KHz.

The resonant voltage, resonant current and output load voltage are shown in Fig. 5(a) and Fig. 5(e). The inductor and capacitor are connected to the output of inverter for resonance purpose and it is used for impedance matching. Another good feature of this converter is that the converter operation is not affected by the non idealities of the output transformer

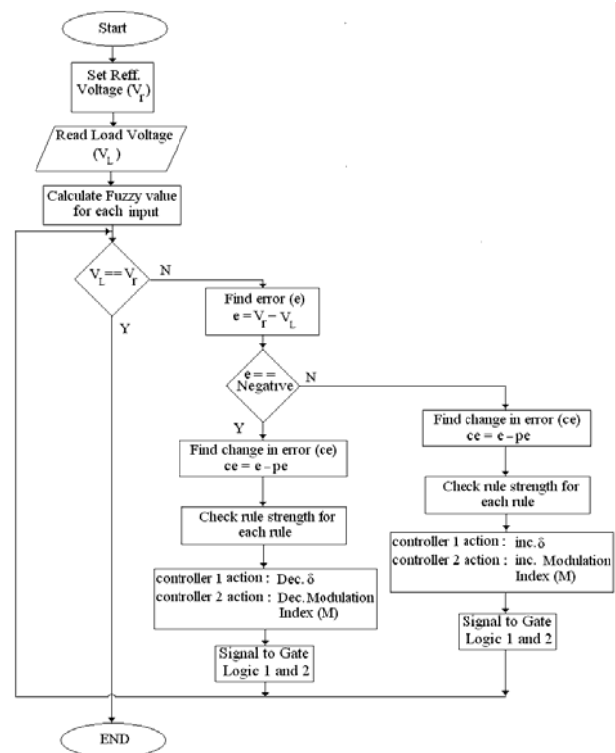


Fig. 4 Flowchart for the Fuzzy controller.

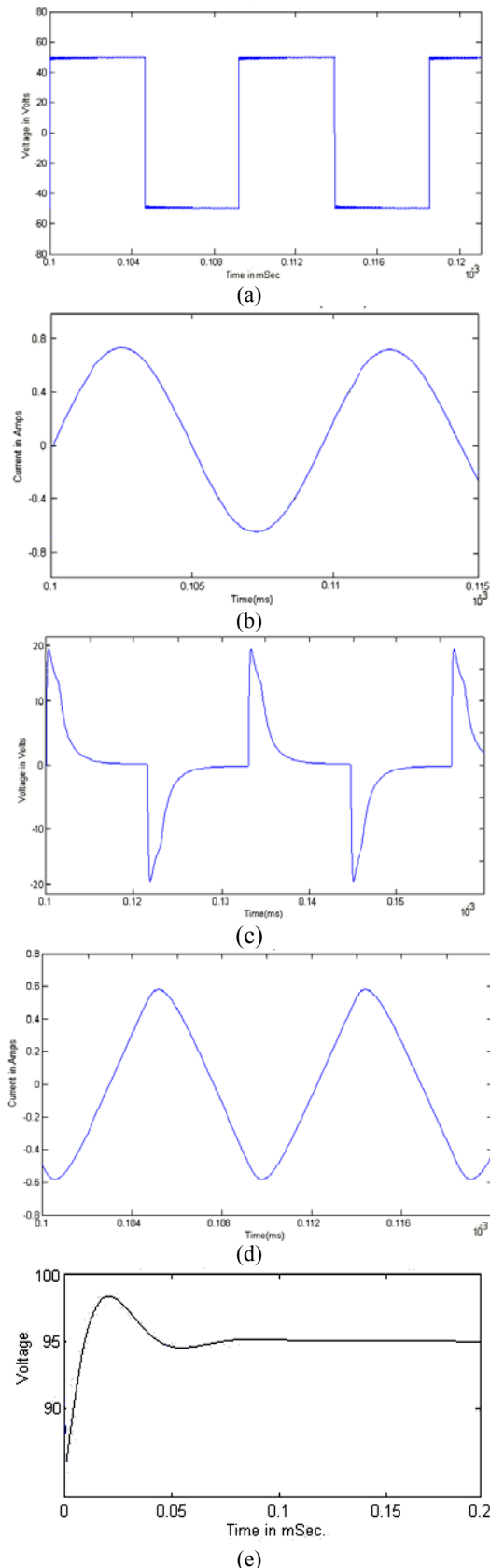


Fig. 5 (a) Inverter Voltage (V_{AB}), (b) Inverter Current (Transformer Primary side), (c) Voltage across Capacitor, (d) Current through Inductance L_1 , (e) Output voltage for RLE load for $V_r=100V$.

(magnetizing inductance) because of the additional resonance inductor L_2 . The output voltage are high, it is observed that the settling time 0.12 sec. The slight droop in the resonant characteristics is due to the increase in conduction losses in the bridge inverter and resonant network. The result is justified that settling time of output voltage in CLL-T SPRC controller is more than that of the settling time.

It is clear that the CLL-T SPRC is ineffective in eliminating the overshoot, rise time and high frequency noise suppression. This happens because of several reasons. The integrator increases the system type number, thus minimizing the steady-state error. It is inferred that the measurement overshoot and noise is highly suppressed. The performance of CLL-T converter response have been estimated and provided in Table 3. This ensures that the system can be controlled effectively with feedback. It is clear from the above table shows that the peak overshoot is eliminated and the settling time is much lower with the fuzzy control strategy. The measurement noise is highly suppressed.

4.4 Stability Studies for the Proposed Converter

Fig. 6(a) represents the stability investigation of the converter using the extended nyquist function technique. the stability is determined if $G(s)H(s)$ contour in the $G(s)H(s)$ plan corresponding to nyquist contour in s -plan encircles the point $-1+j0$ in the anti-clockwise direction as many times as the number of right half s -plan poles of $G(s)H(s)$ then the closed loop system is stable. There is no encirclement of $-1+j0$ point. This impels that the system is stable if there are no poles of $G(s)H(s)$ in the right half s -plan. If there are poles on right half s -plan then the system is unstable.

It is concluded that the CLL-T converter circuit is stable for the system parameters variations. It is observed that $-1+j0$ point is encircled in the both direction in one time. Hence net encirclement is zero. Also the open loop system has no poles at the right half of s -plan.

4.5 Converter Analysis for the Proposed Converter

Fig. 6(b) shows the converter gain (M) versus frequency ratio (ω_s/ω_r) characteristics for $\delta=1$ (L_2/L_1) and different values of $Q(0,0.5,1,1.5,2$ and 2.5).The curve corresponding to $Q=0$ represents the no load characteristics. The no load gain (M) depends on the frequency ratio, transformer turns ratio and δ from Fig.

Table 3 Evaluation of transient and steady state performances by using FLC.

Controller	Settling Time in Sec.	% Over Shoot	Steady state error
Open loop	0.45	10	0.04
Closed Loop (FLC)	0.12	08	0.004

6(b), it has been observed that the converter exhibits the load independent feature. Therefore, if the converter is designed to operate at or near the load independent point, then the output voltage can be controlled by a small change in operating frequency. This allows better utilization of the converter components. The Q decreases the gain value reaches to higher gain as well as the load decrease. The Q increase the gain value reaches to f_r as the load increases. Thus the full load condition should be the worst case for the resonant network design.

Fig. 6(b) shows the $\omega_s/\omega_r=1.15$ and shows the effect of secondary leakage. The peak gain at a given condition can be obtained by using the gain equation (4). It is difficult to express the peak gain in explicit form. The gain (M) has error at frequency below the resonant frequency (f_r) due to the fundamental approximation.

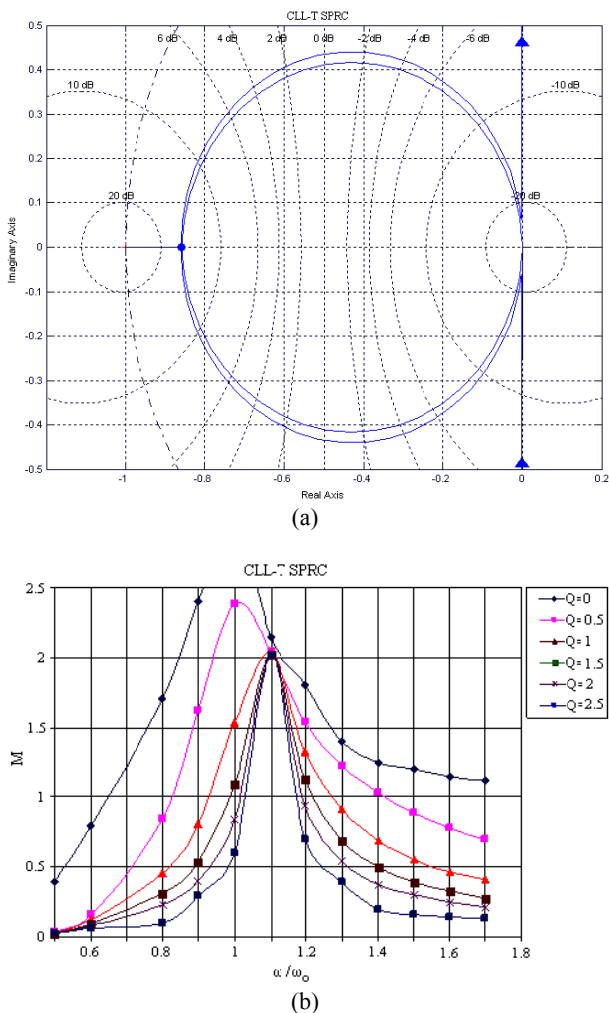


Fig. 6 (a) Stability analysis of CLL-T SPRC (b) voltage gain versus ω_s/ω_r , for different Q values.

5 Experimental Results

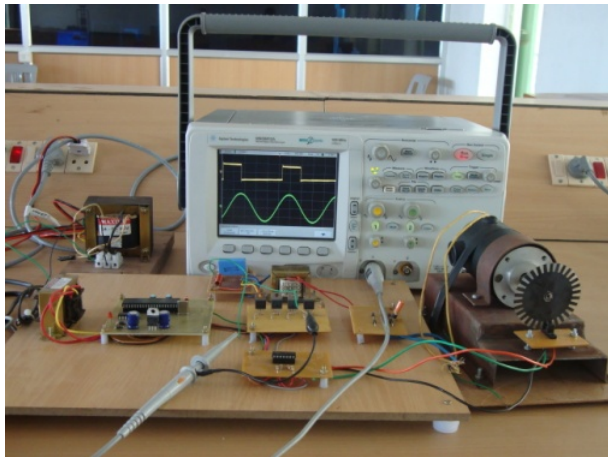
A CLL-T SPRC is fabricated and tested. A prototype CLL-T SPRC is operating at 300 W, 100 kHz was designed. ATMAL microcontroller 89C51 is used to generate driving pulses, these pulses are amplified using the driver IC IR2110, the IRF840 MOSFETs are used as the switches in the bridge converter. The diodes MUR 4100 are used for the output bridge rectifier. It's clearly shown in figures that the power losses in the occurrence of the turn on switching are maintained very low by means of the resonant operation. The hardware module is shown in Fig. 7. The Multi storage oscillogram (MSO) of Inverter voltage, inverter Current, Voltage across parallel capacitor, Current through inductance L_1 and Output voltage fed with the DC motor are shown in Fig. 7. These figures show the good dynamic performance of the controller. Fig. 7(b) CH1: presents the inverter voltage, its measure from the point A and B of the bridge inverter. Fig. 7(b) CH2: presents the resonant current, measured on the primary of the transformer. Fig. 7(c) it can be seen that the peaks are relatively high, but an almost constant level is presented, which is assured by the primary converter controller. Fig. 7(d) it can be seen from this figure that the current contains low harmonics and it presents a nearly sinusoidal shape. Fig. 7(e) the figure shows the good performance of the whole design.

One can conclude that the controller is capable of operating under load- independent operation, again, it can be seen that the output follows the reference with good accuracy and better dynamic performances. The CLL-T SPRC is verified by simulation and experimental studies. It is proved from the performance Table 4, the experimental results shows the control characteristics are observed to closely match the theoretical values and the output voltage is seen to be nearly independent of load.

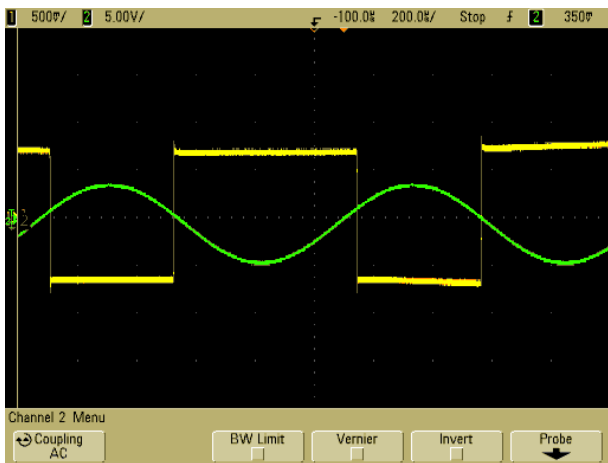
The output power for various input power and Output Power has been shown in Fig. 8(a). It is absorbed that the power drawn decays steeply for lower load and as the load increases the power drawn gradually decreases and remains constant at greater loads. It is also seen that the proposed new control strategy has less load Sensitivity. The results obtained indicate that the FLC based CLL-T SPRC is an effective approach for DC-DC convertor output voltage regulation.

As shown in Figs. 8(a), 8(b) the control characteristics are observed to closely match the theoretical curve, and the output power is seen to be nearly independent of load. The conversion efficiency of the prototype is measured by varying the pulse to the inverter to vary the output power under different loading conditions at 100 V input DC voltage. The plots of experimental efficiency as a function of the output power are shown in Fig. 8(b). The full load conversion efficiency of the prototype is measured to be 0.76 and it remains above 0.80 for 100-300 W output power. Out of

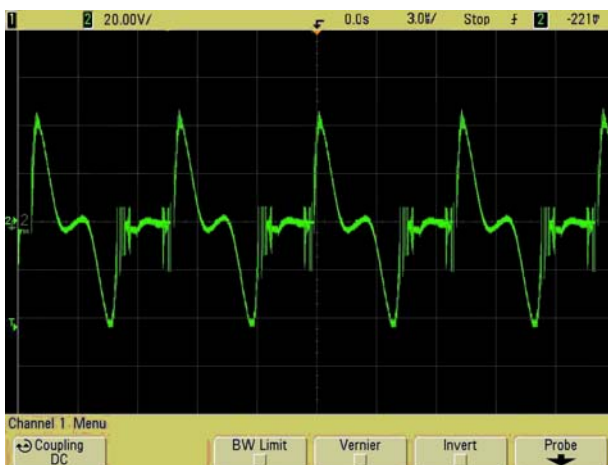
total 40W power loss in the prototype operating at 300W, a major portion ($\approx 20W$) is estimated to occur in the MOSFETs and diodes. The rest of losses can be attributed largely to the core and winding loss in transformer and resonant inductor.



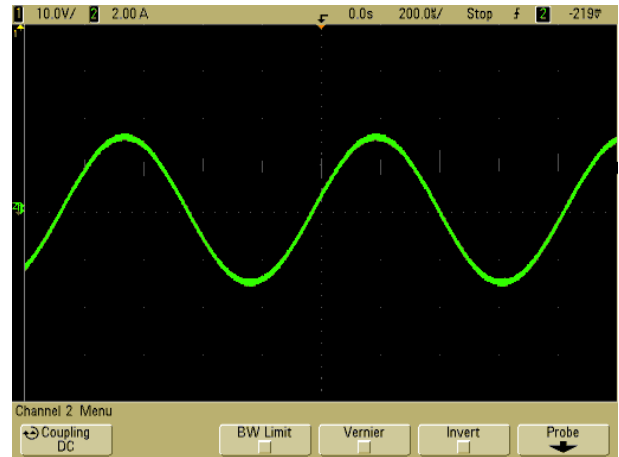
(a)



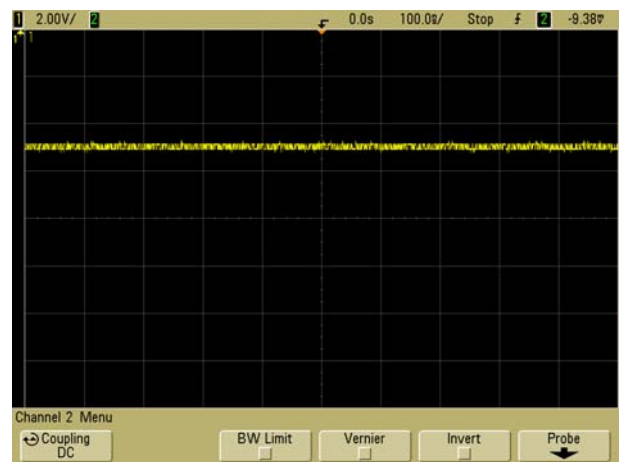
(b)



(c)



(d)



(e)

Fig. 7 Experimental Waveforms for CLL-T SPRC (a) Hardware module (b) CH1: Resonant Voltage [Volt. Scale: 40 V/div.], CH2: Resonant Current [Amp. Scale: 0.5A/div.] (c) Voltage across the Capacitor [Volt. Scale: 20 V/div.] (d) Current through Series Inductor L_1 [Amp. Scale: 0.5A/div.] (e) Output Capacitor Voltage [Volt. Scale: 50 V/div.].

Table 4 Performance measures of Theoretical & Simulink Results for CLL-T SPRC fed with RLE Load.

Performance measures	Simulation Studies	Experimental Studies
Load Voltage in Volts	99.8	94
Load Current in Amps	1.8	2.6
Settling Time in ms	0.01	1.4
% Over Shoot	1	2.1
Steady state error	0.001	2.3

6 Conclusion

The Stability analysis of CLL-T SPRC has been modeled and estimating the performance for various load conditions. This converter with a voltage type load and current type load shows it provides load independent operation. So, the switching power losses

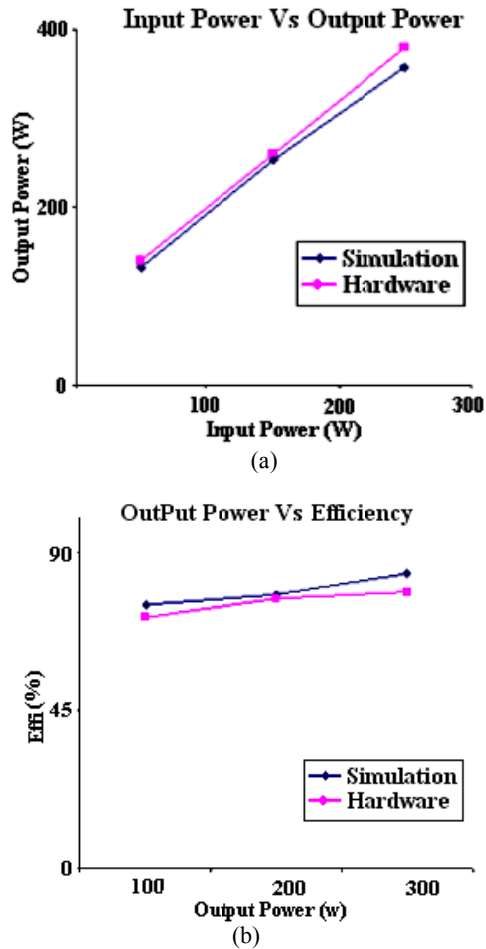


Fig. 8 Experimental results for (a) input power varies with output power, (b) Output Power varies with Efficiency.

are minimized. It has been found from the simulated results that the closed loop controller provides better control strategies. A prototype 300 W, 100 kHz converter was designed and the experiment results are compared with the simulation results. The simulation results agree with the experimental results. This modeling is expected to provide in depth concepts to the design engineers for various converter design required for verity of application.

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