DEVELOPMENT OF DSP BASED ROBUST CONTROL METHOD FOR GENERAL RESONANT CONVERTER TOPOLOGIES USING TRANSFER FUNCTION MODEL

Chinnadurai NAGARAJAN[*], Muthusamy MADHESWARAN[*], Durairaj RAMASUBRAMANIAN[**]
[*]Centre of Advanced Research Centre, Muthayammal Engineering College, Rasipuram, Tamilnadu, India
[**]Apollo Engineering College, Chennai, India
e-mail: nagaraj2k1@gmail.com

ABSTRACT

In this paper the General Series Parallel Resonant Converters (GSPRC) is analyzed using state space techniques and the general mathematical model of the converters has been developed and simulated using MATLAB. The investigations on the series parallel resonant converter topologies such as CLL-T SPRC, LLC-T SPRC and LCL-T SPRC with closed loop operation has been estimated and presented. The comparative analysis of the converters and controllers is presented in this paper. A simple form of transfer function for the GSPRC is developed, which is used to analyses the stability of various resonant topologies. The simulation study indicates the superiority of fuzzy controller over the conventional control methods. A DSP based prototype of 300 W, 100 KHz converter is designed and experimentally demonstrated. The effectiveness of the proposed controller is verified for load and supply disturbance in experimental set up using TMS320F2407 processor. Comparison between experimental and simulations show a very good agreement and the reliability of fuzzy controller.

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

1. INTRODUCTION

High power DC-DC converters are now a day widely used in power electronics applications. In the recent past year it has been found that these converters experience high switching losses, reduced reliability, electromagnetic interference (EMI) and acoustic noise at high frequencies. The research in this field has been shown more interest by many researchers in developing the load independent converters using various concepts. The many resonant topologies, the series parallel resonant converter (SPRC) type has been known as one of the most promising topologies that provides a satisfactory wide operating rang with the modest component ratings. The SPRC is found to be suitable, due to various inherent advantages. It has been suggested to design resonant converter with three reactive components for better regulation. The LCL tank circuit based DC-DC resonant converter has been experimentally demonstrated and reported by many researchers [1-3]. Mangesh Borage et al [4] have demonstrated the LCL-T resonant converter with constant current output fed with resistive load. It can be found that the converter exhibits load-independent voltage and current gain at resonant frequency. The converter operated at fixed resonant frequency and its analyzed using state space approach.

Buck and boost DC-DC converter based fuzzy logic controller have been developed by Ismail Atacak et al [5]. Buccella. C et al [6] have developed the DC/DC resonant converter for the renewable energy source applications. The fuzzy controller was used to regulated the output voltage with constant level if the input voltage varies within a large range change. The transient and steady state performance of the converter was found with fuzzy and PI controllers. Pahlevaninezhad. M et al [7] have demonstrated the H∞ robust controller for a series-parallel resonant converter. The robust controller shows the significant of the improvement in the output voltage regulation and disturbance in the load side.

Chew L et al [8] have demonstrated LCC series parallel resonant converter using robust control method. The closed loop operation was presented using PI controller with load independent operation. Later, T.S.Sivakumaran et al [9] have demonstrated a CLC SPRC with fuzzy logic controller was presented. The performance of controller has been evaluated and found that the load independent operation may not be possible. Chuang, Ying-Chun et al [10] have developed the half-bridge series-parallel resonant converter for dc source and secondary battery interface. The converter operated with above resonant frequency. Operating equations and operating theory are also developed and presented. Here the load independent operations are not possible. A comparative study of the steady-state and a dynamical characteristic of series-parallel resonant converter by using different modulation strategies were presented by Zhiyu Cao et al [11]. Later Mandal. K et al [12] have developed the series parallel resonant converter with capacitive output filter by using constant frequency phase shift modulation technique. The stable region of the controller parameters are found from the nine topological modes and four switching operation modes was presented.

S.Arulselvi et al [13] have demonstrated the fuzzy logic controller based ZVS quasi-resonant converter has been demonstrated by. The simulation results have been presented and the performance of the converter for varying load conditions was evaluated. R. Laouamer et al [14] have developed series, parallel and series parallel resonant converter, the performance of the converter are compared and presented. C.Nagarajan et al [15, 21] have demonstrated 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. Wu Chen et al [16] have demonstrated the DC/DC conversion systems constructed from connecting multiple converter modules in series and parallel at both the input and output sides were presented.

Lakshminarasamma.N et al [17] 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. Later, Martin P.Foster [18] have demonstrated CLL half bridge resonant converter with open loop operation. The AC equivalent circuit analysis and fundamental mode approximation (FMA) analysis was derived. The evaluation of static and dynamic performance was not provided. Guan-Chyn Hsieh [19] have demonstrated LLC half bridge series resonant converter with open loop. The dynamic analysis was presented for two operating region (CCM, DCM). The performance of controller has been estimated and found the load variation and load independent operation may not be possible [20].

To overcome some of these drawbacks, the proposed converter is operated with closed loop operation is introduced with fuzzy controller. The steady state stability analysis of various resonant topologies has been analyzed using state space model. This paper presents a method to predict the steady state and dynamic performance of the resonant topologies (like LCL-T, CLL-T and LLC-T) with load and supply disturbance is presented and tabulated. The LCL-T SPRC provides better performance compared to CCL-T SPRC and LLC-T SPRC. The Comparison of the performance of controllers is also presented. The performance of controller has been found to be better when the fuzzy controller has been considered. A prototype 300 W, 100 kHz is implemented using TMS320F2407 DSP processor. The simulation results have been compared with experimental results and the correlation is fairly good.

2. DEVELOPED RESONANT CONVERTER TOPOLOGY WITH CONTROL CIRCUIT

The block diagram of GSPRC with DSP based controller is shown in Fig.1. The first a DC voltage is inverted in to a high frequency AC voltage and then the ac power is fed to the full bridge resonant converter. The converter operates at very high frequency. After that 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. 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.Fig.2 shows the different resonant topology.

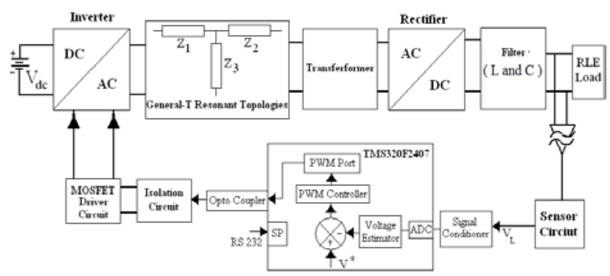


Fig. 1 Block Diagram of General Series Parallel Resonant Converter

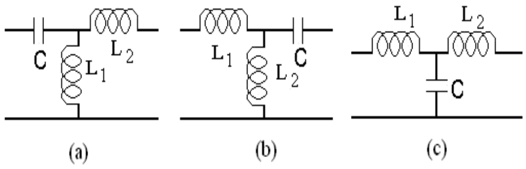


Fig. 2 Resonant topologies (a) CLL-T SPRC (b) LLC-T SPRC (c) LCL-T SPRC

The GSPRC power converter structure is shown in Fig.3. The primary DC/AC converter is a four quadrant bridge converter. The Switches S_1-S_4 is operated at a time one of the switch conducts and other is off. Due to this conduction, it minimizes voltage drop on low voltage input side. The switches share the current equally providing and conduct period at 50% duty cycle and 180^0 out of phase. The square wave from the switches is applied to the transformer will flow through the diodes of MOSFET leading to zero voltage turn on. The RLE load is connected across the bridge rectifier via 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.

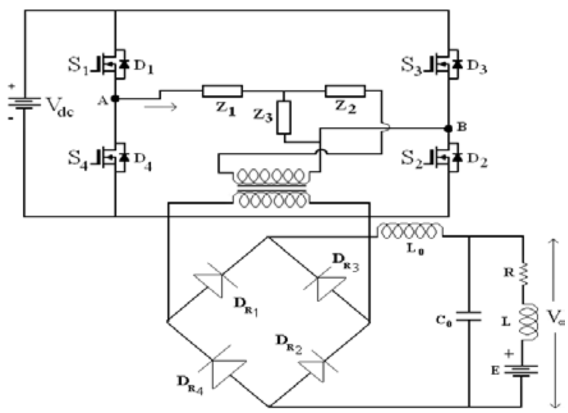


Fig. 3 Circuit diagram of GSPRC

3. STEADY STATE STABILITY ANALYSIS OF GSPRC USING STATE SPACE TECHNIQUE

3.1. General Mathematical Modeling

The equivalent circuit of GSPRC is shown in Fig.4.The mathematical model using state space technique can be obtained assuming all the components to be ideal.

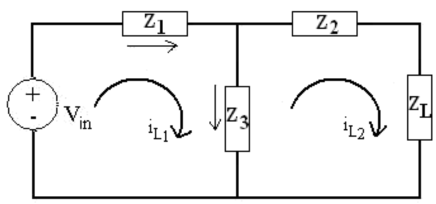


Fig. 4 Equivalent Circuit Model of General SPRC

The transfer function for the general SPRC is given below from figure 2. Appling KVL for the loop i_{L1} and i_{L2} we obtain

$$\begin{bmatrix} V_i(s) \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 + Z_3 & -Z_3 \\ -Z_3 & Z_2 + Z_3 + Z_L \end{bmatrix} \begin{bmatrix} I_1(s) \\ I_2(s) \end{bmatrix}$$

The General equation for SPRC is

$$\frac{V_0(s)}{V_i(s)} = \frac{Z_3 Z_L}{Z_1 Z_2 + Z_1 Z_3 + Z_1 Z_L + Z_2 Z_3 + Z_3 Z_L} \quad (1)$$

The state space representation is a mathematical model of a physical system as a set of input, output and state variables related by differential equations. It provides a convenient and compact way to model and analyze systems with multiple inputs and outputs. However the reason for including the state equation is sufficient information to describe the system behavior. The state model should also be able to given in its solution the time history of the state variables.

3.2. State Space model for CLL-T SPRC

The State Space model for CLL-T SPRC found from the equation (1) $Z_1 = \frac{1}{Cs}$, $Z_2 = L_2 S$, $Z_3 = L_1 S$. Substitute Z_1, Z_2, Z_3 in equation (1) and the equation written as

$$\frac{Y_0(s)}{u_i(s)} = \frac{L_1 Z_L s^2}{\frac{(L_1 + L_2)s}{C} + \frac{Z_L}{C} + L_1 L_2 s^3 + L_1 Z_L s}$$

Taking inverse Laplace transform in the above equation and the state space equations are

$$\dot{X}_1 = x_2$$

$$\dot{X}_2 = x_3$$

$$\dot{X}_3 = -\frac{(L_1 + L_2)}{CL_1 L_2} x_2 - \frac{Z_L}{CL_1 L_2} x_1 - \frac{Z_L}{L_2} x_3 + \frac{Z_L}{L_2} \ddot{U}$$

The state space model equations for CLL-T SPRC is

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ \frac{-Z_L}{CL_1 L_2} & -\frac{L_1 + L_2}{CL_1 L_2} & \frac{-Z_L}{L_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{Z_L}{L_2} \end{bmatrix} [u_i(s)] \quad (2)$$

The output equation is

$$y_0 = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (3)$$

3.3. State Space model for LLC-T SPRC

$Z_1 = L_1 s$, $Z_2 = \frac{1}{Cs}$, $Z_3 = L_2 S$. Z_1, Z_2, Z_3 values are substitute in equation (1)

$$\frac{Y_0(s)}{u_i(s)} = \frac{L_2 Z_L s}{\frac{(L_1 + L_2)}{C} + L_1 L_2 s^2 + [L_1 Z_L + L_2 Z_L]s}$$

the state space equations are

$$\dot{X}_1 = x_1$$

$$\dot{X}_2 = -\frac{(L_1 + L_2)}{CL_1 L_2} x_1 - \frac{(L_1 Z_L + L_2 Z_L)}{L_1 L_2} x_2 + \frac{Z_L}{L_2} u_i(s)$$

In above state space equations are written as in matrix form. The State Space model for LLC-T SPRC is

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{L_1 + L_2}{CL_1 L_2} & -\frac{(L_1 Z_L + L_2 Z_L)}{L_1 L_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{Z_L}{L_1} \end{bmatrix} [u_i(s)] \quad (4)$$

The output equation is

$$y_0 = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (5)$$

3.4. State Space model for LCL-T SPRC

Z_1, Z_2, Z_3 values ($Z_1 = L_1 S$, $Z_2 = L_2 S$, $Z_3 = \frac{1}{Cs}$) is replace in equation (1)

$$\frac{Y_0(s)}{u_i(s)} = \frac{Z_L}{L_1 L_2 Cs^3 + L_1 Z_L Cs^2 + (L_1 + L_2)s + Z_L}$$

Taking inverse Laplace transform above equation and the state space equations are

$$\dot{X}_1 = x_1$$

$$\dot{X}_2 = x_3$$

$$\dot{X}_3 = \frac{-Z_L}{CL_1 L_2} x_1 - \left(\frac{L_1}{CL_1 L_2} + \frac{L_2}{CL_1 L_2} \right) x_2 - \frac{L_1 Z_L}{L_1 L_2} x_3 + \frac{Z_L}{CL_1 L_2} u_i(s)$$

the state space the State Space model for LCL-T SPRC is

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ \frac{-Z_L}{CL_1 L_2} & \frac{-1}{CL_2} - \frac{1}{CL_1} & \frac{-Z_L}{L_2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{Z_L}{CL_1 L_2} \end{bmatrix} [u_i(s)] \quad (6)$$

The output equation is

$$y_0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (7)$$

4. RESULTS AND DISCUSSION

4.1. Fuzzy Logic Control (FLC)

The design procedure of FLC for the voltage control of SPRC is presented [15,21]. Fuzzy control is developed using the fuzzy toolbox. The fuzzy variables 'e', 'ce' and 'Δu' are described by triangular membership functions. The membership functions of the associated input and output linguistic variables are generally predefined on a common universe of discourse. To converter the numerical variables into linguistic variables, the following seven triangular membership functions are chosen for simplicity. Table 1 shows the fuzzy rule base created in the present work based on intuitive reasoning and experience. Fuzzy memberships are defined as NB (Negative Big), NM (Negative Medium), NS (Negative

Small), Z (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

Table 1 Fuzzy Rules

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

It can 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. It is also the output voltage changes even after reaching the reference value then the change of frequency must be changed by a small amount to prevent the output from moving away.

4.2. Simulation Results

The performance of the converter is controlled with PID/Fuzzy controller by evaluated using MATLAB/Simulink software and fuzzy toolbox. The design procedure and system parameters chosen for the performance evaluation of SPRC is present in [21]. The entire system is simulated with a switching frequency of 100 KHz. The resonant topologies are compared with controller performance. The resonant converter topologies operated in change in load from 0.9 Amps to 0.75 Amps. The SPRC for supply voltage disturbance of +10 V change is applied and the results presented.

4.2.1 Simulation Results for CLL-T SPRC with Controllers

The resonant voltage, resonant current and output load voltage are shown in Fig.5a-5f. The overshoot and settling time is more. It is observed that the settling time is 0.18 sec. in CLL-T SPRC. The supply voltage disturbance is applied to the input source at t=0.05ms. The steady state error and settling time is more. The load disturbance is given to the converter at t=0.05ms. The output voltage with load change is shown in Fig.5e-5f for PID and fuzzy controller. It is observed that the settling time of the system 0.036ms.

4.2.2 Simulation Results for LLC-T SPRC with Controllers

It can be seen that the resonant voltage and resonant current are shown in Fig.6(a,b) operated with resonance frequency. It is clearly seen load condition that the resonant current contains harmonics and its presents a sinusoidal shape. The slight droop in the resonant characteristics is due to the increase in conduction losses in the bridge inverter and resonant network. It is observed that the settling time is 0.014 sec. with FLC. The steady state error for the LLC-T SPRC with FLC is 0.004 V.

The output voltage of the converter change with the in load and supply are shown in Fig.66c-f). To regulate the output voltage with the FLC/PID controller is designed. It’s clearly seen in the Fig.6d, the output voltage is constant till the time of disturbance. In Fig. 6e, the input voltage is disturbance gets reflected in the output side, leading to overshoot in the output voltage. The closed loop fuzzy controller helps in reducing the overshoot. It clearly observed that the FLC based converter has less overshoot and lower settling time. Also the controller gives better steady state and dynamic response.

4.2.3 Simulation Results for LCL-T SPRC with Controllers

The resonant current and resonant voltage for RLE load were estimated and shown in Fig.7a-7f. The overshoot and settling time is less compared to other converters and the response is oscillatory. It is seen that the settling time of output voltage is more than that of the settling time in LLC-T SPRC and CLL-T SPRC. It is seen that the inverter output as pure square wave without any harmonics and with resonance frequency.

It can be seen from the Fig.7.(a)-(f) that the after an initial transient the output follows the reference with good accuracy, showing a good tracking performance of the controller. The Fig.7 (b) that the current contains low ripple and it presents a good sinusoidal shape. It is seen that the settling time is 0.01 msec. It is clear that the FLC is eliminating the overshoot, rise time and high frequency noise suppression. The output voltage of the converter changes with change in load disturbance and supply voltage disturbance are shown in Fig.7e and f. It is observed that the closed loop system regulates the output voltage with a settling time of 0.05ms. Also the percentage overshoot in the output voltage is reduced to 0.8% instead of 1.5% in the case of LLC-T SPRC. The fuzzy based controller settles quickly to the steady state value as compared to the PID controller.

It is clear that the CLL-T SPRC, LLC-T SPRC are ineffective in eliminating the overshoot, rise time and high frequency noise suppression in the closed loop operation. The transient and steady state performance of the SPRC with different controller performance is tabulated in Table 2. Similarly the steady state error and the percentage over shoot also reduced with FLC. This ensures that the system can be controlled effectively with feedback. It is clear from the table, its shows that the peak overshoot is eliminated and the settling time is much lower with the fuzzy logic control strategy in LCL-T SPRC compared to other resonant topologies.

Table 2 Comparative Analysis of Various Converters with Fuzzy/PID Controller

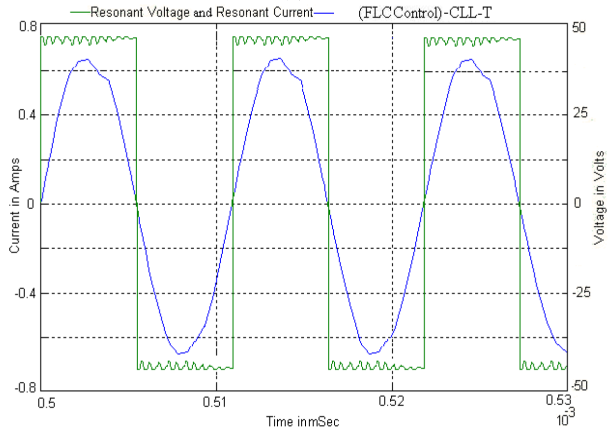
Controller	Rise time in Sec.	Settling time in Sec.	% Over Shoot In Volts	Steady state error
		LLC-T SPRC		
PID	0.56	0.35	2.8	0.04
Fuzzy	0.03	0.01	3	0.04
		CLL-T SPRC		
PID	0.1	0.23	1.65	0.005
Fuzzy	0.02	0.05	1.8	0.004
		LCL-T SPRC		
PID	0.095	0.12	1.2	0.02
Fuzzy	0.032	0.01	1	0.001

4.3. Stability Studies for GSPRC

Fig.8 represents the stability investigation of the converter using the extended nyquist function technique. The CLL-T SPRC extended nyquist plot shown in Fig.8a. It is drawn from the state space model equations (2). It is shown that the CLL-T converter circuit is unstable for the system parameters variations. The counter crosses real axis at a point between 0 and -1 on traveling through nyquist plot along the indicated direction it is observed that the -1+j0 point is encircled in clockwise direction one time. Therefore the system is unstable. The plot for LLC-T SPRC is shown in Fig.8b. The plot drawn from the state space model equations (4).

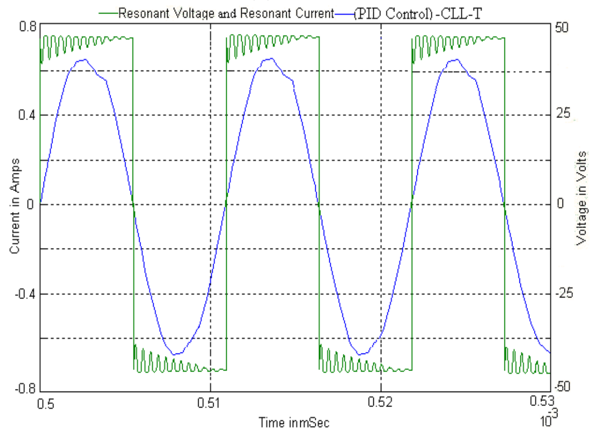
It is concluded that the LLC-T converter circuit is unstable for the system parameters variations. The plot has drawn for LCL-T SPRC from the above state space model equations (6). It is concluded that the LCL-T converter circuit is stable for the system parameters variations. It is observed that -1+j0 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.

(a)

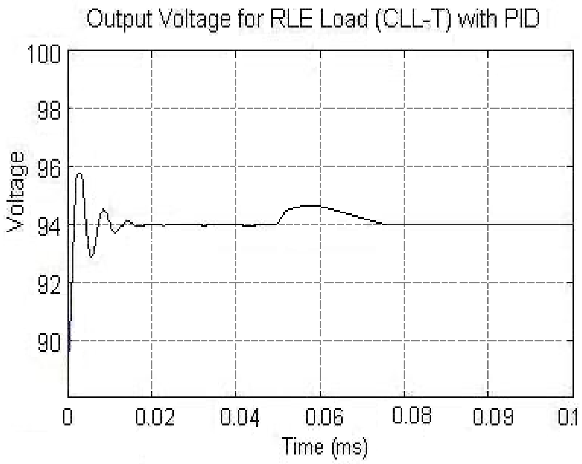


(a)

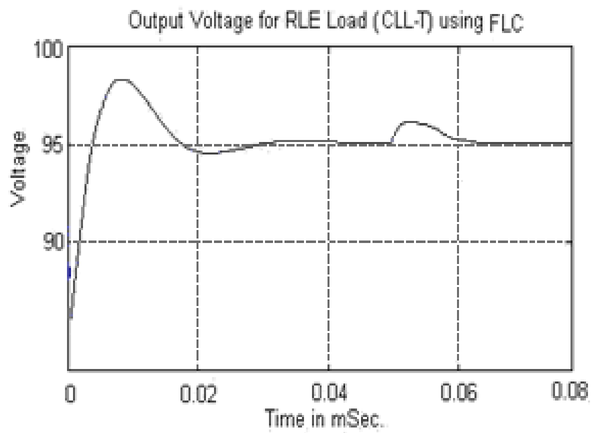
(b)



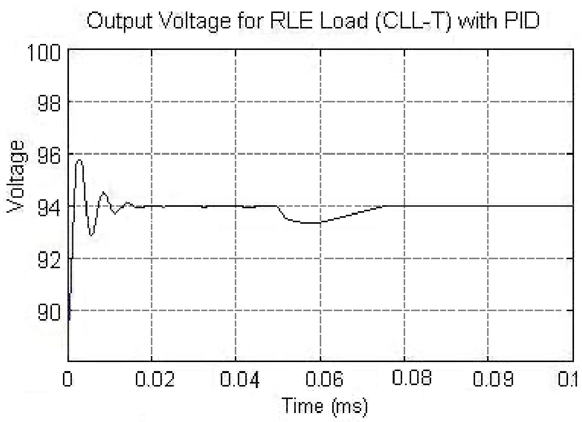
(b)



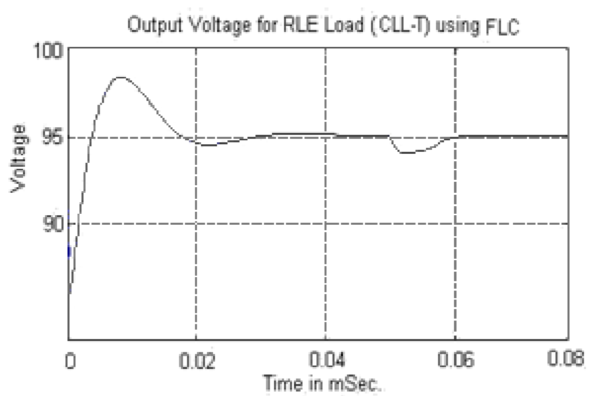
(c)



(d)



(e)



(f)

Fig. 5 Simulation obtained waveforms for CLL-T SPRC (a)Inverter voltage and current with PID controller (b) Inverter voltage and current with FLC (c) Regulated Output Voltage for supply disturbance (PID controller) t=0.05ms (d) Regulated Output Voltage for supply disturbance (FLC controller) t=0.05ms (e) Regulated Output Voltage for load disturbance (PID controller) t=0.05ms (f) Regulated Output Voltage for load disturbance (FLC controller) t=0.05ms

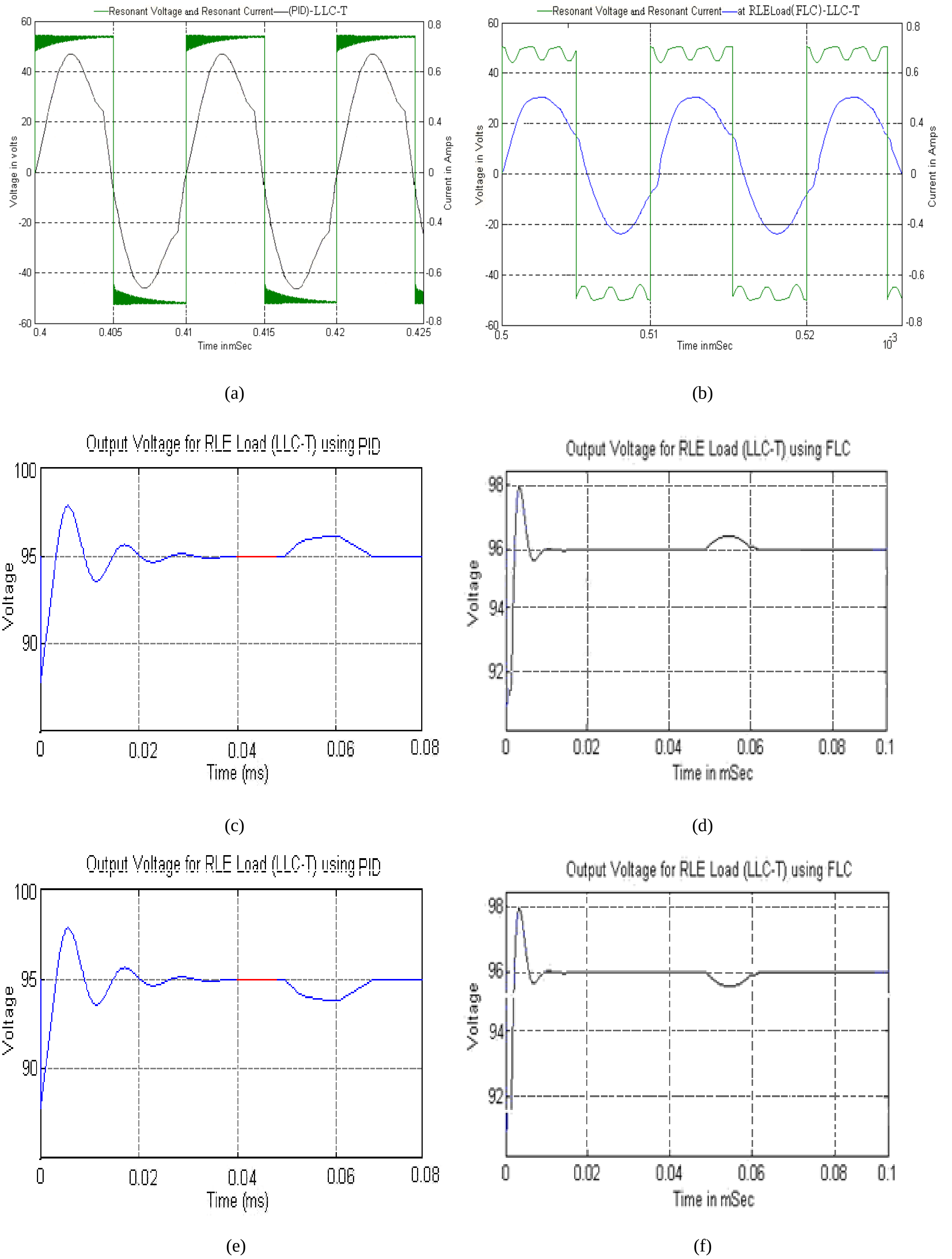


Fig. 6 Simulation obtained waveforms for LLC-T SPRC (a)Inverter voltage and current with PID controller (b) Inverter voltage and current with FLC (c) Regulated Output Voltage for supply disturbance (PID controller) t=0.05ms (d) Regulated Output Voltage for supply disturbance (FLC controller) t=0.05ms (e) Regulated Output Voltage for load disturbance (PID controller) t=0.05ms (f) Regulated Output Voltage for load disturbance (FLC controller) t=0.05ms

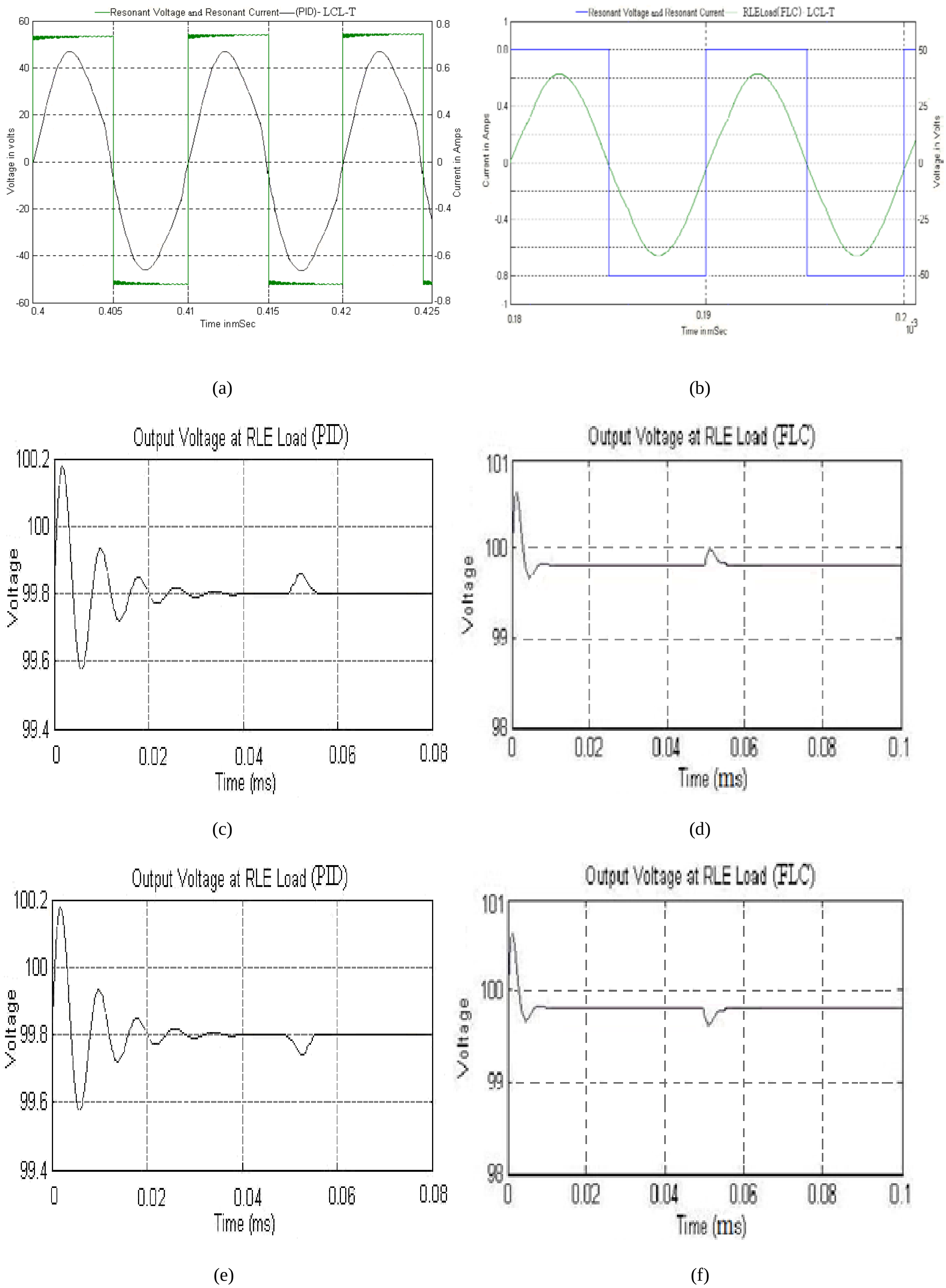
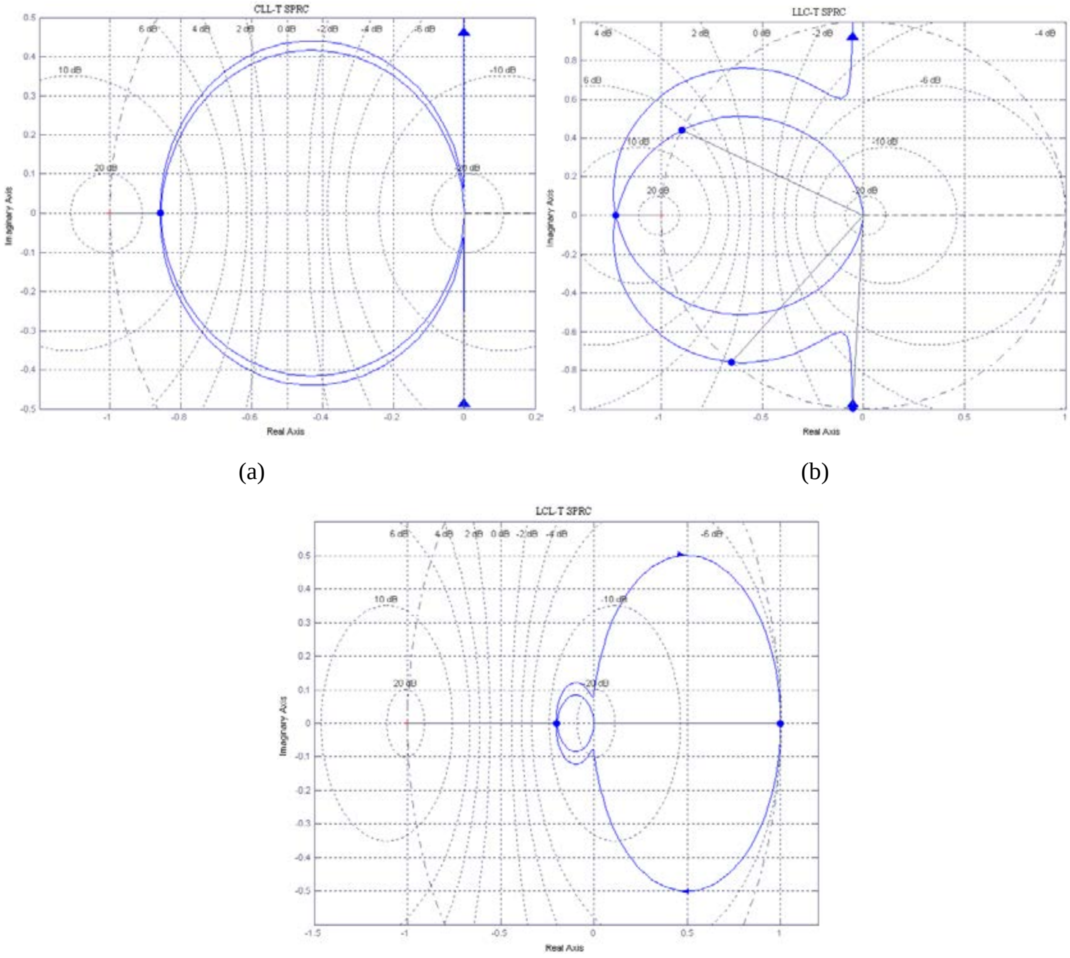


Fig. 7 Simulation obtained waveforms for LCL-T SPRC (a)Inverter voltage and current with PID controller (b) Inverter voltage and current with FLC (c) Regulated Output Voltage for supply disturbance (PID controller) t=0.05ms (d) Regulated Output Voltage for supply disturbance (FLC controller) t=0.05ms (e) Regulated Output Voltage for load disturbance (PID controller) t=0.05ms (f) Regulated Output Voltage for load disturbance (FLC controller) t=0.05ms



(a) (b)

(c)

Fig. 8 Stability analysis of (a)CLL-T SPRC (b) LLC-T SPRC (c)LCL-T SPRC

5. EXPERIMENTAL RESULTS

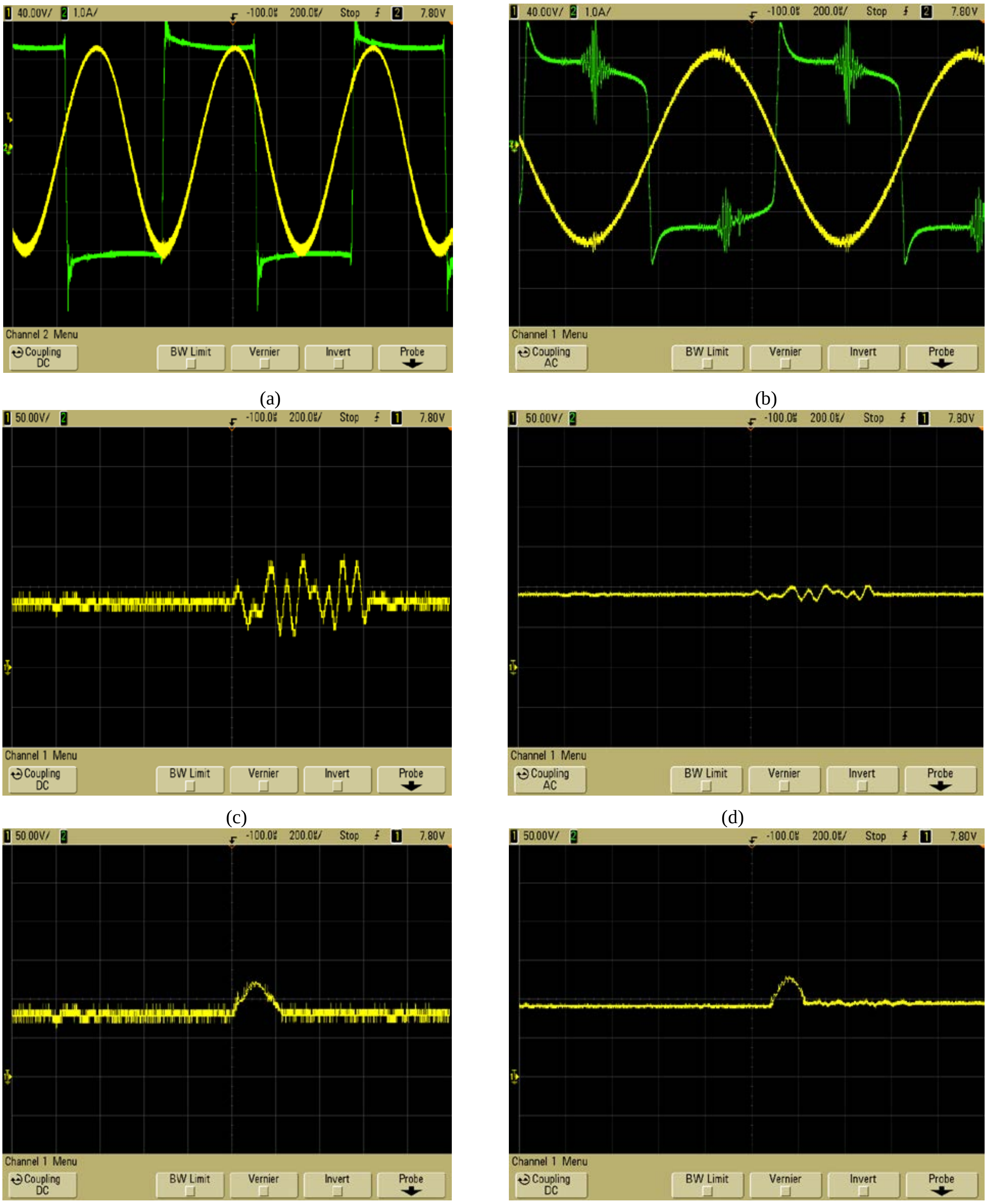
The proposed converter is designed and implemented with closed loop. A prototype CLL-T, LLC-T and LCL-T SPRC is operating at 300 W, 100 KHz was designed. The Digital Signal Processor TMS320F2407 is used for the realization of the proposed control techniques. The event manager module of the DSP generates the firing pulses. Opto couplers HCPL 4506 provides isolation between the event manager module of DSP and gates of MOSFET switches. The PWM signal from the DSP is not capable of driving MOSFET. In order to strengthen the pulses, IR2110 driver is used for each firing pulses.

A drop in the actual voltage, the FLC controller to increase the duty cycle of the inverter switches thereby increasing the output voltage of the converter to reach the reference value. The actual voltage after suitable signal conditioning is fed to the on chip ADC of DSP. The signal instruction cycle execution time of the processor is 50 ns. The error between the reference and actual voltage are maintained by DSP controller. Its to provide an appropriate change in duty cycle of the firing pulses to the inverter circuit so as to maintain the output voltage constant in spite of load and supply disturbance. The change in load from 0.9 Amps to 0.75 Amps are applied to the converter and performance of the converter results are shown. The SPRC for supply voltage disturbance of +10 V change is applied and the results presented. It is concluded that the CLL-T SPRC and LLC-T SPRC settles at a new value after a load and supply disturbance.

These figures show the good dynamic performance of the controller. It is clearly seen form the Fig.9 (a-f) the resonant voltage, resonant current and output voltage contains harmonic, this harmonics effect relatively hard for the whole circuit, because non-linear loads affect the resonant circuit. The Fig.9 (c-f) shows the regulatory response of converter under sudden load and supply disturbance respectively.

Fig.10.(a,b) presents the inverter voltage and inverter current for LLC-T SPRC, its measure from the point A and B of the bridge inverter. 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. The voltage regulation of the converter with the same load and supply changes applied as in CLL-T SPRC are shown in Fig.10(c-f) respectively. It is seen that the output voltage is regulated after the load changes with settling time of 3 and 2 ms respectively.

It is clearly shown in Fig.11 (a,b) that the power losses in the occurrence of the turn on switching are maintained very low by means of the resonant operation i.e during the switching both the voltage and current are minimum. Fig.11. (b) it can be seen from this figure that the current contains low harmonics and it presents a nearly sinusoidal shape.



(a) (b) (c) (d) (e) (f)

Fig. 9 Experimental Waveforms for CLL-T SPRC (a) PID controller (b) FLC Controller, [CH1: Resonant Voltage (Volt. Scale: 40 V/div.).CH2: Resonant Current (Amp. Scale: 0.5A/div.)] (c) Output voltage for load disturbance using PID (d) Output voltage for load disturbance using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)] (e) Output voltage for change in Supply using PID (f) Output voltage for change in Supply using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)]

Its 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. It can be seen that, the output voltage is regulated well within 1 second for both load and supply voltage changes. It is proved that the settling time is reduced compared to CLL-T SPRC and LLC-T SPRC. In LCL-T SPRC acts effectively and forces the converter to settles quickly to follow reference output voltage after a load change and supply disturbance. It is clearly seen from the Table 3, the experimental results show the control characteristics are observed to closely match the theoretical values and the output voltage is seen to be nearly independent of load.

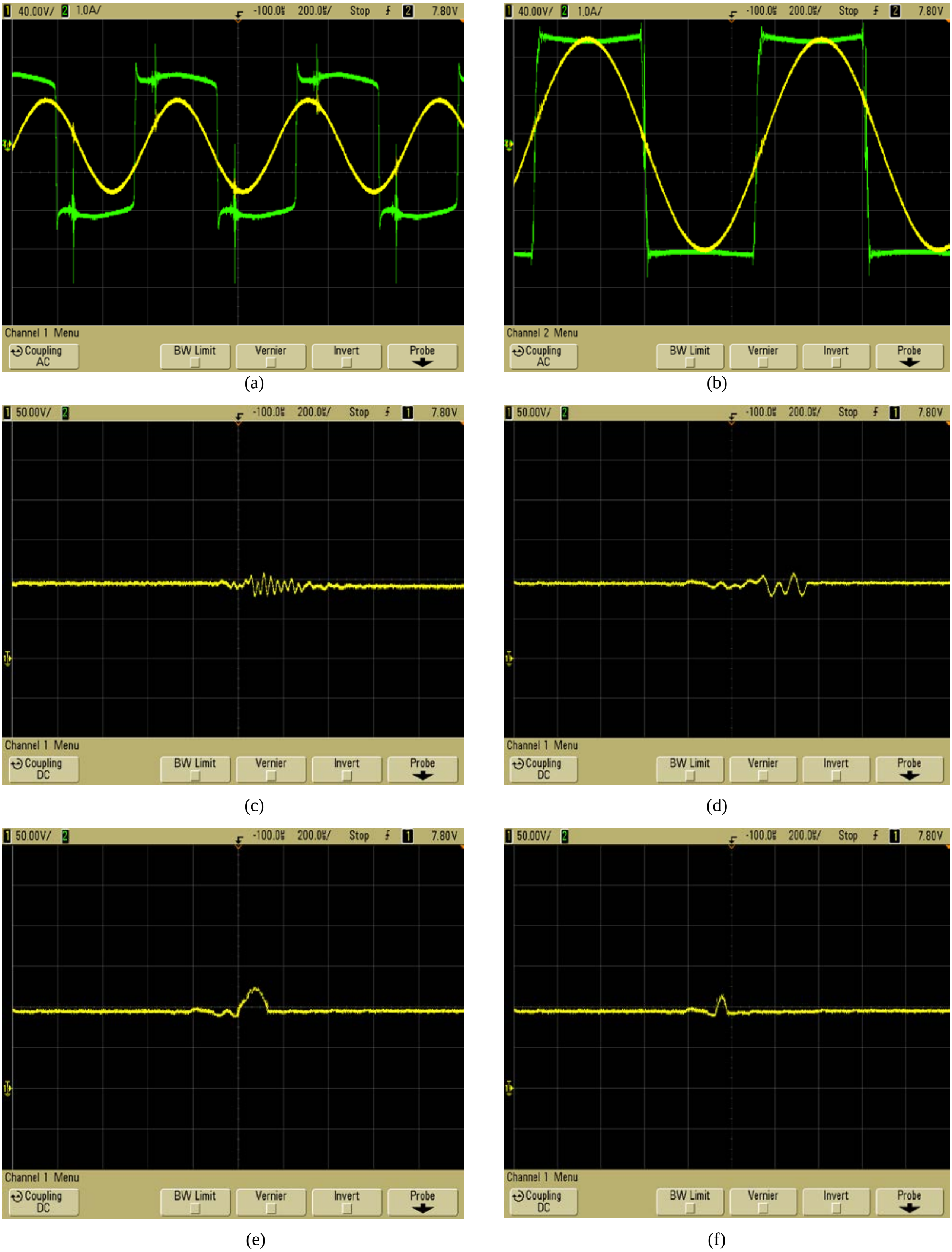


Fig. 10 Experimental Waveforms for LLC-T SPRC (a) PID controller (b) FLC Controller, [CH1: Resonant Voltage (Volt. Scale: 40 V/div.).CH2: Resonant Current (Amp. Scale: 0.5A/div.)] (c) Output voltage for load disturbance using PID (d) Output voltage for load disturbance using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)] (e) Output voltage for change in Supply using PID (f) Output voltage for change in Supply using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)]

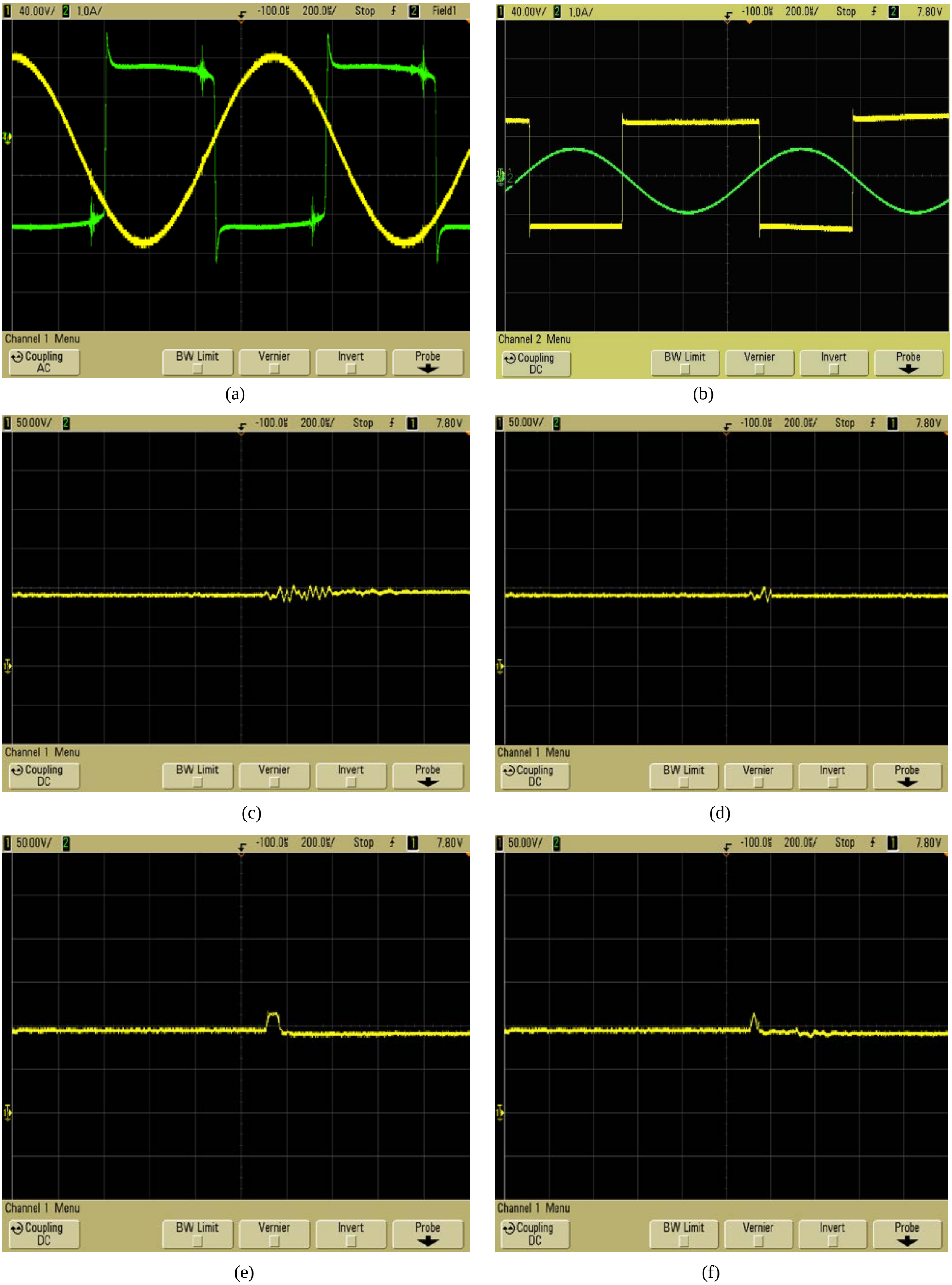
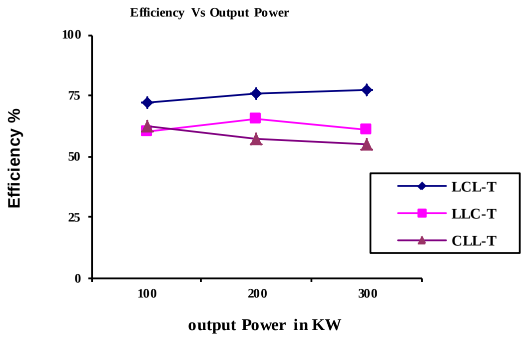


Fig. 11 Experimental Waveforms for LCL-T SPRC (a) PID controller (b) FLC Controller, [CH1: Resonant Voltage (Volt. Scale: 40 V/div.).CH2: Resonant Current (Amp. Scale: 0.5A/div.)] (c) Output voltage for load disturbance using PID (d) Output voltage for load disturbance using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)] (e) Output voltage for change in Supply using PID (f) Output voltage for change in Supply using FLC [CH1:Output Voltage (Volt. Scale: 50 V/div.)]

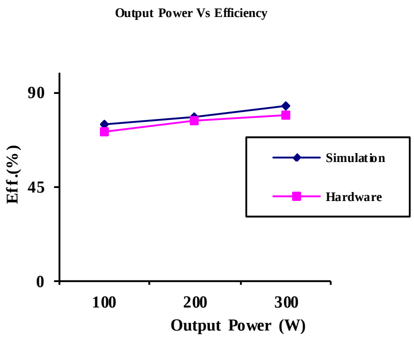
Table 3 Performance Measures of Theoretical & Simulation Results for Different Resonant Topologies with Fuzzy/PID Controller

Controller	Simulation Studies Load Disturbance		Experimental Studies		Simulation Studies Supply Disturbance		Experimental Studies	
	Settling Time in msec.	% Over Shoot	Settling Time in msec.	% Over Shoot	Settling Time in msec.	% Over Shoot	Settling Time in msec.	% Over Shoot
CLL-T SPRC								
PID	0.068	0.23	0.7	2	0.082	0.3	2.5	2
Fuzzy	0.046	0.2	0.25	0.8	0.03	0.2	0.9	1
LLC-T SPRC								
PID	0.07	0.21	0.6	0.9	0.08	0.29	1.2	1.5
Fuzzy	0.04	0.16	0.3	0.75	0.032	0.15	0.6	1
LCL-T SPRC								
PID	0.52	0.18	0.5	1.8	0.07	0.23	0.5	1.6
Fuzzy	0.025	1	0.2	0.9	0.025	0.09	0.1	0.8

The comparison chart shows in Fig.12. Its clearly show in Fig.12 (a) that the LCL-T SPRC better output power compared to other converters. The results obtained indicate that the FLC is an effective approach for DC-DC converter output voltage regulation. The LCL-T SPRC is better efficiency compared to other converters by using FLC.



(a)



(b)

Fig. 12 (a) Output Power various with Efficiency, (b) Output Power various with Efficiency

It's clearly show in Fig. 12(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 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 (≈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.

6. CONCLUSION

The Mathematical model of GSPRC for closed loop system with PID and Fuzzy controller were developed and resonant converter topologies were simulated using MATLAB. The converter performance was estimated under load and supply disturbance. It has been found from the results that the Fuzzy controller provides better control strategies and better voltage regulation compared to other resonant topologies. A TMS320F2407 DSP was used to implement the controller. The experiment results are compared with the simulation results. The results show that the feedback system with proposed controller is effective in tracking the reference as well as in stabilizing the output voltage under various disturbances. The proposed method can be effectively implemented for any application requiring constant power supply with load independent.

REFERENCES

[1] RAJU, G. S. N. – DORADLA, S.: An LCL Resonant converter with PWM Control Analysis, simulation, and Implementation, *IEEE Transactions On Power Electronics*, vol. 10, no. 2, pp. 164-174, March 1995.

[2] BORAGE, M. – TIWARI, S. – KOTAIAH, S.: Analysis and Design of an LCL-T Resonant Converter as a Constant-Current Power Supply, *IEEE Transactions on Industrial Electronics*, vol. 52, no. 6, pp. 1547-1554, December 2005.

[3] BORAGE, M. – TIWARI, S. – KOTAIAH, S.: 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, pp. 741-746, April 2007.

[4] MANGESH, B. – BORAGE, K. V. – BHATIA, N. M. S. – TIWARI, S.: Characteristics and Design of an Asymmetrical Duty-Cycle-Controlled LCL-T Resonant Converter, *IEEE Transactions on Power Electronics*, vol. 24, no. 10, pp. 2268-2275, October 2009.

[5] ATACAK, I. – BAY, O. F.: A type-2 fuzzy logic controller design for buck and boost DCDC converters, *The 2005 IEEE International Conference on Fuzzy Systems.*

[6] BUCCELLA, C. – CECATI, C. – SIANO, P.: A fuzzy-logic-controlled resonant converter for renewable energy sources applications, *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, pp. 2450-2455, 7-10 Nov. 2011.

[7] PAHLEVANINEZHAD, M. – SHAFIEI, N. – EREN, S. – BAKHSHAI, A. – JAIN, P.: A low ripple series-parallel resonant converter based on robust H∞ control approach, Energy Conversion Congress and Exposition (ECCE), 2010 IEEE, pp. 3403 – 3408, 12-16 Sept. 2010.

[8] CHINA, C. L. – SNG, E. K. K.: A Noval Robust Control Method for the Series-Parallel Resonant Converter, *IEEE Transactions on Power Electronics,* vol. 24, no. 8, pp. 1896-1904, August 2009.

[9] SIVAKUMARAN, T. S. – NATARAJAN, S. P.: Development of Fuzzy Control of Series-Parallel Loaded Resonant converter-Simulation and Experimental Evaluation, *Proceedings of India International Conference on Power Electronics 2006*, pp. 360-366.

[10] CHUANG, Y. C. – KE, Y. L. – CHUANG, H. S. – CHEN, Y. M.: Analysis and implementation of half-bridge series-parallel resonant converter for battery chargers, *Industrial and Commercial Power Systems Technical Conference (I&CPS), 2010 IEEE*, pp. 1-11, 9-13 May 2010.

[11] CAO, Z. – NZEUGANG, F. H. – FROHLEKE, N. – BOCKER, J.: A comparative study of series-parallel resonant converter by using different modulation strategies, *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, pp. 1006-1011, 7-10 Nov. 2011.

[12] MANDAL, K. – BANERJEE, S. – CHAKRABORTY, C.: Determination of stable region of controller parameters for series-parallel resonant converter with capacitive output filter, *Industrial Electronics (ISIE), 2011 IEEE International Symposium on 27-30 June 2011*, pp. 229 – 232.

[13] ARULSELVI, S. – GOVINDARAJAN, U. – SAMINATH, V.: Development of Simple Fuzzy Logic Controller (SFLC) for ZVS Quasi-Resonant Converter: Design, Simulation and Experimentation, *Indian institute of science. J. Indian inst. Sci.*, vol. 86, pp. 215–23, June 2006.

[14] LAOUAMER, R. – FERRIEUX, J. P. – BENQASSMI, H. – NORMAND, O. – BUCHHEIT, N.: A Comparison of Resonant Converter Topologies with Three and Four Energy Storage Elements for Automatic Inductive Charging Application, *Electrical Power Components and Systems*, vol. 27, issue 3, 1999, pp. 221-236.

[15] NAGARAJAN, C. – MADHESWARAN, M.: Performance Analysis of LCL-T Resonant Converter with Fuzzy/PID Using State Space Analysis, *Springer, Electrical Engineering*, vol. 93, no. 3, March 2011.

[16] WU, C. – XINBO, R. – HONG, Y, – TSE, C. K.: DC/DC Conversion Systems Consisting of Multiple Converter Modules: Stability, Control, and Experimental Verifications, *IEEE Transactions on Power Electronics*, vol. 24, no. 6, pp. 1463-1474.

[17] LAKSHMINARASAMMA, N. – MASIHUZZAMAN, M. – RAMANARAYANAN, V.: Steady state stability of Current Mode Active Clamp ZVS DC-DC Converter, *IEEE Transactions on Power Electronics,* vol. 24, no. 10, October 2009.

[18] FOSTER, M. P. – GOULD, C. R. – GILBERT, A. J. – STONE, D. A. – BINGHAM, C. M.: Analysis of CLL Voltage-Output Resonant Converters using Describing Function, *IEEE Transactions on Power Electronics*, vol. 23, no. 4, July 2008.

[19] HSIEH, G. C. – TSAI, C. Y. – HSIEH, S. H.: Design Considerations for LLC Series-Resonant Converter in Two-Resonant Regions, *IEEE Transactions on Power Electronics*, vol. 17, no. 2, pp. 731 – 736, June 2007.

[20] CHOI, H. S.: Design Considerations of Half Bridge LLC Series-Resonant Converter, *International Journal of Power Electronics*, vol. 7, no. 1, January 2007.

[21] NAGARAJAN, C. – MADHESWARAN, M.: Stability Analysis of Series Parallel Resonant Converter with Fuzzy Logic Controller Using State Space Techniques, *Taylor & Francis, Electric Power Components and Systems,* Vol. 39 (8), pp. 1-14, 2011.

Received December 26, 2012, accepted June 25, 2013

BIOGRAPHIES

Chinnadurai Nagarajan received the B.E degree from K.S.Rangasamy College of Technology, affiliated to Madras University, during 1997-2001, India, and the M.Tech degree from the Vellore Institute of Technology, Vellore, Tamilnadu India, in 2004. He obtained his PhD degree at Bharath Institute of Higher Education and Research (BIHER) University, Chennai, India. He has been a member of the faculty at Centre for Advanced Research, Muthayammal Engineering College, Rasipuram, Tamilnadu, India since 2005. His research interests include fuzzy logic and neural network applications to power electronics and drives.

Muthusamy Madheswaran received the BE Degree from Madurai Kamaraj University in 1990, ME Degree from Birla Institute of Technology, Mesra, Ranchi, India in 1992, both in Electronics and Communication Engineering. He obtained his PhD degree in Electronics Engineering from the Institute of Technology,Banaras Hindu University, Varanasi, India, in 1999. At present he is a Principal of Muthayammal Engineering College, Rasipuram, India. He has authored over forty five research publications in international and national journals and conferences.He was awarded the Young Scientist Fellowship (YSF) by the State Council for Science and Technology, TamilNadu, in 1994 and Senior Research Fellowship (SRF) by the Council of Scientific and Industrial Research (CSIR), Government of India in 1996. Also he has received YSF from SERC, Department of Science and Technology, Govt. of India. He is named in Marquis Who's Who in Science and engineering in the year 2006. He is a life member of IETE, ISTE and IE (India) and also a senior member of IEEE.