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Fuzzy Gain Scheduled PI Based Fourth Order Resonant Power Converter with Capacitive Output Filter Converter

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Abstract:

DC-DC power conversion used in industry and various applications where the demand for compact power supplies grows significantly. Conventional DC-DC converters have relatively poor voltage regulation. However, the resonant DC-DC converters have numerous advantages for DC-DC power conversions. This paper proposed a fourth order Resonant Power Converter (LCLC) topology by considered, and the steady-state stability of the converter is analysed using state space approach. PI and fuzzy controllers used for the improvement of efficiency, settling time, rise time, and steady-state error.

Keywords: DC-DC resonant converter, LCLC resonant tank, PI controller, Fuzzy Gain Scheduled PI controller, State space approach.

INTRODUCTION

In recent years the design and development of various DC-DC Resonant Converters (RC) have been focused on telecommunication and Aerospace applications. Resonant converters experience high switching losses, reduced reliability, electromagnetic interference (EMI) and acoustic noise at high frequencies. The series and parallel Resonant Converter (SRC and PRC respectively) circuits are the basic resonant converter topologies with two reactive components. The merits of SRC include better power conversion efficiency due to the series capacitor in the resonant network and the inherent DC blocking capability of the isolation transformer. PRC offers better no-load regulation but suffers from poor power conversion efficiency due to the deficiency of a DC blocking element before the isolation transformer. Hence an RC with three reactive components is suggested for better regulation [1-2]. In this paper, a four-element resonant power converter with a combination of LCLC topology is chosen, and the steady-state stability of the LCLC resonant power converter is analyzed using state space technique. The operation of the proposed LCLC DC-DC resonant converter closed loop control is implemented using PI and fuzzy controller, performance parameters like efficiency, settling time, ascent time and steady-state error are analysed.

RESONANT CONVERTERS

In search of converters capable of operating at higher frequencies, power electronics engineers started to develop converter topologies that shape either a sinusoidal current or a sinusoidal voltage waveform, significantly reducing switching losses. The fundamental idea is to use a resonant circuit with a sufficiently high-quality factor. Such converters are called resonant DC-DC converters [3-5]. There are three main types of resonant networks are Series Resonant, Parallel Resonant, and Series-Parallel Resonant, which are shown in Fig. 1 [6].

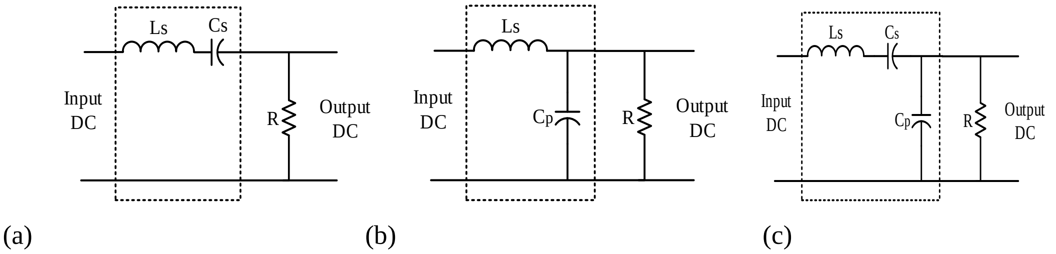


Figure 1. Resonant networks: (a) Series Resonant; (b) Parallel Resonant; (c) Series- Parallel Resonant.

Fourth order Resonant Power Converter (LCLC)

The closed-loop control of series-parallel resonant DC-DC converter (LCLC) with capacitive output filter is shown in Fig. 2.

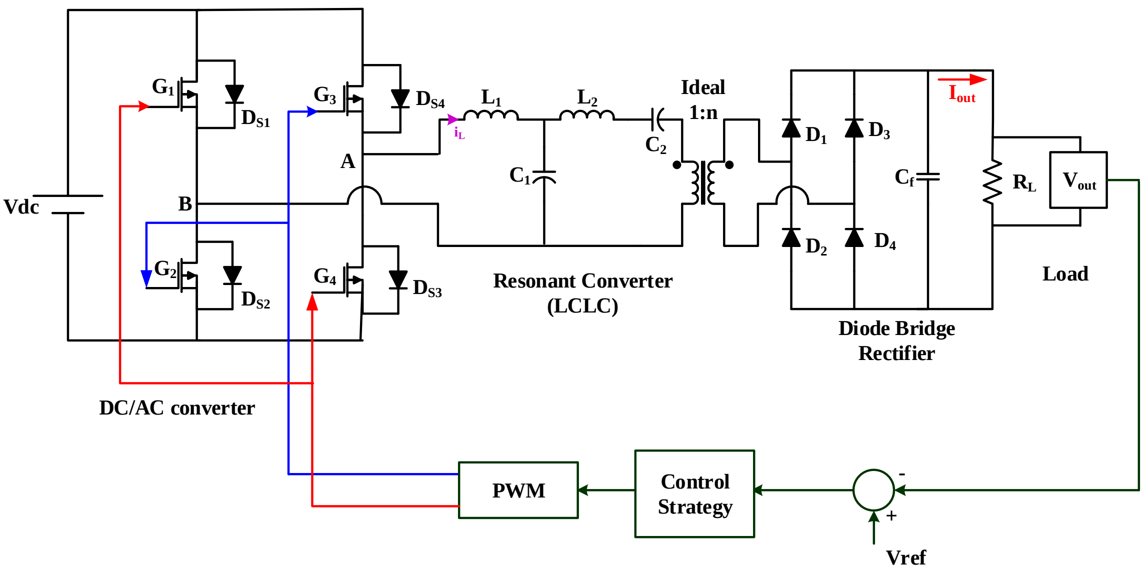


Figure 2. Closed loop control of resonant converter with LCLC configuration

This converter has also been often used with inductive output filter [7]. However, in the current work, the focus will be on the converter with capacitive output filter because this configuration is better suited for high-voltage applications. Eq. (1) gives the voltage conversion ratio of the series-parallel resonant converter.

$$\frac{V_o}{nV_{in}} = \frac{4}{\pi} \cdot \frac{k_{21}}{k_v} \qquad (1)$$

$$k_{21} = \frac{1}{\sqrt{\left[1-\alpha\cdot\left(f_{s,N}^2-1\right)\cdot\left(1+\frac{\tan(|\beta|)}{\omega C_p R_e}\right)\right]^2 + \left[.\alpha\cdot\left(f_{s,N}^2-1\right)\cdot\frac{1}{\omega C_p R_e}\right]^2}}$$

$$k_v = 1 + 0.27 \cdot \sin\left(\frac{\theta}{2}\right)$$

Where

$\alpha = .C_p/C_s$ is the ratio of the parallel to the series capacitor

θ is the output rectifier conduction angle

β is phase displacement of the fundamentals of the voltage across the parallel capacitor and the input current of the output rectifier

$\omega C_p R_e$ is a dimensionless parameter

N is the transformer turns ratio

$f_{s,N} = f_s/f_o$ is normalized switching frequency

f_s is switching frequency

$f_o = \left(2\pi\sqrt{L_s C_s}\right)^{-1}$ is series resonant frequency

This converter operates for low power close to the parallel resonant frequency $(2\pi\sqrt{L_p C_s})^{-1}$) and for a full load, close to the series resonant frequency $(2\pi\sqrt{L_s C_s})^{-1}$). The resonant inductor then resonates with the parallel capacitor, and the converter operates in the parallel resonant mode [8]. By proper selection of the resonant elements, the series-parallel resonant converter has better control characteristics than the resonant converters with only two resonant elements [9] being less sensitive to component tolerances. This configuration aims to take advantage of the desirable characteristics of the series and the parallel converter while reducing or eliminating their drawbacks. Unlike the series resonant converter, the series-parallel resonant converter is capable of both step-up and step-down operation [10]. The main disadvantage of the parallel resonant converter, i.e. the high device current independent on the load is supposed to be eliminated in the series-parallel resonant converter. Unfortunately, this drawback cannot be removed entirely but, with the proper choice of the resonant elements, it can be considerably reduced for certain load levels [11-12].

MODELLING OF LCLC RESONANT POWER CONVERTER

The equivalent circuit of LCLC resonant converter is shown on in Fig.2. The mathematical model using obtained assuming all the components to be ideal. The state space equation for the proposed converter is given by

$$\dot{X} = AX + BU \qquad (2)$$

Where,

$$\dot{X} = \frac{d}{dt}\begin{bmatrix} iL_1 \\ vC_1 \\ iL_2 \\ vC_2 \end{bmatrix}, \quad X = \begin{bmatrix} iL_1 \\ vC_1 \\ iL_2 \\ vC_2 \end{bmatrix}, \quad U = \begin{bmatrix} V_i \\ V_o \end{bmatrix}$$

The state space equation for LCLC resonant converter is get from Fig.2.

$$\frac{diL_1}{dt} = m\frac{V_i}{L_1} - \frac{vC_1}{L_1} \tag{3}$$

$$\frac{dvC_1}{dt} = \frac{1}{C_1}\left(iL_1 - iL_2\right)$$

$$\frac{diL_2}{dt} = \frac{1}{L_2}\left(vC_1 - vC_2\right)$$

$$\frac{dvC_2}{dt} = n\frac{V_o}{C_2} - \frac{iL_2}{C_2}$$

From equations (2) and (3), we can get,

$$\frac{d}{dt}\begin{bmatrix} iL_1 \\ vC_1 \\ iL_2 \\ vC_2 \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L_1} & 0 & 0 \\ \frac{1}{C_1} & 0 & -\frac{1}{C_1} & 0 \\ 0 & \frac{1}{L_1} & 0 & -\frac{1}{L_2} \\ 0 & 0 & -\frac{1}{C_2} & 0 \end{bmatrix} \begin{bmatrix} iL_1 \\ vC_1 \\ iL_2 \\ vC_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{L_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{L_2} \end{bmatrix} \begin{bmatrix} V_i \\ V_o \end{bmatrix} \tag{4}$$

From equation (4), we get,

$$A = \begin{bmatrix} 0 & -\frac{1}{L_1} & 0 & 0 \\ \frac{1}{C_1} & 0 & -\frac{1}{C_1} & 0 \\ 0 & \frac{1}{L_1} & 0 & -\frac{1}{L_2} \\ 0 & 0 & -\frac{1}{C_2} & 0 \end{bmatrix}, \quad B = \begin{bmatrix} -\frac{1}{L_1} & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & -\frac{1}{L_2} \end{bmatrix}$$

PERFORMANCE ANALYSIS OF LCLC RESONANT CONVERTER

PI Controller

A Proportional – Integral (PI) control is a particular case of the traditional controller family known as Proportional-Integral-Derivative (PID). These types of controllers are up to date the most common way of controlling industrial processes in a feedback configuration [13-14]. Fig. 3 shows the structure of proposed converter with PI controller. The proportional part is responsible for following the desired set-point while the integral part accounts for the accumulation of past errors.

The closed-loop simulation using a PI controller for the LCLC Resonant Converter is carried out using MATLAB/Simulink software. Depending on an error and the change in error, the value of change of switching frequency is calculated. Set parameter instruction and function blocks available in MATLAB are used to update the new switching frequency of the pulse generators. Controllers based on the PI approach are commonly used for DC-DC converter applications. Power converters have relatively of low order dynamics that can be well controlled by the PI method. PI-based closed loop Simulink diagram of LCLC is shown in Fig.4.

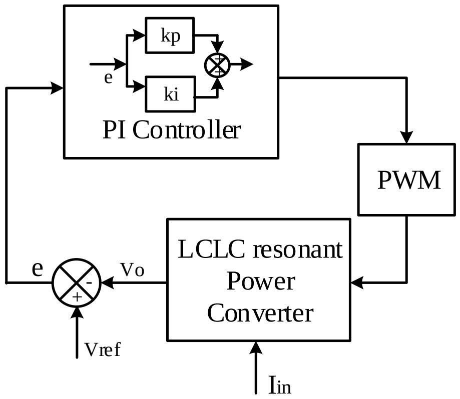


Figure 3. Structure of PI controller with LCLC resonant converter

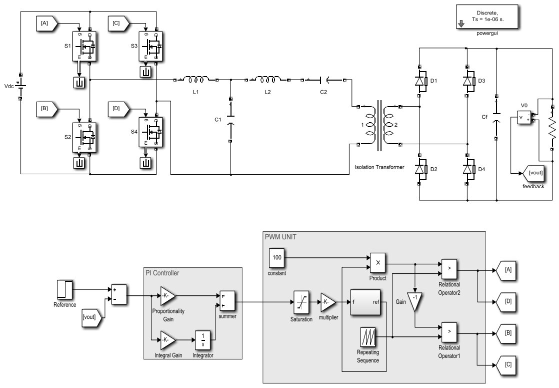


Figure 4. Closed loop Simulink model of LCLC resonant converter using PI controller

Fuzzy Gain Scheduled PI Controller (FGSPI)

Fuzzy Logic Toolbox is available in MATLAB used in this research work for implementation of the Fuzzy controller. It allows several things to be done, but the most important things are to be a place where a fuzzy inference system can be created or edited. For this LCLC RC control simulation system, the fuzzy boundaries can be considered according to the rules that are going to be used. As the numbers of rules increased, the degree of membership will become more accurate. The designed Fuzzy Proportional Integral (Fuzzy-PI) controller is a hybrid controller that utilizes two sets of PI gains in order to achieve a non-linear response. The switching in this controller is achieved with a fuzzy logic section that depends on the input $V_{in}(t)$. At every sampling interval, the instantaneous RMS values of the sinusoidal 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 gain of PI controller. The closed-loop Simulink diagram of LCLC Resonant Converter using Fuzzy Gain Scheduled PI is shown in Fig. 5.

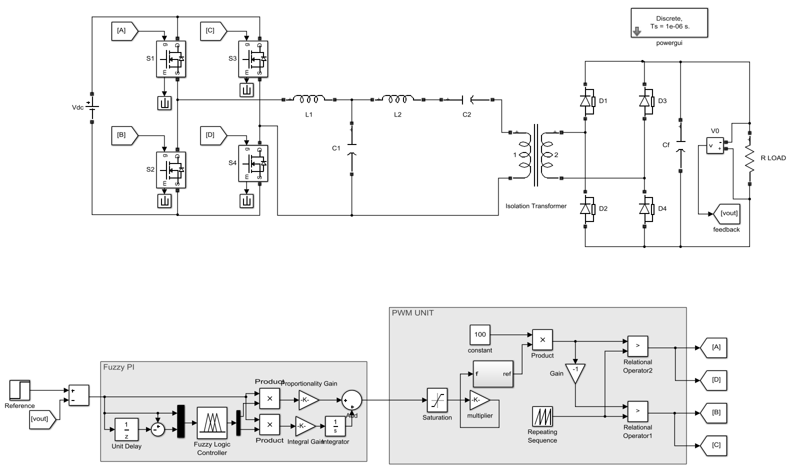
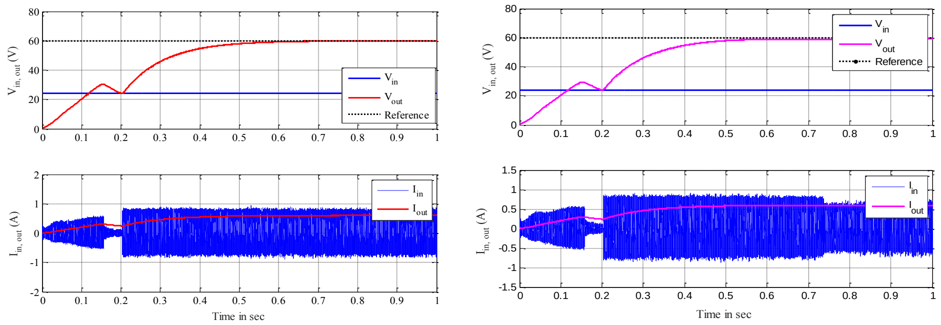


Figure 5. Closed loop Simulink model of LCLC resonant converter using Fuzzy Gain Scheduled PI controller

RESULTS AND DISCUSSION

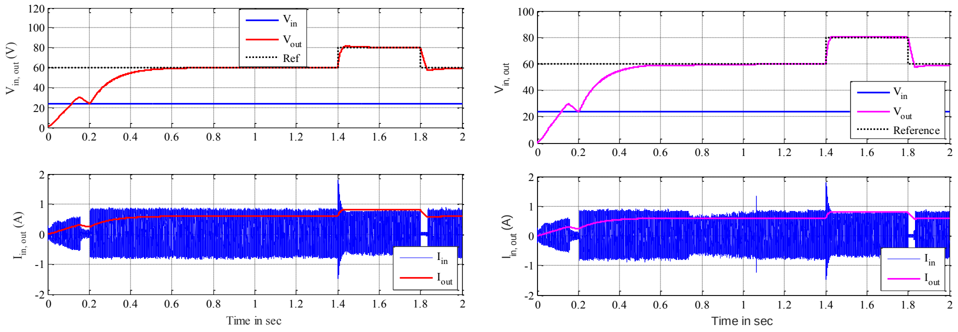
Figs.6-8 show the simulated closed loop response of LCLC resonant converter using a PI controller. The system is simulated with a switching frequency of 100 KHz. The simulated converter output voltage Vo and load current Io for applied at 2 seconds. It is observed that the PI controller for LCLC converter regulates the output voltage with a settling time of 0.7012 seconds. The following parameter settings are considered for PI controller: Proportional gain constant (Kp) = 0.5010 and integral time constant (Ki) = 4.8940. Input Voltage is 24VDC, Inductors L1=L2 is 38.02μH and Capacitors C1=C2 is 66nF, Load Resistor RL is 100Ω and the filter capacitor Cf is 1000μH.

Fig. 8(a) shows the output voltage and current response of the LCLC resonant converter for the nominal case of set value at V=60V with PI controller, the controller response has reached its set value of 0.7012 seconds with a rise time of 0.5319 Seconds. Similarly, the nominal case of LCLC converter using Fuzzy Gain Scheduled PI controller settled at 0.5517 seconds with a rise time of 0.4663 seconds as shown in Fig. 8(b). It is observed that the Fuzzy Gain Scheduled PI for LCLC regulates the output voltage with minimum settling time. Fig. 7(a) shows the servo response of the LCLC resonant converter, the input voltage sudden incremented 33% at 1.4 seconds and decremented 33% at 1.8 seconds. The PI controller regulated the voltage during this servo response and reached its steady state at 0.148 seconds with PI controller and the servo response of Fuzzy Gain Scheduled PI controller settled at 0.131 seconds as shown in Fig. 6(b). Similarly, the Fig. 8(a) shows the regulated response of the LCLC resonant converter with PI controller; the load disturbance occurred between 1.4 and 1.8 seconds. During this period the load current slightly varied but there are no effects in the output voltage of the LCLC resonant converter. Also, the response of Fuzzy Gain Scheduled PI controller has no effects on the output voltage of the LCLC resonant converter shown in Fig. 8(b) respectively. From the simulation analysis, it is observed that the Fuzzy gain scheduled PI controller regulates the output voltage of the proposed LCLC converter with very fast compared to PI controller. The Table 1 depicts the responses of PI and Fuzzy Gain Scheduled PI controller under nominal, servo and regulatory conditions. The input voltage of the converter is 24V DC.



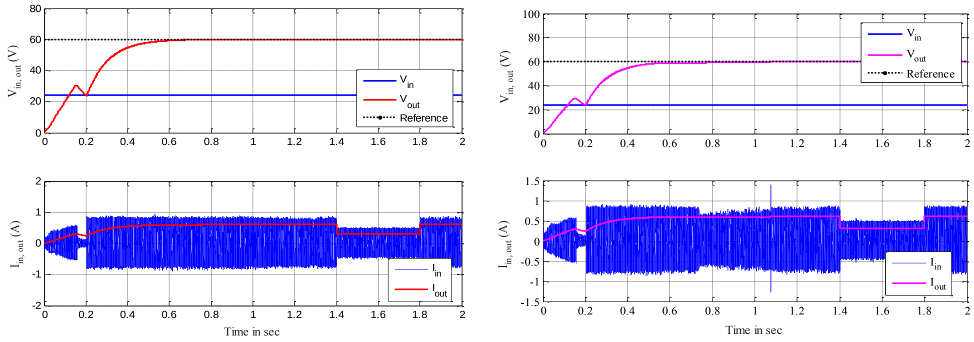
(a) PI controller (b) Fuzzy PI controller

Figure 6. Voltage and current response of LCLC resonant converter for nominal set value of V=60V



(a) PI controller (b) Fuzzy PI controller

Figure 7. Voltage and current response of LCLC resonant converter for set value of V=60V at t=0-1.4 sec, V=80V at t=1.4-1.8 sec & V=60V at t=1.8 -2.0 sec



(a) PI controller (b) Fuzzy PI controller

Figure 8. Voltage and current response of LCLC resonant converter for a load of R=100 Ω at t=0-1.4 sec, R=200 Ω at t=1.4-1.8 sec & R=100 Ω at t=1.8 -2.0 sec

Table 1. Performance evaluation of PI controller for LCLC resonant converter with resistive load using MATLAB

Controller	Nominal Case				Servo Response (Input)				Regulatory Response (Load)			
	Rise Time (sec)	Peak Time (sec)	Overshoot (%)	Settling Time (sec)	Supply Increase 33%		Supply Decrease 33%		Load Increase 100%		Load Decrease 100%	
					Over shoot (%)	Settling time (sec)	Under shoot (%)	Settling time (sec)	Over shoot (%)	Settling time (sec)	Under shoot (%)	Settling time (sec)
PI	0.5319	0.9443	-	0.7012	1.939	0.211	3.78	0.177	No change			
FGSPI	0.4663	0.6448	-	0.5517	0.77	0.131	3.22	0.095	No change			

CONCLUSION

Analysis of performance of the LCLC resonant converter clearly projected in this paper with various disturbances and load conditions. Comparison of PI and Open Loop Controller was carried out and concluded that PI-based fourth order Resonant Power Converter (LCLC) has effective output voltage regulation and high efficiency. To improve the dynamic response of the controller Fuzzy Gain Scheduled PI controller was tried. Using Fuzzy Gain Scheduled PI controller, a sudden variation of load and dynamic response of LCLC resonant converter was verified. Comparison of performance estimation for open loop, PI controller and Fuzzy Gain Scheduled PI was carried out. The results obtained indicate that the Fuzzy Gain Scheduled PI controller is an effective approach for the output voltage regulation and high efficiency of the LCLC resonant converter.

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