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Simulation and implementation of phase shifted series resonant converter

Jayandiran S*, Karpagam R** and Elanchezhian P***

This paper deals with digital simulation of phase shifted series resonant DC to DC converter using Matlab Simulink^TM. The simulink models for open loop and closed loop systems are developed and they are used for simulation studies. Normally single voltage feedback is required for the system. This system consists of two control loops with one inner resonant vector and one outer voltage loop. The dynamic response improved by this dual loop method. This converter is capable of producing ripple free DC output. Switching losses and switching stresses are reduced by using soft switching. This converter has advantages like high power density and low switching losses. Theoretical predictions are well supported by the simulation results.

Keywords: *Dynamic performance, dynamic response, phase shifted series resonant converter, quasi current mode control, soft switching.*

1.0 INTRODUCTION

H-BRIDGE system used in high power DC-DC conversion is a popular and well-received method in many applications. The basic H-bridge converter can be modified easily by introducing soft switching to the converters. There are many types of soft switching converters including load resonant, square-wave resonant, zero-voltage and zero current resonant. The Phase-shifted Series Resonant Converter (PSRC) [1] based on an H-bridge has the advantage of inherent short circuit protection characteristic and high conversion efficiency. Unbalanced switching signal will not cause saturation to the transformer due to presence of the series resonant capacitor. Figure 3 shows the schematic diagram of the PSRC. The two switching devices (S_1 and S_3, S_2 and S_4) in each leg of the H-bridge are switched alternatively with almost 50% duty ratio. The switching pulses to the two legs have a phase angle of α in order to change the voltage applied to the resonant tank as shown in Figure 1. The general design rule is that the switching frequency fs of PSRC is always chosen to be close to the resonant frequency fr, defined by the resonant inductor *L*r and resonant capacitor *C*r to make the resonant current waveform be quite sinusoidal. Of course, to reduce the size of energy storage components such as inductor, capacitor and transformer, the switching frequency fs is very high. The resonant current ir is regulated by changing the phase angle α. By regulating the resonant current the rectified output voltage is controlled. Normally the value of the load resistance and the input DC voltage are variable within a specific range, the voltage feedback and certain closed-loop control law should be employed to keep the output voltage at the desired values. Though the error can be eliminated through the algorithm of the controller, the dynamic performance may not

* EEE Department, University College of Engineering, Kanchipuram-631552, e-mail:jayandiran@gmail.com
** Associate professor, Easwari Engineering College, Chennai-600089
*** Senior Research Fellow, ERED, CPRI, Bangalore-560 080, e-mail:elanchezhian_srf@cpri.in

be satisfied especially for nonlinear systems. Other publications on load range extension using ZCS, ZVS[2] and PWM with phase shift are the primary control for the switching signal. Some more advanced control strategies were developed recently to improve the performance of control system but they depend on the accuracy of the plant model or much more complicated computation is required. The control methods in the past have been reported in using the adaptive control such as auto-disturbance rejection control (ADRC) [5]. By regulating the resonant current which is rectified for supplying the load, the dynamic control performance of the converter system is improved as compared with that of the conventional PSRC control system. This method is called quasi-current mode because the current controlled is regulated indirectly using the resonanttank voltage vector. The method is similar to the dand q current control for multilevel but the present method is based on the control using resonant component phasor in the Figure 1.

2.0 ANALYSIS OF THE PHASE-SHIFTED SERIES RESONANT CONVERTER

The main circuit of the PSRC and its waveforms are shown in Figures 3 and 5, respectively. The resonant circuit is fed by a quasi-square voltage signal V_i in which the width of α is adjustable. The frequency of the voltage V_i generated by the H- bridge is the switching frequency f_s. The waveform of the primary voltage V_p of the transformer is square which has the same polarity as the resonant current i_r because V_p is actually the direct reflection of the output voltage through diode bridge and transformer. The resonant tank is characterized by its resonant frequency denoted by $f_r = 1/(2\pi\sqrt{LrCr})$. If the switching frequency f_s is chosen to be close to the resonant frequency, then the resonant current is quite sinusoidal. Now then V_s and V_p are taken as fundamental component for the following analysis of the resonant tank at steady-states. Using Fourier analysis, the amplitude of V_i is

$$V_i = \frac{2}{\pi}(1 - \cos\alpha)E \qquad \text{... (1)}$$

Where E is the input DC voltage and the amplitude of V_p is

$$V_p = kV\frac{4}{\pi} \qquad \text{...(2)}$$

Where $k = N_p / N_s$ and V is the output voltage.

The voltage balance equation of the resonant circuit can be expressed as:

$$\overrightarrow{Vi} = \overrightarrow{Vp} + \overrightarrow{\Delta Vx} \qquad \text{...(3)}$$

$$\overrightarrow{\Delta Vx} = \overrightarrow{VLr} + \overrightarrow{VCr} \qquad \text{...(4)}$$

$$\Delta V_x = I_m (X_L - X_C) \qquad \text{...(5)}$$

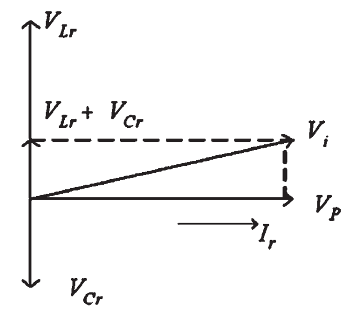

FIG. 1. PHASOR DIAGRAM OF RESONANT TANK

Where $X_L = \omega_s L_r$, $X_C = 1/\omega_s C_r$, $\omega_s = 2f_s$ and I_m is the peak value of i_r. The voltage across the primary side of the transformer has the same phase as the resonant current, hence the voltage phasor diagram of the resonant tank is shown as Figure 1 and equation (6) is true

$$V_i = \sqrt{(\Delta Vx)^2 + (Vp)^2} \qquad \text{...(6)}$$

The function $F(V_i)$ can be obtained using equation (2.1)

$$\alpha = F(V_i) = \cos^{-1}\left(1 - \frac{\pi\, Vi}{2E}\right) \qquad \text{...(7)}$$

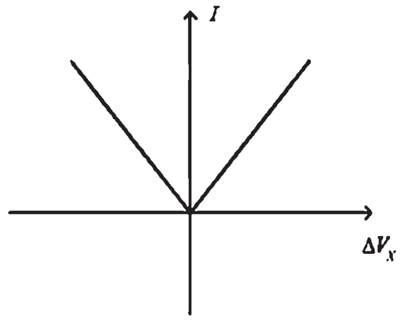

FIG. 2. CURRENT I AGAINST ΔV_X

The resonant current is rectified for supplying the load. The capacitor constitutes a low pass filter. The load is represented by a purely resistive element. The dynamics of the output circuit is given by

$$\frac{dV}{dt} + \frac{1}{rC}V = \frac{1}{C}I \qquad ...(8)$$

From equation (8) it can be seen that it is the current that affects the output voltage V directly. If the voltage V is controlled by regulating the current I, the dynamic performance of the converter would be perfectly controlled. Usually the capacitor C is of large value in order to smooth the output voltage. However, the time constant of the resonant tank is very small compared with that of the output filter for the sake of high switching frequency. Hence the analysis of the tank can be carried out at steady-states. Assume I_m is the peak value of the resonant current. Consequently the current I is treated as the average value of the rectified current as described by

$$I_m = \frac{\pi}{2k}I \qquad ...(9)$$

Substituting equation (9) into equation (5) yields

$$\Delta V_x = k_1 * I \qquad ...(10)$$

$$\text{Where } k_1 = (\pi * (X_L - X_C)/ 2k) \qquad ...(11)$$

3.0 CIRCUIT DIAGRAM

The Figure 3 shows the circuit diagram of Phase Shifted Series Resonant Converter (PSSRC).

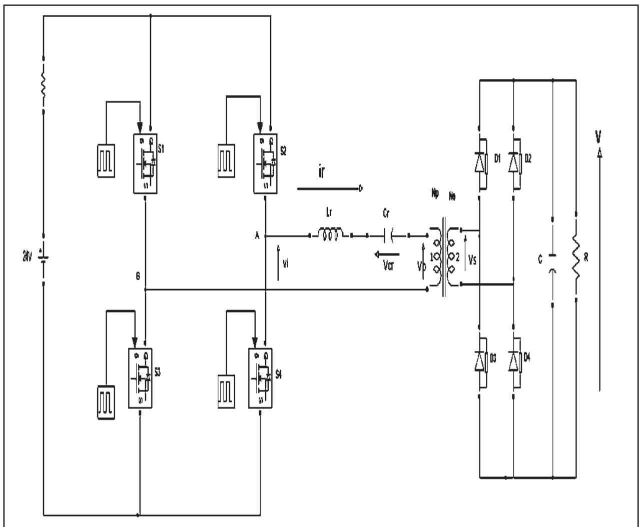

FIG. 3. CIRCUIT DIAGRAM OF PSRC

4.0 SWITCHING SEQUENCE AND WAVEFORMS

The switching sequence of the phase shifted series resonant converter is given in the Figure 4. The two switches S_1 and S_3 in the Leg A is alternatively turned ON, this is also same in Leg B but the Phase difference of Leg A and Leg B is α. The larger is the phase angle α, the higher is the voltage V_i. The voltage V_i is applied to the resonant tank and therefore the resonant current, which is rectified for supplying the load, can be regulated by adjusting the phase angle α.

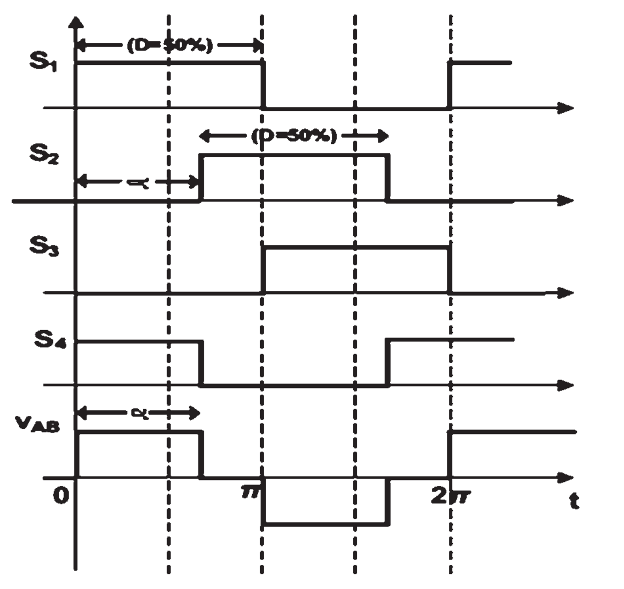

FIG. 4. SWITCHING SEQUENCE

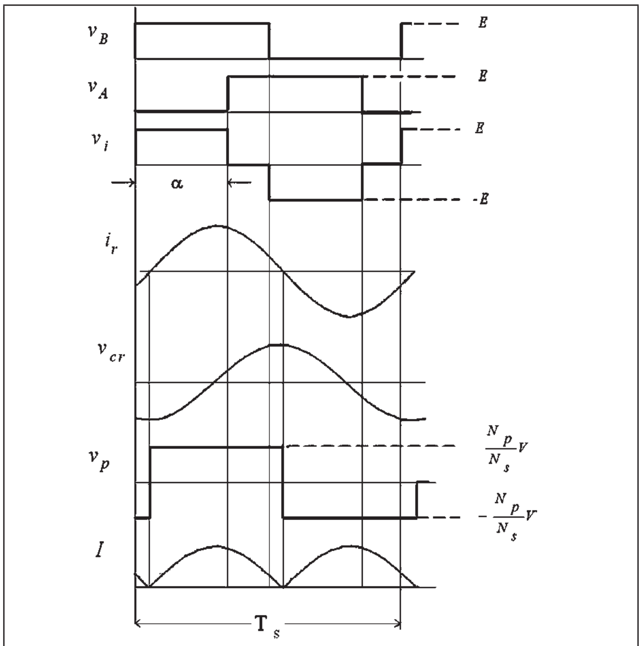

FIG. 5. WAVEFORM

5.0 SIMULATION RESULT

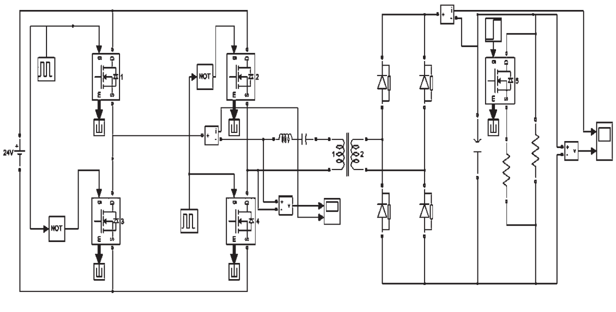

FIG. 6. OPEN LOOP WITH DISTURBANCE

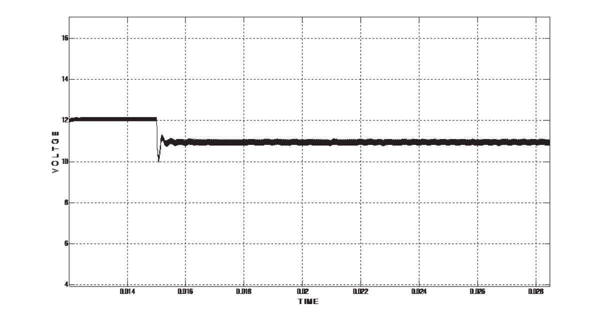

FIG. 7. OPEN LOOP OUTPUT WITH DISTURBANCE

TABLE 1			
PARAMETERS OF THE CONVERTER			
Resonant inductor (L_r)	56 µH	Rated input voltage E	24 V
Resonant capacitor (C_r)	0.5 µF	Power rating	10.5 W
Filter capacitor (C)	47 µF	Rated output voltage	12 V
Switching frequency (f_r)	33 KHz	Rated load resistance	14 Ω

Digital simulation is done using Matlab™ and the results are presented here. Open loop system is shown in Figure 6. The output voltage in open loop system is shown in Figure 7. The output voltage increases with the increase in the disturbance.

The load is reduced from full load to half load. The open loop system is shown in Figure 7.

The simulink model of closed loop system is shown in Figure 9. Output voltage is sensed and it is compared with the reference voltage. The error is processed through a PI controller.

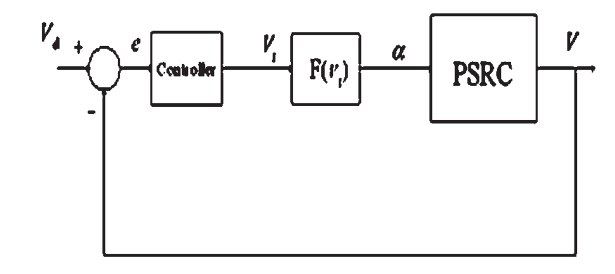

FIG. 8. BLOCK DIAGRAM OF CONVENTIONAL CONTROL OF PSRC

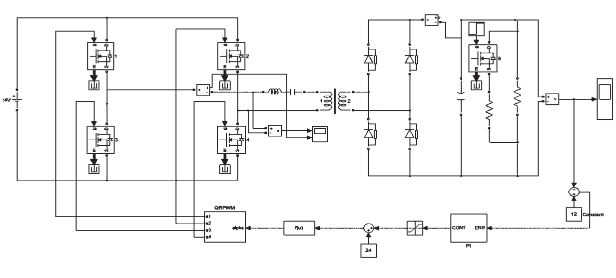

FIG. 9. CLOSED LOOP WITH DISTURBANCE

A controlled rectifier is recommended at the output to regulate the output voltage. When the output voltage decreased by reducing the load from full load to half load, the error decreases and the pulse width applied to the MOSFETs of the rectifier is increases to maintain the output voltage constant. The response of closed loop system is shown in Figure 9. The output voltage reduces to the steady state value. Thus the steady state error is reduced by using closed loop system is shown in Figure 10.

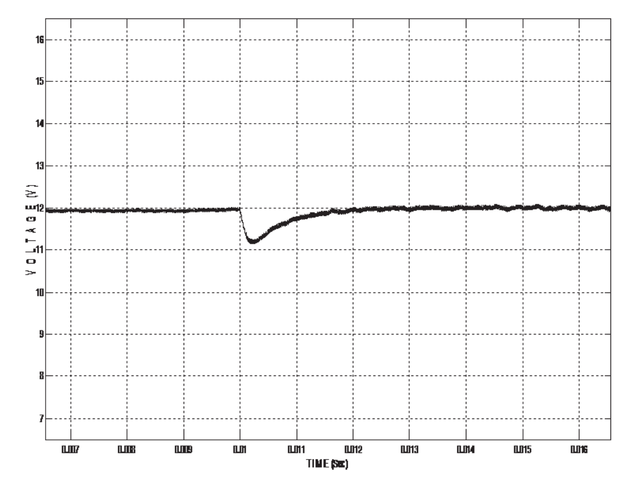

FIG. 10. CLOSED LOOP OUTPUT WITH DISTURBANCE

6.0 QUASI CURRENT CONTROL MODE

In a conventional control system of PSRC as shown in Figure 8. The reference signal V_d is the command value to controller to gives the required output voltage V. The resonant current is regulated and rectified to supply the load. Therefore the output voltage is controlled at desired value. The structure of the system is simple. Only voltage feedback is needed. As the resonant current which is rectified for supplying the load is not regulated, the dynamic performance of the system is poor.

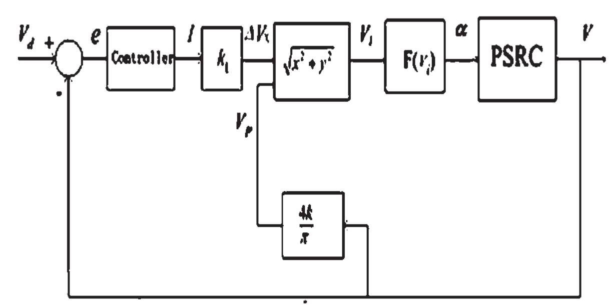

FIG. 11. BLOCK DIAGRAM OF PSRC WITH QUASI CURRENT MODE CONTROL

Figure 11. is the block control diagram of the PSRC system based on quasi current mode control. The dynamic performance is now modified into a dual loop control. The output signal of the conventional controller is now the command signals of the current I which affects the output voltage directly. The voltage ΔV_x can be determined using equation (10). The voltage v_p can be calculated from equation (2) which the output voltage V is measured via a voltage sensor. Hence command signal of the voltage V_i can be achieved after the synthesis of the voltage ΔV_x and the voltage V_p governed by equation (6). The phase angle α is calculated using equation (7). The phase shift control can be carried out with the phase angle. The dual loop control makes use of the idea of the energy handling in the resonant loop. V_i, V_p and ΔV_x are strongly related to the input energy from the inverter, output energy and the stored energy of the resonant components, respectively. Therefore, it gives an alternative concept of control for power converter.

7.0 SIMULATION AND RESULTS OF QUASI CURRENT CONTROL MODE

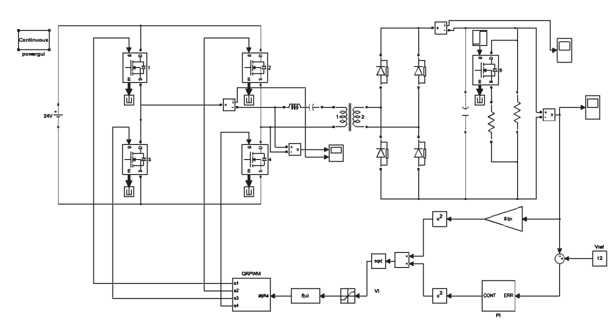

FIG. 12. PSRC WITH QUASI CURRENT CONTROL

The Figure 12 shows the quasi current mode control of phase shifted series resonant converter. The output feedback loop is divided into voltage feedback loop and resonant tank vector loop. The output voltage of quasi current mode control is shown in the Figure 13. The load is reduced from full load to half load and the dynamic response is shown in the Figure 13.

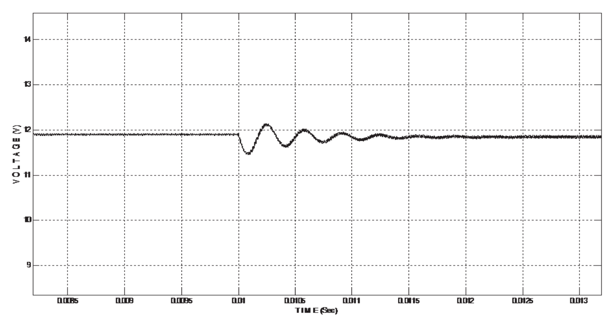

FIG. 13. DYNAMIC RESPONSE OF QUASI CURRENT MODE CONTROL SYSTEM WITH RESPECT TO LOAD RANGE FROM FULL LOAD TO HALF LOAD

TABLE 2		
RESPONSES OF THE OUTPUT VOLTAGE		
Simulation results	Quasi current mode control	Conventional control
Undershoot voltage	0.5 V	0.8 V
Settling time	1.5 ms	2.1 ms

8.0 CONCLUSION

The quasi current mode control method based on the indirect regulation of the resonant current is applied to the phase shifted series resonant converter. Only single voltage feedback is needed and it is converted to resonant tank vector components. Thus the output voltage is controlled more effectively and the dynamic performance is improved. This converter can be used for battery charging, electrolysis and speed control of servo drives.

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