

# Quasi Current Mode Control for the Phase-Shifted Series Resonant Converter

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**Abstract**—A novel indirect current mode control is applied in the phase-shifted series resonant converter system. The current is generated from resonant tank vector and the resonant current is regulated indirectly through quasi current mode control and thus the dynamic performance of the converter system is improved. Only single voltage feedback is required for the system. The proposed system consists of two control loops with one inner resonant vector and one outer voltage loop. Analysis and practical experiments are carried out and the results show the better performance compared with that of the conventional control.

**Index Terms**—Dynamic performance, dynamic response, phase-shifted series resonant converter (PSRC), quasi current mode control.

## I. INTRODUCTION

**H**-BRIDGE system used in high power dc–dc conversion is a popular and well-received method in many applications [1]–[4]. 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 [5], square-wave resonant [2], and zero-voltage and zero-current resonant [3]. The phase-shifted series resonant converter (PSRC) 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 present of the series resonant capacitor. Fig. 1 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  $\alpha$  in order to change the voltage applied to the resonant tank as shown in Fig. 2. The general design rule is that the switching frequency  $f_s$  of PSRC is always chosen to be close to the resonant frequency  $f_r$ , defined by the resonant inductor  $L_r$  and resonant capacitor  $C_r$  to make the resonant current waveform be quite sinusoidal [5]. Of course, to reduce the size of energy storage components such as inductor, capacitor and transformer, the switching frequency  $f_s$  is very high. The resonant current  $i_r$  is regulated by changing the phase angle  $\alpha$  and rectified as the input power signal of the output filter. Thus the 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 be satisfied especially for nonlinear systems. Other publication on load range extension using ZCS and ZVS [6] and PWM with phase shift [7] are the primary control for the switching signal. Some more advanced control strategies were developed recently to improve the performance of control system [8]–[10], 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) [11] and passivity-based control [12]. A novel control system for the PSRC is proposed in this paper. 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. The ability against load disturbance is close to that of the system employing ADRC though structure of the reformed system is simpler and only voltage feedback is required. The proposed method is called quasi-current mode because the current controlled is regulated indirectly using the resonant tank voltage vector. The method is similar to the d and q current control for multilevel converter [13] but the present method is based on the control using resonant component phasor.

## II. ANALYSIS OF THE PHASE-SHIFTED SERIES RESONANT CONVERTER

The main circuit of the PSRC and its waveforms are shown in Fig. 1 and Fig. 2, respectively. The resonant circuit is fed by a quasi-square voltage signal  $v_i$  in which the width of  $\alpha$  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 a direct reflection of the output voltage through the diode bridge and transformer. The resonant tank is characterized by its resonant frequency denoted by  $f_r = 1/(2\pi\sqrt{L_r C_r})$ . If the switching frequency  $f_s$  is chosen to be close to the resonant frequency, then the resonant current is quite sinusoidal. In this case, using fundamental waveform for approximation is reasonable for analyzing the resonant circuit [8]. Now then,  $v_i$  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

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

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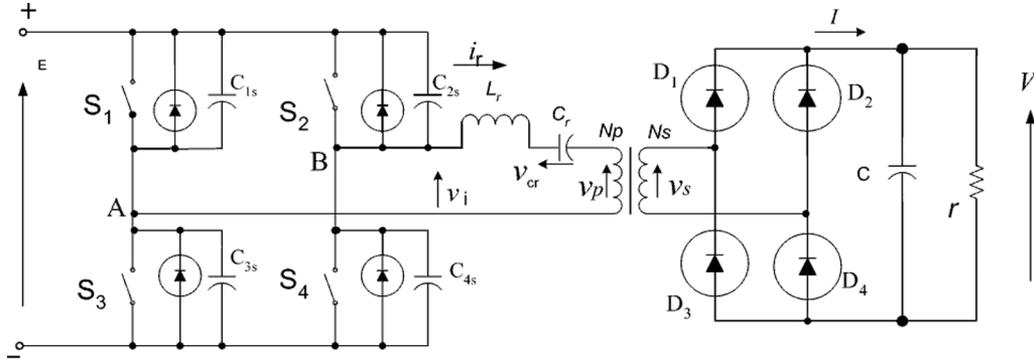


Fig. 1. Main circuit of the PSRC.

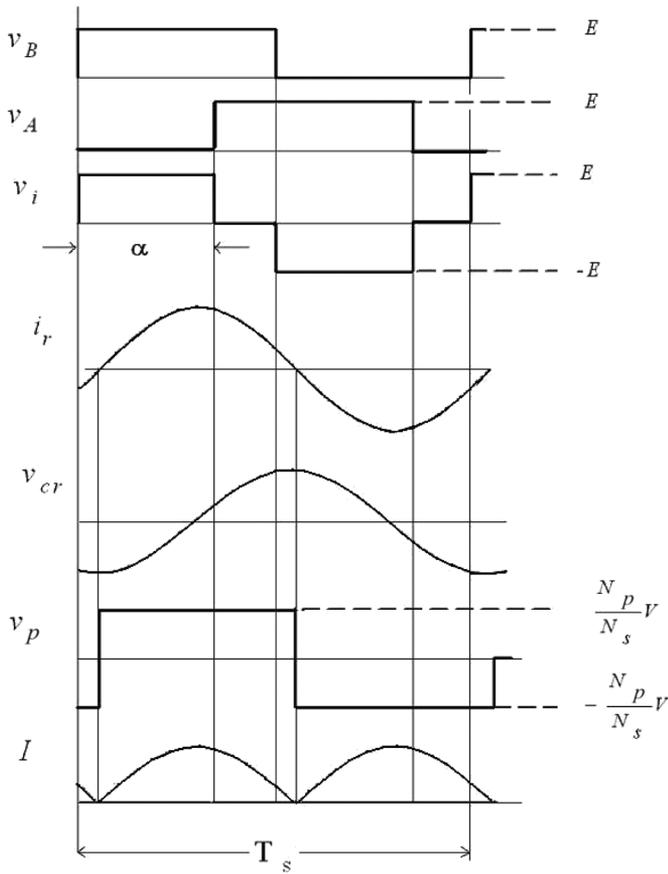


Fig. 2. Waveforms of the PSRC.

where  $E$  is the input dc voltage and the amplitude of  $v_p$  is

$$V_p = kV \frac{4}{\pi} \quad (2)$$

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

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

$$\vec{V}_i = \vec{V}_p + \Delta \vec{V}_x \quad (3)$$

$$\Delta \vec{V}_x = \vec{V}_{Lr} + \vec{V}_{Cr} \quad (4)$$

$$\Delta V_x = I_m(X_L - X_C) \quad (5)$$

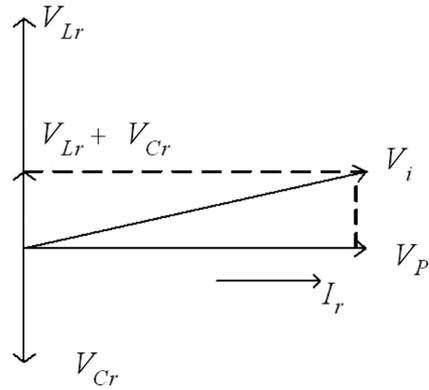
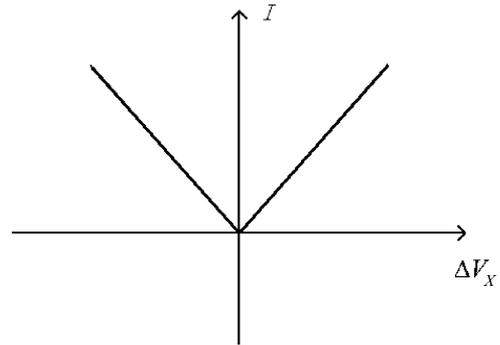


Fig. 3. Phasor diagram of the resonant tank.

Fig. 4. Current  $I$  against the voltage  $\Delta V_x$ .

where  $X_L = \omega_s L_r$ ,  $X_C = 1/\omega_s C_r$ ,  $\omega_s = 2\pi f_s$  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 Fig. 3 and (6) is true

$$V_i = \sqrt{(\Delta V_x)^2 + (V_p)^2} \quad (6)$$

The function  $F(V_i)$  can be obtained using (1)

$$\alpha = F(V_i) = \cos^{-1} \left( 1 - \frac{\pi V_i}{2E} \right) \quad (7)$$

The resonant current is rectified for supplying the load. The capacitor  $C$  constitutes a lower pass filter. The load is repre-

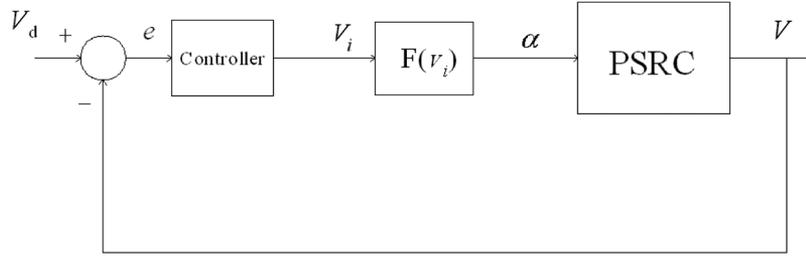


Fig. 5. Block diagram of a conventional control system for the PSRC.

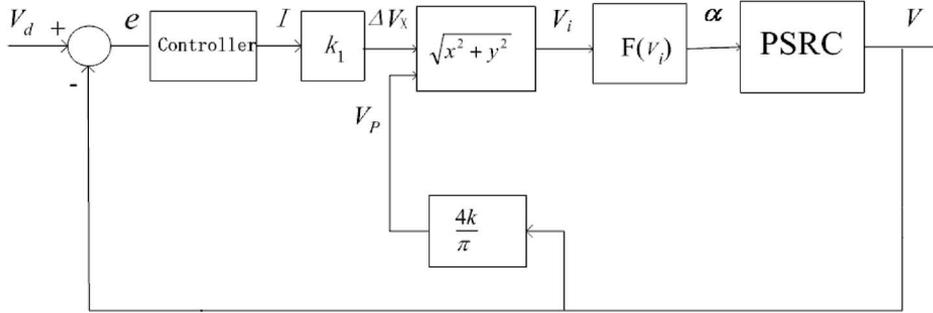


Fig. 6. Block diagram of the PSRC system with quasi current mode control.

sented by a purely resistive element  $r$ . The dynamics of the output circuit is given by

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

From (8) it can be seen that it is the current  $I$  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

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

Substituting (9) into (5) yields

$$\Delta V_x = k_1 \cdot I \quad (10)$$

where  $k_1 = (\pi \cdot (X_L - X_C))/2k$ .

Fig. 4 shows the graphical relationship which shows  $I$  is always positive.

### III. QUASI CURRENT MODE CONTROL SYSTEM FOR THE PSRC

In a conventional control system of PSRC as shown in Fig. 5, the reference signal  $V_d$  is the command value to controller to give the required output voltage  $V$ . The resonant current is regulated and rectified to supply the load. Therefore the output voltage is controlled at desired values. 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. 6 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 signal of the current  $I$  which affects the output voltage directly. The voltage  $\Delta V_x$  can be determined using (10). The voltage  $V_p$  can be calculated from (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  $\Delta V_x$  and the voltage  $V_p$  governed by (6). The phase angle  $\alpha$  is calculated using (7). The phase shift control can be carried out with the phase angle. The proposed dual loop control makes use of the idea of the energy handling in the resonant loop.  $V_i$ ,  $V_p$  and  $\Delta V_x$  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.

### IV. MODELLING

Assume the system transfer function of the converter is expressed as

$$\frac{\tilde{V}}{\tilde{V}_i} = G. \quad (11)$$

For conventional control system as shown in Fig. 5, assume the controller has a gain of

$$\frac{\tilde{V}_i}{\tilde{e}} = H. \quad (12)$$

The closed loop transfer function is

$$\frac{\tilde{V}}{\tilde{V}_d} = \frac{GH}{1 + GH}. \quad (13)$$

For simple conventional controller,  $H$  is a PI controller which is

$$H = K_p + \frac{K_i}{s}. \quad (14)$$

The plant transfer function can be approximated as

$$\frac{\tilde{V}}{\tilde{V}_i} = G = \frac{s + \frac{1}{R_e c}}{c(Z + R_e)} \quad (15)$$

where

$$Z = sL_r - \frac{1}{sC_r} \quad (16)$$

and  $R_e$  is the equivalent resistance  $= 8r/\pi^2$ . The converter gain  $G$  is large in high frequency and hence the overall system closed loop gain is closed to unity for all frequencies under concern and the dynamic performance is poor.

For the proposed quasi-control method, assume

$$\frac{\tilde{V}_p}{\tilde{V}} = H_2 = \frac{4k}{\pi} \quad (17)$$

and the controller's transfer function is

$$\frac{\Delta \tilde{V}_x}{\tilde{e}} = H_1 = K'_p + \frac{K'_i}{s}. \quad (18)$$

The closed loop transfer function is approximated as

$$\frac{\tilde{V}}{\tilde{V}_d} = \frac{G^2 H_1^2}{G^2 (H_1^2 + H_2^2) - 1} \approx \frac{H_1^2}{H_1^2 + H_2^2} \quad (19)$$

hence the proposed system is relatively independent of the converter gain and can be tuned easily by  $H_1$ .

## V. EXPERIMENTAL RESULTS

The parameters of the PSRC were tabulated in Table I. The resonant frequency determined by the resonant components is  $f_r = 30.1$  kHz which is close to the switching frequency  $f_s$  listed in the table, therefore the resonant current is quite sinusoidal. The PSRC system based on quasi current mode control was implemented as well as the conventional version in order to compare their performances under the same conditions. PI controllers were employed as the controller for both the systems and their parameters were chosen via experiments to achieve better dynamic responses near rated load. For the improved system, the set of parameters of the controller are  $K_p = 1.62$  and  $K_i = 0.046$ . The set of parameters of the controller for the conventional system are tuned to be  $K_p = 2.67$  and  $K_i = 0.053$ . A DSP system was employed to implement proposed control method. The sampling period is  $100 \mu s$ .

Figs. 7 and 8 show the dynamic responses of the output voltage of the PSRC system based on quasi current mode control and conventional control, respectively. The load is changed

TABLE I  
PARAMETERS OF THE CONVERTER

Resonant inductor $L_r$	56 $\mu H$	Rated input voltage $E$	270 V
Resonant capacitor $C_r$	0.5 $\mu F$	Power rating	1.4 kW
Filter capacitor $C$	47 $\mu F$	Rated output voltage	140 V
Switching frequency $f_s$	33 kHz	Rated load resistance	14 $\Omega$

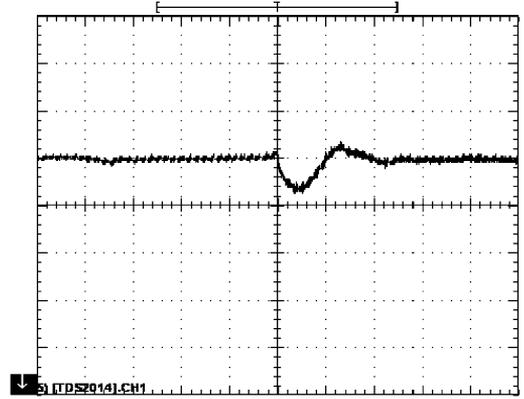


Fig. 7. Dynamic response of the output voltage of the quasi current mode control system with respect to the load change from half load to full load, (y-axis: 20 V/div, x-axis: 1 ms/div).

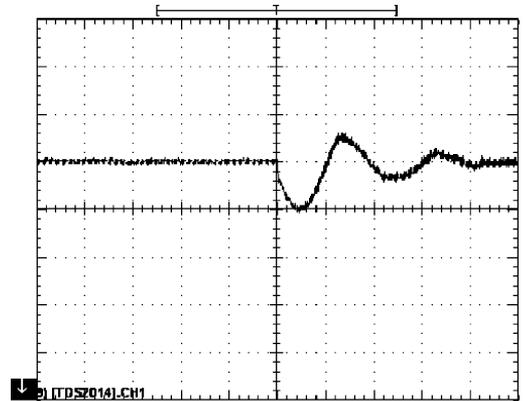


Fig. 8. Dynamic response of the output voltage of the conventional control system with respect to the load change from half load to full load, (y-axis: 20 V/div, x-axis: 1 ms/div).

from half load ( $28 \Omega$ ) to full load ( $14 \Omega$ ). It can be seen from the waveforms that the undershoot voltage caused by the load variation is less for the system employing quasi current mode control. The transient oscillation is of a larger magnitude and the settling time is longer for the conventional control system. The data indicating the performance are given in Table II.

Contrast to the first experiment, the load is changed from full load to half load in this experiment. The dynamic responses of the output voltage of the two control systems are shown in Figs. 9 and 10. By comparing the two measurements it can be seen that the overshoot of the output voltage caused by the decreasing of load resistance is less and the restore time is shorter

TABLE II  
RESPONSES OF THE OUTPUT VOLTAGE (A)

Experimental results	Quasi current mode control	Conventional control
Undershoot voltage	14.5V	20V
Settling time	1.6ms	3.6ms

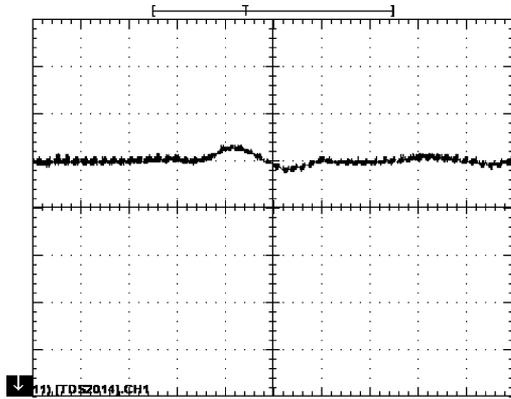


Fig. 9. Dynamic response of the output voltage of the quasi current mode control system with respect to the load change from full load to half load (*y*-axis: 20 V/div, *x*-axis: 1 ms/div).

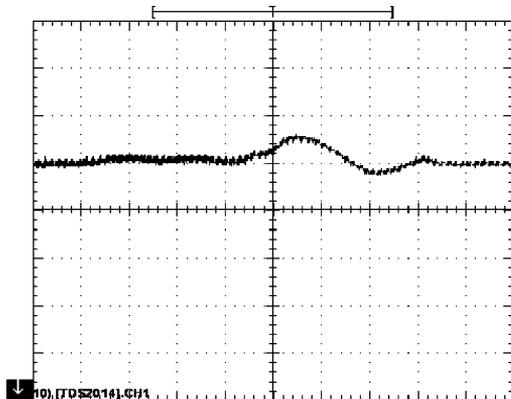


Fig. 10. Dynamic response of the output voltage of the conventional control system with respect to the load change from full load to half load (*y*-axis: 20 V/div, *x*-axis: 1 ms/div).

TABLE III  
RESPONSES OF THE OUTPUT VOLTAGE (B)

Experimental results	Quasi current mode control	Conventional control
Overshoot voltage	7.0V	10.5V
Settling time	2.1ms	3.2ms

for the system based on quasi current mode control. The data indicating the performance are listed in Table III.

VI. CONCLUSION

The proposed control method based on the indirectly regulation of the resonant current is applied to the phase-shifted 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. Better performance has been verified through system analysis and experiments. In addition, the construction of the reformed control system is simple because only single voltage sensor is required. No current sensor is needed and the reformed control is monitored internally through quasi-current vector.

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