Switching Frequency Control based on Phase-locked Loop for a Current-fed Parallel Resonant Inverter

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Abstract: This paper proposes a computer simulation in PSCAD program of a current-fed parallel resonant inverter. Even though the circuit parameters such as permeability and conductivity have changed regarding to the changing temperature during the heating period. The proposed idea is able to control the phase difference $\Delta \theta$ between the output voltage and output current to be constant at desired value. The principle of the proposed controller utilizes the phase-locked loop with a phase frequency detector. If the $\Delta \theta$ is constant without any effect from the temperature change, then the output power will be controlled precisely by adjusting only the dc-link current. The proposed idea is verified by the experimental results.

Keywords: frequency control, phase-locked loop, current-fed parallel resonant inverter.

I. INTRODUCTION

Both series resonant inverter and parallel resonant inverter are widely used in the induction heating and induction melting. In this paper, we choose the parallel resonant inverter because it is popular induction heating and melting applications in the medium frequency range (1-10kHz.) and medium power (10-10,000 W) [1]. This configuration can operate during the unloaded condition. It causes no damage when the load is short circuit as well as it does not require high voltage rating resonant capacitor [2]. The induction heating/melting is widely use in surface hardening, welding, heating, cutting applications. It has higher efficiency compared to the conventional power supply because it generates heat in short duration and also controls heat in the specific area. There are no pollutions such as smoke or acoustic noise. When the metal load heats up, the electric and magnetic properties of the material are changed (e.g. conductivity or permeability). Consequently the resonant frequency of the tank circuit changes [3]. Equation (1) and (2) represent the output voltage and output current respectively. Then the output power the circuit is given in (3) [4]

$$v_o = \sum_{n=1}^{\infty} v_n \sin(n \alpha \theta)$$

$$i_o = \sum_{n=1}^{\infty} i_n \sin(n \alpha \theta)$$

$$P_{\text{output}} = \left[ \sum_{n=1}^{\infty} \sum_{n=1}^{\infty} v_n \sin(n \alpha \theta + \theta) \right] \left[ \sum_{n=1}^{\infty} i_n \sin(n \alpha \theta) \right] \cos \theta$$  (3)

From (3), the output power is a function of voltage, current and the phase differences ($\Delta \theta$). If the load parameters are changed due to the rising temperature this could cause the deviation of the $\Delta \theta$. So this paper proposes a method of how to control the phase difference without influence from the temperature variation.

II. PARALLEL RESONANT INVERTER

A parallel resonant inverter is shown in Fig. 1. It is consist of a three-phase controlled rectifier with an inductor, $L_d$. There is a close loop controller to control the dc link current with low ripple level by adjusting the firing angle of the SCRs. The RC snubber is added to reduce $dv/dt$ across SCRs. When the coil is unloaded, the resonant frequency is at the natural resonant frequency. If the metal load is inserted in the coil, the inductance of the coil may be increasing or decreasing which depends on the material property.
There are three operation modes for a parallel resonant inverter. For mode I, switch T1 and T2 conduct current. Output voltage is positive sinusoidal waveform as shown in Fig. 2. Equation (4) – (6) are used to solve for $i_d$, $i_L$, and $v_c$ respectively.

$$\frac{di_d}{dt} = \frac{v_d}{L_d} - \frac{v_c}{L_d}$$  \hspace{1cm} (4)

$$\frac{di_L}{dt} = -\frac{r_i}{L} + \frac{v_c}{L}$$  \hspace{1cm} (5)

$$\frac{dv_c}{dt} = \frac{i_d}{C} - \frac{i_L}{C}$$  \hspace{1cm} (6)

Fig.3. Inverter is operating in mode II.

For mode II, T3 and T4 are on. The output voltage is negative as shown in Fig. 3. Quantities of the circuit are shown in (7) – (9).

$$\frac{di_d}{dt} = \frac{v_d}{L_d} + \frac{v_c}{L_d}$$  \hspace{1cm} (7)

$$\frac{di_L}{dt} = -\frac{r_i}{L} + \frac{v_c}{L}$$  \hspace{1cm} (8)

$$\frac{dv_c}{dt} = \frac{i_d}{C} - \frac{i_L}{C}$$  \hspace{1cm} (9)

Fig.4. Inverter is operating in MODE III.

For mode III, T1, T2, T3 and T4 are turned on as shown in Fig.4 and described by (10) and (11).

$$\frac{di_d}{dt} = \frac{v_c}{L_d} - \frac{i_L}{L}$$  \hspace{1cm} (10)

$$\frac{dv_c}{dt} = -\frac{i_L}{C}$$  \hspace{1cm} (11)

where $i_d$ is dc-link current, $i_L$ is the output current, $v_d$ is the input voltage, $v_c$ is the output voltage, $L_d$ is smoothing reactor, $L$ is the Inductance, $r$ is the resistance and $C$ is the capacitance.

III. PROPOSED CONTROLLER

As shown in Fig. 5, PLL is used to generate the output signal to be locked with the reference signal. In this paper, we want to control the phase shift between the tank voltage $v_o$ and current $i_o$. Then $\theta_1$ and $\theta_2$ are the phase of $v_o$ and $i_o$, respectively. PFD detects the phase differences between both $v_o$ and $i_o$. The output from the PFD is in the square waveform which the duty cycle depends on the phase differences. A low pass filter (LPF) eliminates the high frequency components and the output is the average value of the phase differences. The output from the low pass filter is then compared to the referenced phase difference ($\Delta \theta_{ref}$). A PI controller is added to control the characteristic of the system response. A voltage-controlled oscillator creates the sinusoidal waveform whose output frequency is proportional to the input signal.

Fig. 6 is a block diagram of PLL-based controller integrated with the current-fed inverter. The current and voltage across tank circuit is detected by zero-crossing detector (ZCD). The output from ZCD then fed to the PFD. At this stage we know the phase error between current and voltage. The average of the phase error is taken by using a low pass filter. This error is used to find
the difference with the referenced phase differences. The error is then fed to a PI controller. The command signal is the input of a voltage-controlled oscillator (VCO). The output is the sinusoidal waveform and the frequency is adjustable depend on the phase error whether it is lead or lag. The outputs of VCO are switching signals of the inverter. Consequently, the tank circuit is operating with a controllable phase shifting. If $\Delta \theta_{\text{ref}}$ is set at zero then the resonant inverter will operate in resonant all the time even the tank circuit’s parameters have changed. Moreover if $\Delta \theta_{\text{ref}}$ is set to lead or lag, the proposed controller is still able to keep automatically tracking the desired phase shift between the $v_o$ and $i_o$. This statement is verified by the simulation results. PSCAD program is used for the computer simulation. From the simulation, the values of $\Delta \theta_{\text{ref}}$ are set at different values and the coil inductance is varying to simulate the effect from the temperature.

### IV. SIMULATION AND EXPERIMENTAL RESULTS

The comparison between the simulation results and Experimental result show the $v_o$ and $i_o$ with different phase shift at $0^\circ$, $\pm 10^\circ$ and $\pm 20^\circ$ with two load conditions to simulate the effect from temperature change. The first one is $L=6.8 \mu H$, $C = 18 \mu F$, $R = 0.05 \Omega$, and the second condition is $L=7.8 \mu H$, $C=18 \mu F$, $R=0.05 \Omega$. (+ sign means $v_o$ leads $i_o$ and – sign means $v_o$ lags $i_o$.) Fig. 7 - 16 show the simulation results and the experimental results for the $v_o$ and $i_o$ with differential phase shift at different phase-shifting angles. The experimental results are consistent with the simulation.
(a) Simulation result         (b) Experimental result
Fig.13. +20º phase shift, $L = 6.8 \mu H$, $C = 18 \mu F$, $R = 0.05 \Omega$

(a) Simulation result         (b) Experimental result
Fig.14. +20º phase shift, $L = 7.8 \mu H$, $C = 18 \mu F$, $R = 0.05 \Omega$

(a) Simulation result         (b) Experimental result
Fig.15. -20º phase shift, $L = 6.8 \mu H$, $C = 18 \mu F$, $R = 0.05 \Omega$

(a) Simulation result         (b) Experimental result
Fig.16. -20º phase shift, $L = 7.8 \mu H$, $C = 18 \mu F$, $R = 0.05 \Omega$

V. CONCLUSION

By implementing the automatic switching frequency controller, the current-fed resonant inverter is able to operate with desired phase shifting between output current and output voltage. In which, the experimental results are according to the simulation results. This control technique can be implemented with the power control. If the $\Delta \theta$ is constant without any effect from the temperature change, then the output power is controlled precisely by adjusting only the dc-link current. Moreover if the phase shifting is controlled at zero degree, this means that the maximum power is transferred to the load through out the heating period. The output power control scheme will be investigated in the near future.

REFERENCE


APPENDIX

Appendix shows the PSCAD diagram of a parallel current-fed inverter and the proposed control scheme.