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DESIGN AND ANALYSIS OF SINGLE PHASE PURE SINE INVERTER BASED ON PHASE LOCKED LOOP

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Abstract. *This article proposes the new technique of the PWM oscillation based on phase locked loop that controls the inverter. The PWM works together with push-pull where it is connected to the step-up transformer. The advantages of proposed technique are that the PWM circuit is non-complicated of structure and that the PWM circuit can prevent from a noise signal. In addition, a carrier frequency can be adjusted at a frequency running with the VCO of a phase locked loop. The PWM output which is obtained from the push-pull inverter has high symmetry voltage. Ultimately, the PWM is passed through the LC low pass filter where high pure sine wave signal occurs. As a result, the total harmonic distortion (THD) is decreased which is equal to 2.27%. Due to the related proposed technique, the output voltage regulation is improved and the dynamic response of a step load change is also improved.*
Keywords: Pure sine wave inverter, Phase locked loop, Pulse width modulation

1. **Introduction.** Nowadays, the power generation from renewable energy is interesting, namely solar energy, wind power, water power, etc. The power energy output obtained from renewable energy has low DC voltage. Therefore, the DC-to-AC inverter has a role on DC to high AC voltage conversion by switching technique. The inverter that has been continuously developed is controlled by pulse width modulation (PWM henceforth). To illustrate, the PWM is constructed by microcontroller in order to control an inverter [1-4], the PWM is constructed by SPWM [5-8] and the PWM is constructed based on delta modulated PWM [9]. Moreover, each principle provides different advantages. One of the PWM oscillation principles is the application of PWM with phase locked loop (PLL henceforth) [10]. The advantage of PLL is to be able to eliminate as better with noise signal. The PWM application based on PLL is used with a Class-D amplifier [11]. However, the PWM based on PLL principle has not been used for controlling the inverter.

In this article, the new technique of the PWM oscillation based on PLL that controls the inverter, is proposed. The PWM works together with push-pull circuit where it is connected to the step-up transformer. The advantages of proposed technique are as follows. The PWM circuit is non-complicated of structure and the PWM circuit can prevent from a noise signal. In addition, a carrier frequency can be adjusted at a frequency running with the VCO of a phase locked loop. The PWM output which is obtained from the push-pull inverter has high symmetry voltage. Ultimately, the PWM is passed through the LC low pass filter where high pure sine wave signal occurs. As a result, the total harmonic distortion (THD) is decreased. Thus, it can be concluded that the proposed pure sine wave inverter is ideal for the photovoltaic power system in residential applications.

2. **Conventional Pulse Width Modulation for Single Phase Inverter.** The conventional PWM that is employed to control the inverter consists of the PWM oscillation, the gate driver circuit, the push-pull switching that works together with step-up transformer, and the LC low pass filter. This system is illustrated in Figure 1.

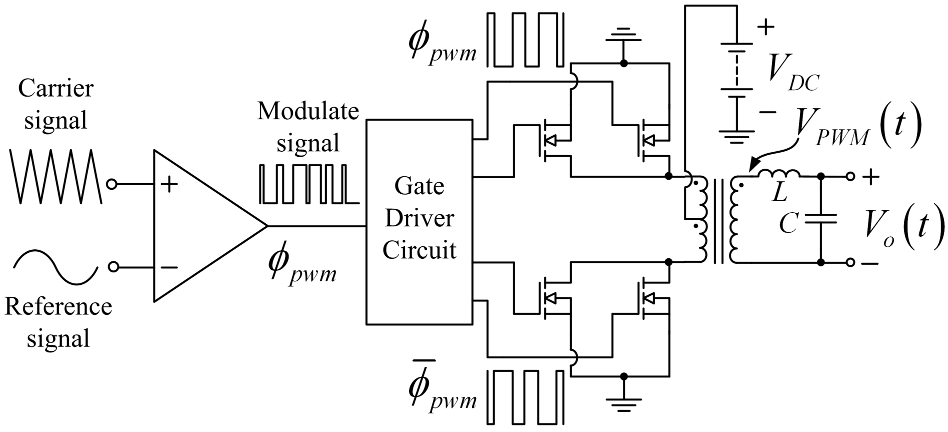

FIGURE 1. Block diagram of conventional PWM control

The PWM oscillator is generated by a comparison of voltage between the triangular signal as carrier and the sine wave as information. The PWM is passed through the push-pull circuit that works together with the step-up transformer. Then, the PWM is transferred to the secondary winding. Thus, the relation is

$$V_{PWM}(t) = \frac{kV_{DC}m(t)}{T} + \frac{kV_{DC}}{\pi}\sum_{n=1}^{\infty}\left(\frac{\sin(n\omega_o t) - \sin(n\omega_o t - n\omega_o km(t))}{n}\right) \quad (1)$$

where V_{DC} is a voltage of renewable energy, k is a transformer ratio, ω_0 is a frequency of carrier signal, $m(t)$ is an information signal and T is a period of carrier. From Equation (1), it consists of two terms, which are $m(t)$ and high frequency components. Therefore, the PWM is passed through the LC low pass filter. As a result, the high frequency components are eliminated. Furthermore, the information input is fed to the system that is sine wave signal $m(t) = E\cos(\omega_m t)$. Thus, Equation (1) becomes

$$V_o(t) = \frac{kV_{DC}E\cos(\omega_m t)}{T} \quad (2)$$

Equation (2) is the voltage of pure sine wave that achieved an inverter output. However, a conventional PWM was a large circuit. While the frequency of carrier was adjusting, the structure of carrier oscillator was also modified a circuit.

3. **Pulse Width Modulation Based on Phase Locked Loop Technique for Single Phase Inverter.** In terms of the inverter, the PWM based on PLL is proposed which is illustrated in Figure 2.

The PWM technique is constructed based on PLL which consists of an FM modulation. The PLL principle is divided into 2 phases. At first, if there is the absence input, VCO(I) will oscillate at some frequency. Then, a sine wave input is entered into the circuit. The result that is VCO(I) can cause the FM modulation oscillation. To compare the phase of

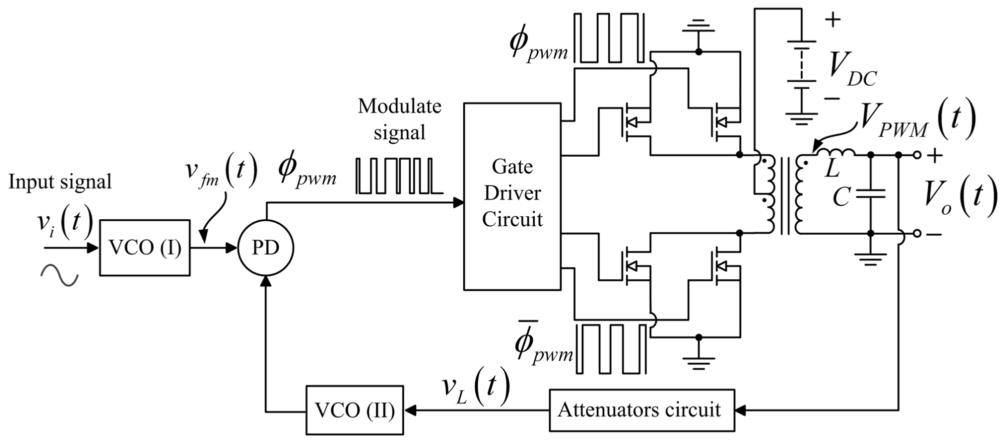

FIGURE 2. Block diagram of a PWM based on PLL

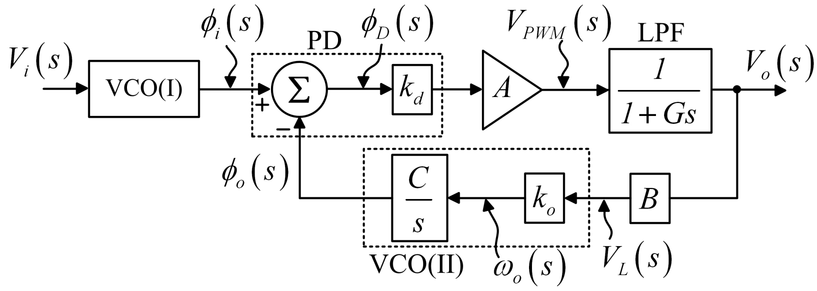

FIGURE 3. The structure of a PWM based on PLL

the FM modulation with VCO(II) output, the PWM output would be varied regarding the input of VCO(I). Therefore, the structure of a PWM based on PLL is given in Figure 3.

From Figure 3, the structure of a PWM based on PLL is composed of a VCO(I), a phase detector (PD), a low pass filter, a VCO(II), and an integrator. It is noted that the notations are: $\phi_i(s)$ is a phase input function, $\phi_o(s)$ is a phase output function, $\phi_D(s)$ is a phase difference function, $V_L(s)$ is a loop filter output, $\omega_o(s)$ is a frequency output of VCO(II), $\omega_r(s)$ is a running frequency of VCO(II), k_d is a gain of phase detector, k_o is a gain of VCO(II), A is a gain of $V_{PWM}(s)$, B is a gain of attenuators circuit and C is a gain of an integrator. From Figure 3, the relation of the system can be written as

$$\frac{ABCk_dk_o\phi_o(s)}{s(1+Gs)} + \phi_o(s) = \frac{ABCk_dk_o\phi_i(s)}{s(1+Gs)} + \frac{C\omega_r(s)}{s} \tag{3}$$

where $K = ABCk_dk_o$. Then, Equation (3) is rewritten as follows:

$$Gs^2\phi_o(s) + s\phi_o(s) + K\phi_o(s) = K\phi_i(s) + C\omega_r(s) + CGs\omega_r(s) \tag{4}$$

By taking inverse Laplace transform of both sides of Equation (4), whereat $\omega_r(t)$ is a constant running frequency, Equation (4) becomes

$$G\frac{d^2\phi_o(t)}{dt^2} + \frac{d\phi_o(t)}{dt} + K\phi_o(t) = K\phi_i(t) + C\omega_r(t) \tag{5}$$

From Equation (5), the solution for $\phi_o(t)$ can be determined by solving this differential equation, of which, the forced response is particularly considered. To determine the forced response, $\phi_i(t)$ is assumed as $\phi_i(t) = \omega_i t + \theta_i$ where $\omega_i(t)$ is an input frequency. Then, $\phi_o(t) = at + b$ is assumed where a and b are constants. By replacing $\phi_i(t)$ and $\phi_o(t)$ into Equation (5), it becomes

$$\phi_o(t) = \omega_i t + \theta_i + \frac{C\omega_r}{K} - \frac{\omega_i}{K} \tag{6}$$

Therefore,

$$\phi_D(t) = \phi_i(t) - \phi_o(t) = \frac{\omega_i}{K} - \frac{C\omega_r}{K} \tag{7}$$

From Figure 2, the output of VCO(I) is input signal which delivers to a PD of PLL. If the input signal $v_i(t)$ is sine wave signal, then the VCO(I) functions as a frequency modulator (FM). Thus, the phase of FM signal is shown as follows:

$$\phi_{fm}(t) = \omega_c t + k_f \int v_i(t)dt \tag{8}$$

where $\phi_{fm}(t)$ is a phase of FM signal, ω_c is a running frequency of VCO(I) (is carrier), and k_f is a modulation constant. It implies that the $\phi_{fm}(t)$ is equivalent to $\phi_i(t)$, and the input frequency ω_i can be determined from the derivative of $\phi_{fm}(t)$ in Equation (8), as this

$$\omega_i = \omega_c + k_f v_i(t) \tag{9}$$

From Equations (7) and (9), Equation (7) can be rewritten as follows:

$$\phi_D(t) = \frac{\omega_c}{K} + \frac{k_f v(t)}{K} - \frac{C\omega_r}{K} \tag{10}$$

While, the system of PLL is at the edge of locking capture condition that is $\omega_c/K \approx C\omega_r/K$. Thus, the phase difference is

$$\phi_D(t) = K_D v(t) \tag{11}$$

where $K_D = k_f/K$ is constant of phase difference.

From Equation (11), it can be seen that the phase difference $\phi_D(t)$ is directly proportional to input signal $v_i(t)$. It implies that if $v_i(t)$ is sine wave signal $v_i(t) = E\cos(\omega_m t)$, then, the duty cycle of pulse which is taken from digital phase detector (X-OR) is also directly proportional to input signal $v_i(t)$. The PWM signal occurs. Thus, the voltage output of the proposed technique is shown as follows:

$$V_o(t) = \frac{AEk_dK_D\sqrt{1+G^2\omega_m^2}}{1+G^2\omega_m} \cos\left[\omega_m t - \tan^{-1}(G\omega_m)\right] \tag{12}$$

4. **Experiment and Results.** In order to verify the proposed technique, we set up experiment as follows. According to Figure 2, IC 4046 is used as VCO, and phase detector while loop filter is made by RC component. The frequency of PWM carrier is given in 1.5 kHz and $V_{DC} = 30$ V while input is also determined as 3.5 V_{PP} and 50 Hz sine wave signals. Finally, we provide an LC low pass filter with L = 85 mH and $C = 10$ μF. The experimental results are demonstrated in Figure 4 to Figure 7.

Figure 4 shows the output of VCO(I), where the upper trace is sinusoidal input signal and the lower trace is FM signal. As an experimental result, an FM signal can be consistent as well with the frequency modulation principle. The phase of FM signal is according to Equation (8) and it is depending on the input signal.

Figure 5 presents that the upper trace is a sinusoidal input signal, the medium trace is a PWM signal $\phi_{PWM}(t)$ and the lower trace is inverted PWM signal $\bar{\phi}_{PWM}(t)$, where $\phi_{PWM}(t)$ and $\bar{\phi}_{PWM}(t)$ are the outputs of gate driver circuit in which these are driven to the upper and lower side MOSFETs source of push-pull circuit.

Figure 6 displays that the upper trace is a sinusoidal input signal and the lower trace is a pure sine wave output of the inverter. This pure sine wave output voltage of the experiment is consistent with the PLL principle to analysis in which the PLL principle is applied with the generation of PWM signal for controlling the inverter that is presented in Section 3.

Figure 7 shows the pure sine wave output voltage of the inverter and the fast Fourier transform (FFT). The FFT demonstrates that the fundamental harmonic component lies at 50 Hz and the rest of the harmonic components are negligible. After filtering the output voltage, the total harmonic distortion (THD) reduced too much lower level of less than 2.27% which was calculated by Equation (13).

$$THD = \frac{\sqrt{\sum (Harmonics)^2}}{Fundamental\ Voltage} \times 100\% \tag{13}$$

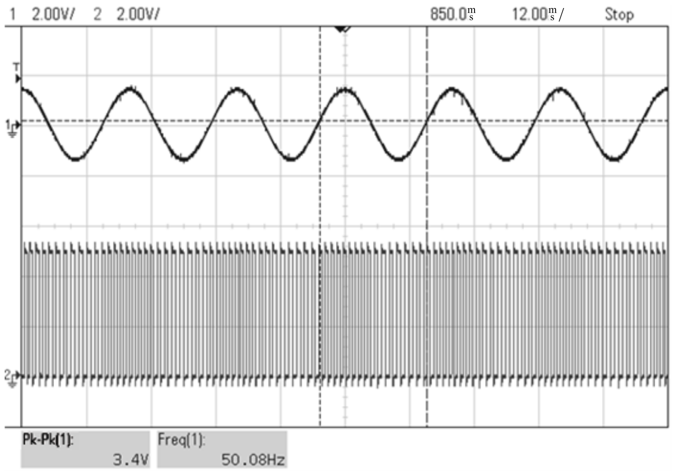

FIGURE 4. The FM signal output of VCO(I) circuit

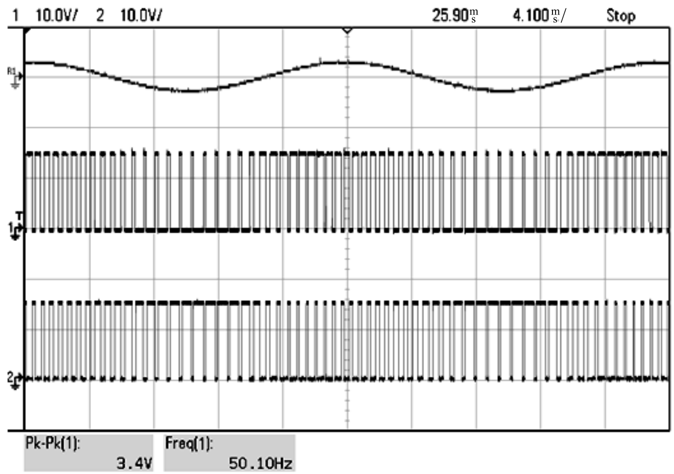

FIGURE 5. The PWM signal output based on PLL

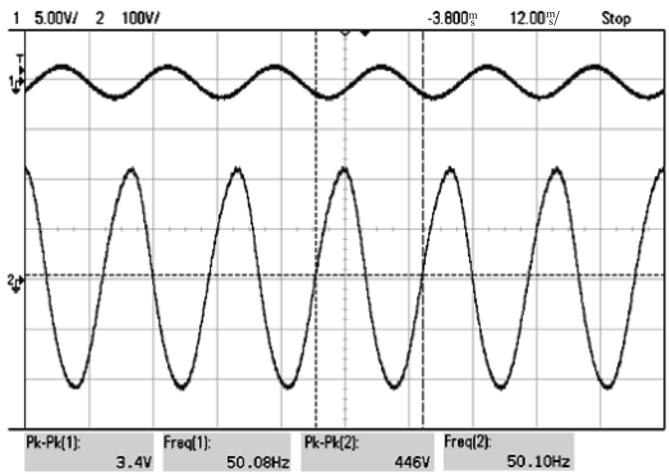

FIGURE 6. The pure sine wave output of inverter

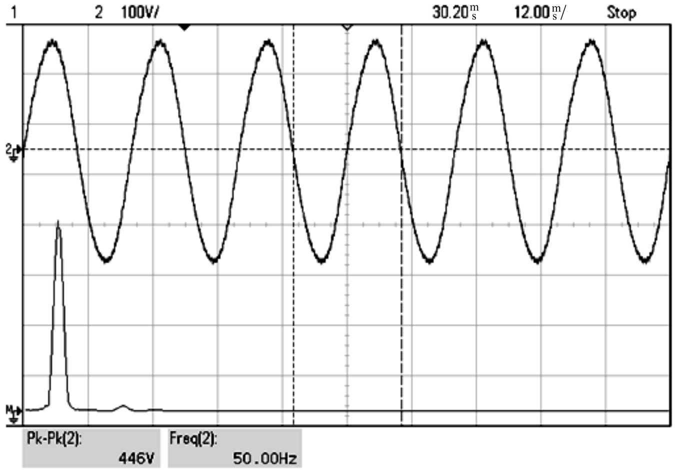

Figure 7. The inverter output and the spectrum components of the proposed technique

5. **Conclusions.** This paper discusses on the design and development of a pure sine wave inverter based on phase locked loop. Various advantages exist in the proposed system such as low switching loss, low cost, small size and simple control. The experimental results are verified that the THD is equal to 2.27% which it is less than the IEEE 519 standards for total harmonic voltage distortion limits. Furthermore, this proposed circuit allows the feedback of the inverter output in controlling the system. As a result, the output voltage regulation is improved and the dynamic response due to a step load change is also improved. Thus, it can be concluded that the proposed pure sine wave inverter is ideal for the photovoltaic power system in residential applications.

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