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A Zero Crossing PWM Controller of a Full Bridge Single Phase Synchronous Inverter for Microgrid Systems

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Abstract—*The controlling method of microgrid connected inverter is complicated. Therefore, researchers have designed a different way to improve the control system. Improving the control system by synchronizing the phase is still a critical issue. This paper introduces a zero crossing with the aid of PWM technique to synchronize the microgrid frequency and phase, decreased ripple noise while forced discrete mode provides low output ripple current. Besides, to reduce the ripple current and phase synchronized with same phase and frequency, an LC lowpass filter has been used in input and output on both sides of the inverter. Designed inverter is validated through simulations using Matlab 2016a. Two parameters, a balanced resistive load of star configuration (R_L = 20.5 Ω) and input DC voltage, ± 35V are considered. The initial parameters of the design are phase angle of 0^0, switching frequency of 1.65kHz, microgrid frequency of 50 Hz and cut-off frequency of 33Hz. Simulated results indicate that the designed inverter has better performance regarding with overall efficiency of 96.01% and phase angle of only 3.45^0. Therefore, it is expected that the proposed design will improve the performance of microgrid system.*

Keywords—full phase PSI; PWM; zero crossing; LC filter; microgrid

1. INTRODUCTION

A microgrid system is defined as an open system which integrates the transmission and distribution energy systems especially as wind power, a photovoltaic array, fuel generator, wave maker and solar power along with different storage strategies like flywheels, batteries and electric capacitors which rely both on high and low voltage [1]. The transmission and distribution generators are also as PV or wind turbine system that is directly coupled to the microgrid or an asynchronous wind turbine which require the AC to DC conversion on input and then convert back to AC. In the same manner, the battery storage devices are utilized as the piece of the structure might potentially involve an electrical inverter circuit interface as on clarification of the respectively, flywheel and capacitor banks. In this system, the output can be a direct current or an alternating current or maybe a high voltage returns AC all together [2].

Microgrid system inverters can generate three types of output waveforms: square wave, modified square wave and pure sine wave. Square wave inverter is a simple category of the electrical inverter. The harmonic distortion of the square wave is high. This square wave is not efficient and provides serious loss to the device which is not desired for the household appliances. The modified sine wave contains rougher and more noise compared to a sine wave. The pure sine wave inverter may be like the voltage waveform which is usual from the micro-grid. In microgrid system, a voltage source and current source inverter are much familiar [3]. Voltage fed inverter (VFI) also was known as voltage source inverter (VSI) which is an electrical power inverter where the freely controlled output AC is a voltage waveform. The input and output voltage and current waveforms stay unaffected by the output inverter load. Because of this characteristic, the VSI achieves numerous modern applications, for example, movable velocity drives, further in an AC power transmission for microgrid [4]. According to the single phase, VFI circuit can also be considered with two half-phase circuits which have the constant DC bus. During this method, the single stage circuit has two legs of switches; each one leg comprises a high side switch and a low side switch. The intersection point of the upper and lower switches is the output end of that specific leg. The voltage between output point of legs and the mid-point of the DC terminal are named as 'terminal voltage' which indicates to the mid-point of the DC bus. The two terminal voltages of the single-stage electrical inverter have same magnitude and frequency but their phase angles are 0° and 180° separated [5]. Hence the load joined between these two terminals can have a voltage equivalent to twice of the magnitude of the individual terminal voltage. On the other hand, the terminal voltages of the three-phase electrical inverter are indicated with 90° phase separation each [6]. On the other hand, current source type inverter may be the freely controlled by an AC output current waveform. In most of the cases, the current waveform stays unaffected by the load. Usually, the CFI microgrid inverters are still utilized in low-voltage and medium-voltage industrial applications, where high-voltage waveforms are needed. The class of setup is characterized as auto-sequential commutated inverter [7]. A steady current supply is accepted here, which can be acknowledged by utilizing an inductance of appropriate quality that should be high, in series with the limited primary DC voltage supply. The IGBT sets are instead turned ON to induce a concerning square wave current waveform. In addition, two capacitors are utilized. On the other hand, four diodes are joined in series with every IGBT to keep the capacitors from releasing into the load. The output frequency of the electrical inverter may control in the usual path, i.e., by shifting the half period, (T/2), at that the IGBT in a pair which is activated by a pulse fed to the specific gates by the negative feedback circuit [8].

This paper proposes the design of full bridge single phase PSI that includes two terminals where both terminals have two electrical power IGBT switches including a parallel diode (freewheeling) in each for releasing the reverse current. In the case of resistive-inductive load, the other diodes are used to flow the load current. These diodes deliver an alternative path to flow current in the switching logic condition which is dependent on the inductive current. Also, LC lowpass filter is used to reduce the noise by providing the second set of phase variables compared to a 0^0 phase shift. Even though a sample circuit needs a least of two self-regulating phases in the system; it is probable to offer a second stage for change by creating a zero-crossing circuit. The zero-crossing circuit is designed from the sampling circuit of the inverter by separating the state variables of the PWM circuit. This technique has the benefits of eliminating the phase delay which progresses the response of the controller during transients.

2. Design of Full Bridge PSI System

Block diagram represent of single phase full-bridge inverter system has shown in Fig. 1, where inversion of renewable DC voltage has done with the help of control switches. Due to different switching controlling time, output voltage, V_{ab} level can be $+V_{DC}$, 0 or $-V_{DC}$.

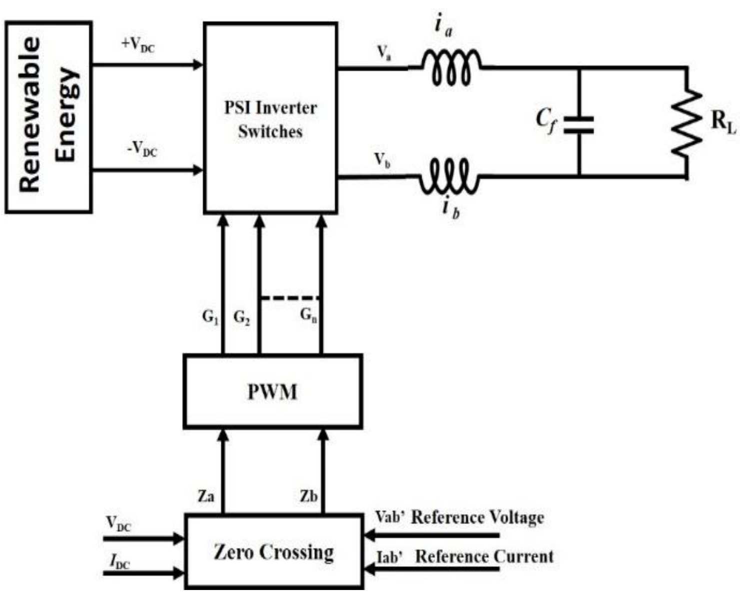

Fig. 1. *Block diagram of PSI system.*

Switch have controlled accurately by using Pulse Width Modulation (PWM) technique as this can controlling the amplitude and frequency of the output voltage. To generate pure output sinusoidal voltage, a low pass filter has been designed. Single-phase inverter has been analyzed through state space equations, representing in (1) and (2) [9].

$$\begin{bmatrix} i_L \\ v_c \end{bmatrix} = \begin{bmatrix} \frac{Z(R_L+R_C)-R_LR_C}{L(Z+R_C)} & \frac{-Z}{L(Z+R_C)} \\ \frac{1}{C(1+\frac{R_C}{Z})} & \frac{-1}{ZC(1+\frac{R_C}{Z})} \end{bmatrix} \begin{bmatrix} i_L(t) \\ v_c(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{AB} U(t) \quad (1)$$

$$V_{0UT} = \begin{bmatrix} \frac{ZR_C}{Z+R_C} & \frac{Z}{Z+R_C} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} \quad (2)$$

Where, i_L, v_c, and Z refers to inductor current, capacitor voltage and load impedance correspondingly. The full bridge voltage, V_{ab} has defined as:

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$$U(t)=\begin{cases} 1 & V_{AB}(t) = +\frac{V_{DC}}{2} \\ 0 & V_{AB}(t) = 0 \\ -1 & V_{AB}(t) = +\frac{V_{DC}}{2} \end{cases} \quad (3)$$

2.1 PSI Switching Method

In full H-bridge inverter circuit, the load voltage has controlled by holding the switching delay angle (α) of the inverter. It is always operating in the discontinuous conduction mode. The potential form factor of single-phase half H-bridge inverter along with resistive, inductive load is inadequate compared to the same inverter with a resistive load. When, the load current form factor of a single-phase half H-bridge inverter with a resistive, inductive load is better compared to the same inverter with a resistive load [10]. Fig. 2 has shown the full H-bridge inverter that intended of two half bridge circuits, sharing the same input DC supplies.

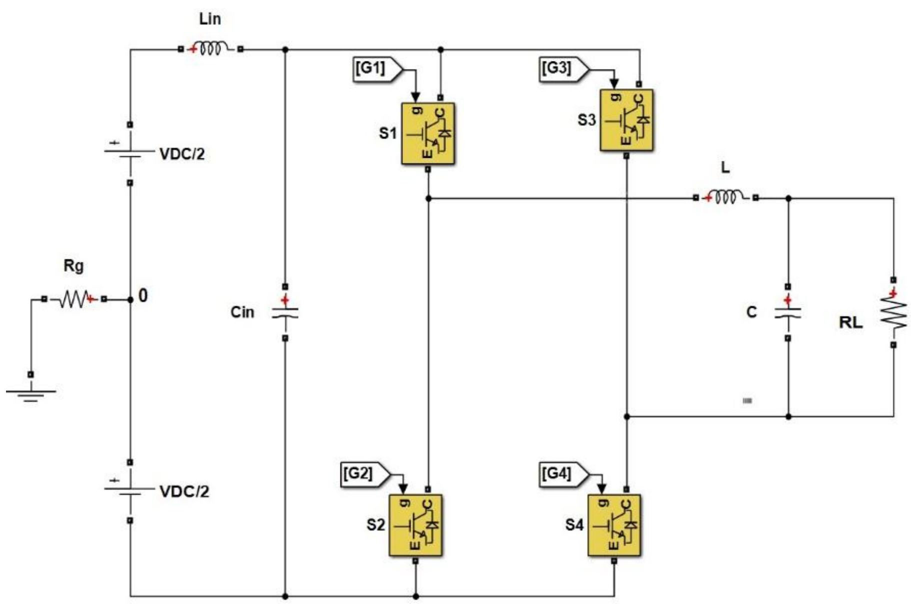


Fig. 2. *Single phase half bridge inverter.*

In continuous condition mode, at least two IGBT conduct always. The output voltage waveform does not depend on the load parameters. The minimum frequency is a higher of the output voltage harmonic in a single phase full H-bridge inverter is twice the input supply frequency. The input displacement factor of a single phase full H-bridge inverter in the continuous conduction mode is equal to the cosine of the firing angle. In the discontinuous conduction mode, the load current remains zero for a portion of the input wheel. For the same triggering angle, the load voltage in the discontinuous conduction mode is higher compared to the continuous conduction mode. The load current ripple factor in the continuous conduction mode is lower compared to the discontinuous conduction mode as shows in Fig. 3. In the inverter mode of operation, electrical power is transferred from the input DC side to the output AC side. In the continuous conduction mode, the firing angle should be higher than 90^0 degrees to operate in the inverter mode [11].

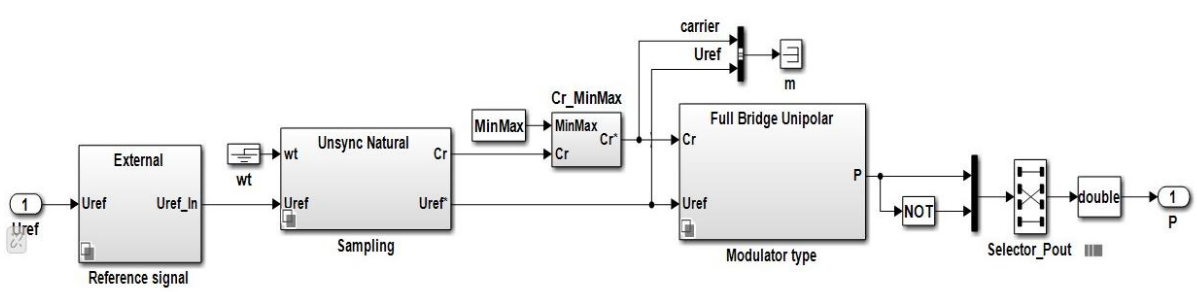


Fig. 3. *Matlab circuit of the PWM controller.*

2.2 Design of a Zero Crossing Circuit

The phase angle of microgrid and inverter are determined, zero crossing circuit has developed with the aid of fundamental frequency. Fig.4 has shown the single-phase inverter output voltage and the current waveform. Signal frequency has a measure by measuring the number of cycles of a reference signal for one or more-time periods of the signal. Reduction of errors due to phase noise is made accessible through measuring multiple times by providing the perturbations in zero crossings small in compared to the total measurement period.

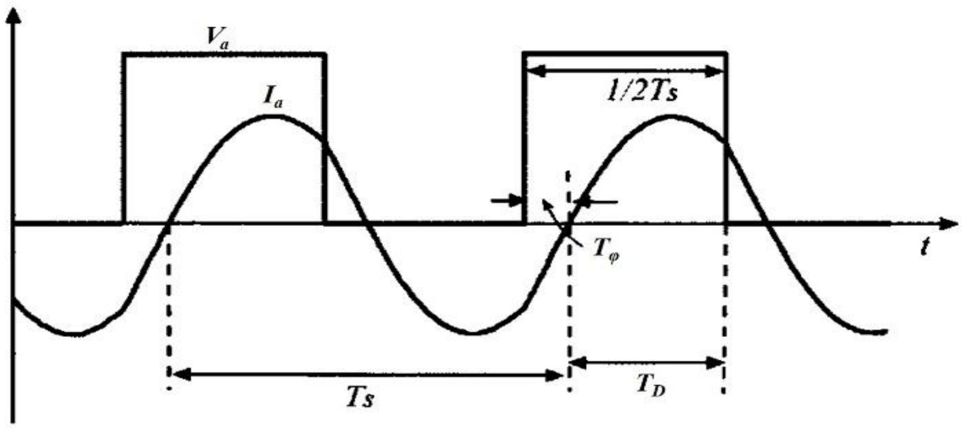


Fig. 4. *Half phase PSI voltage and current.*

Zero crossing MatLab circuit has done by changing the power IGBT switch state means to turn 'ON' to turn 'OFF' to detect the desired phase. Then, the phase angle can varie from 0^0 to 90^0 [12] as follows in the equation (4) to (8).

$$T_C + T_\phi = \frac{T_S}{2} \quad (4)$$

$$T_D = \frac{T_S}{2} - \varphi_{ref} \times \frac{T_S}{360^0} \quad (5)$$

Where,

$$\alpha = \frac{\varphi_{ref}}{90^0}$$

$$T_C = \frac{T_S}{2}(2-\alpha) \quad (6)$$

$$T_C[n] = \frac{T_S[n-1]}{4}(2-\alpha[n]) \quad (7)$$

Where, T_C, T_ϕ and φ_{res} are indicated the control variable, phase angle command to current phase and time response of current phase.

Again,

$$\alpha[n] = \frac{\varphi_{ref}[n]}{90^0}$$

When, $0 \leq \alpha[n] \leq 1$

$$T_D[n] = \frac{T_S[n-1]}{4}\left[\frac{(2^S-1)+(2^S-1-\alpha_1[n]}{2^S}\right] \quad (8)$$

Where, S denotes the number of sample in the zero-crossing phase command and $\alpha^1[n]= 0$ parallels to 0^0 while $\alpha^1[n]= 2^{S-1}$ parallels to 90^0. This error can avoid for a large value of n. Fig. 5 has shown the schematic of zero crossing Matlab circuit.

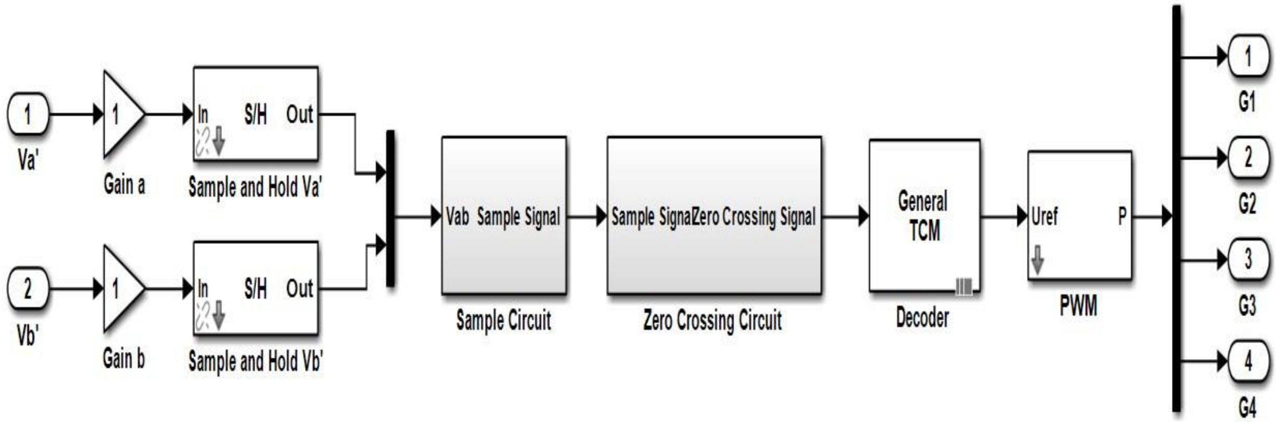


Fig. 5. *Zero crossing Matlab Circuit.*

2.3 Output Filter Design

Fig.6 has demonstrated that the output filter circuit in where the value of inductor and capacitor value should be defined to create LC filter. The filter has reduced the phase noise in the inverter output voltage. If filter used for resistive loads, then output impedance should be minimum means inductance must be minimized, and the capacitance should be maximized to reduce the noise If the cut-off frequency is specified [13].

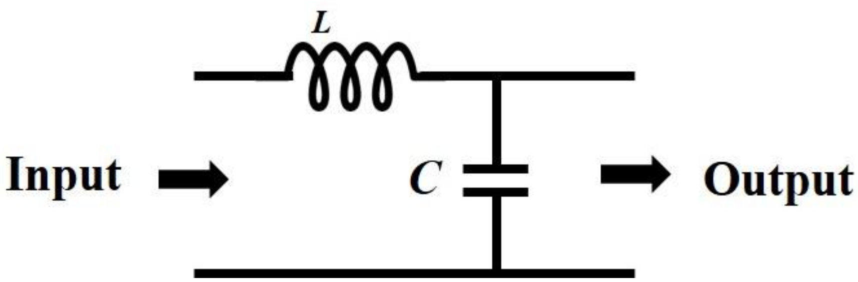


Fig. 6. *Output LC filter*

Inductor value has calculated by utilizing the following equations (9):

$$V_L = V_a + V_o \tag{9}$$

The maximum ripple current of the inductor has calculated, V_a and V_o values are as in equation (10).

$$V_L = \frac{1}{2}V_{DC} + \frac{1}{2}V_{DC} \tag{10}$$

According to the phase noise usual [14], 20% has assumed while allowable of the rated current is 15–20%. The calculation has done in equations (11) and (12) to measure the maximum ripple current that depends on switching frequency, input DC voltage, and inductance. In ripple measurement case, switching frequency and input DC voltage are considered constant. Inductance value has determined from Equation (13):

$$V_L = L\,\frac{\Delta I}{D_{max}\,T_s} \tag{11}$$

$$\Delta I_{max} = \frac{1}{4}\frac{D_{max} \times V_{DC}}{L} \tag{12}$$

$$L = \frac{1}{4}\frac{V_{dc}}{\Delta I_{max} \times f_c} \quad (13)$$

Where, L, V_{dc}, f_c refers to filter inductor, DC link voltage, switching frequency respectively. ΔI_{max} and D_{max} are the allowable ripple current and the maximum duty cycle.

The ripple voltage has calculated to the following equations (14) to (16):

$$\Delta V_o = \Delta V_c \quad (14)$$

$$\cong \frac{\Delta I_c}{C \times f_s} + r_{ESR} \times \Delta I_c \quad (15)$$

$$\cong \frac{\Delta I_L}{C \times f_s} + r_{ESR} \times \Delta I_L \quad (16)$$

Where, ΔV_{out}, ΔI_L and r_{ESR} have represented the output voltage ripple, inductor current ripple and equivalent series resistance of the output capacitor, respectively.

The transfer functions of the bode plots of the LC filter approximate control are shown in Fig. 7. The gain margins and phase for the LC low pass filter are 90° and -3dB and a crossover frequency is 1.65 kHz. In this graph, it is performed that at the fundamental frequency is 50 Hz, the LC obtained by the estimated technique presents a higher gain.

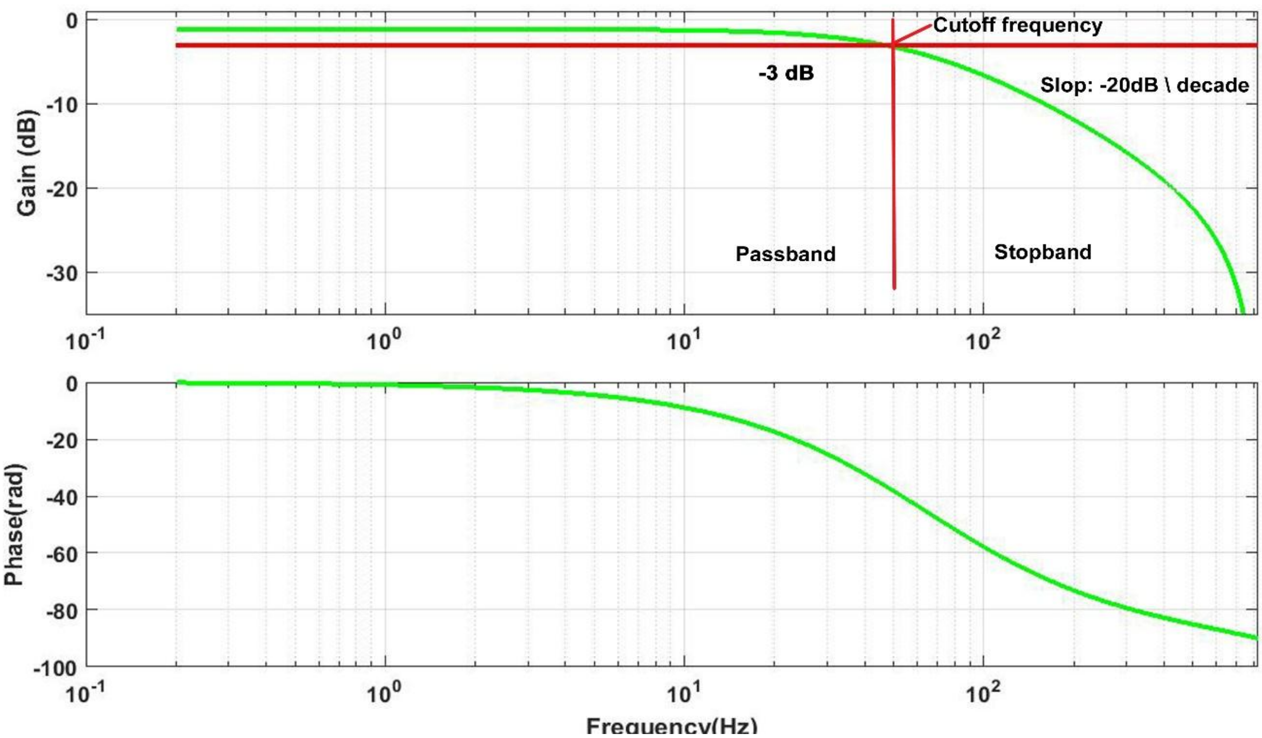
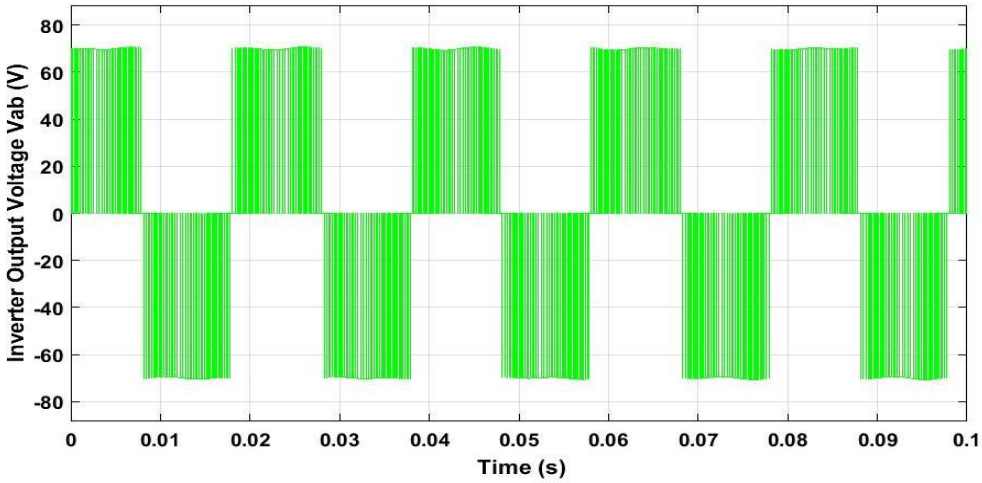


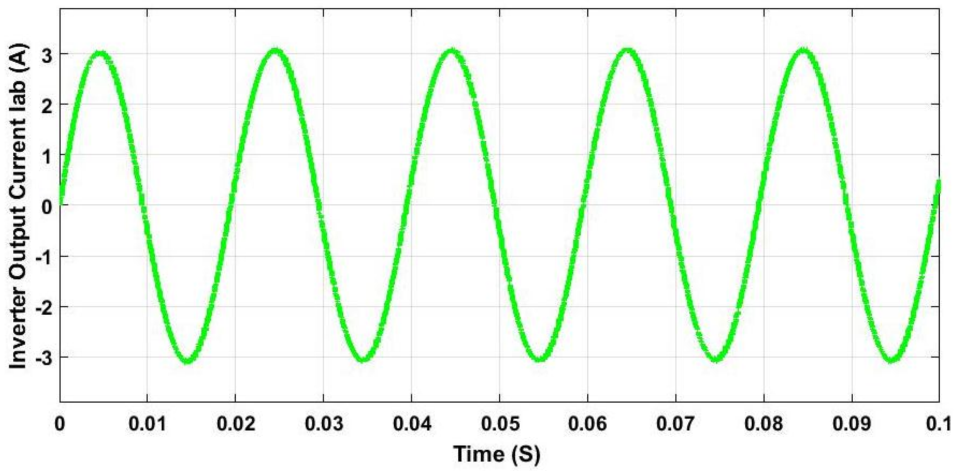
Fig. 7. *The output lowpass LC filter gain-magnitude frequency response.*

3. Results and Discussion

Simulated result of the single-phase half bridge PSI voltage and current waveform has shown in Fig. 8. The zero-crossing based PWM controller that employed in inverter has created the pure sine wave and also the sampled phase signal is utilized to synchronize the phase and frequency of the inverter. 50 Hz sinusoidal wave has made, 1.65 kHz carrier frequency, 95% of maximum duty cycle and 0^0 phase angle have used in the controller. Without filtering condition, designed inverter output phase to phase voltage V_{ab} is approximately 141.4 V (peak to peak) and load current, I_{ab} is about 6.3 A (peak to peak).



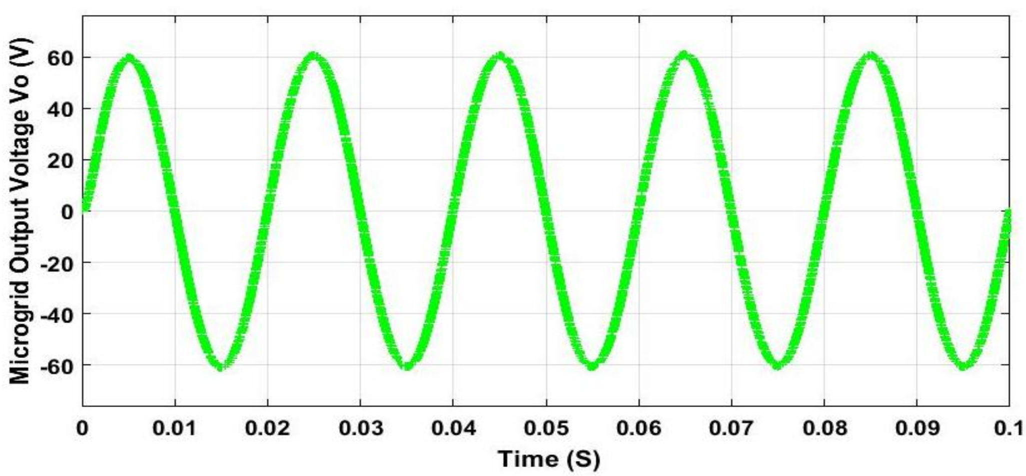
(a)



(b)

Fig. 8. *Inverter output waveform without filtering for (a) voltage and (b) current.*

However, in the case of filtering condition, the output voltage is almost 121.9V peak to peak and output current is 6.1 A peak to peak and 50Hz pure sine wave output voltage and current waveform as shown in Fig. 9.



(a)

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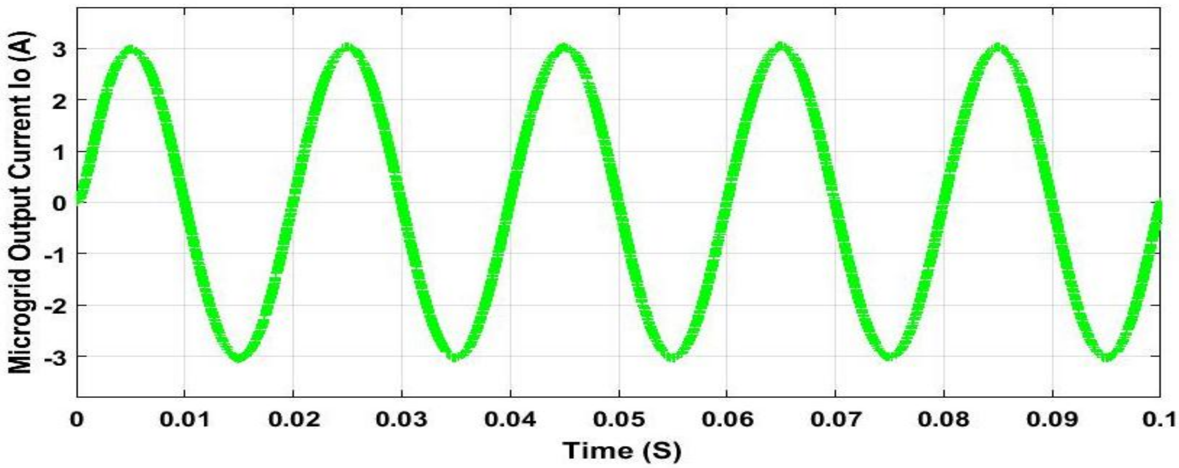
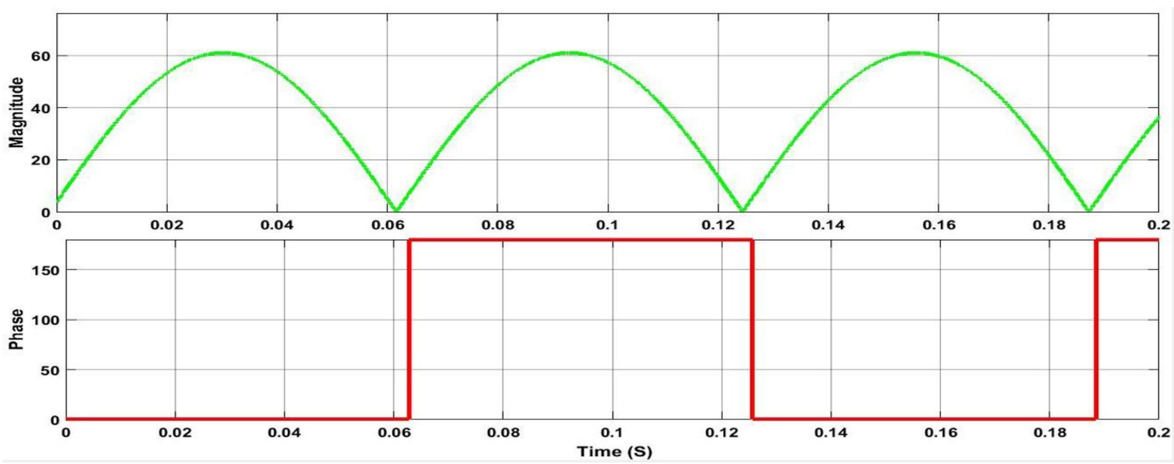


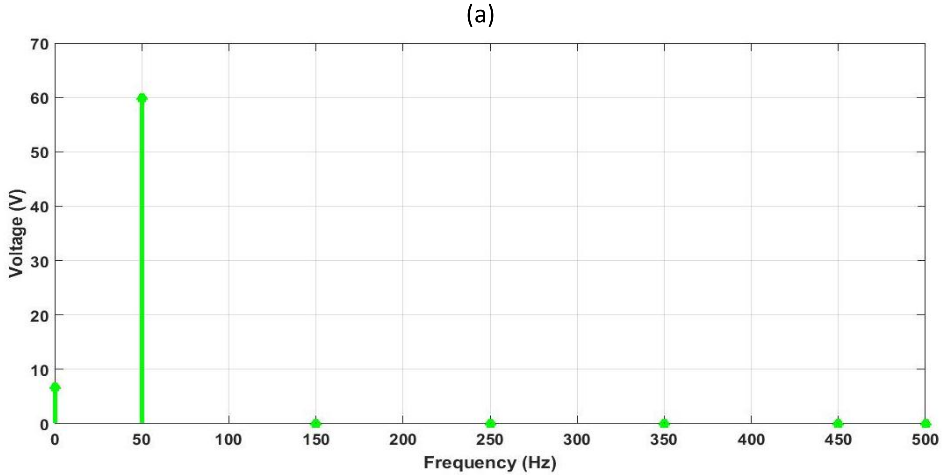
(b)

Fig. 9. *With filtering condition, the inverter output (a) voltage and (b) current.*

Fig. 10 has illustrated the microgrid interface phase synchronization for full phase inverter output waveform. Form Fig. 10, it has observed that the magnitude and phase angle of the inverter is almost same as a micro-grid, amounting 0^0 to 180^0. It is also found that the inverter output voltage with FFT analysis for filtering condition. the inverter output has a low level of THD, approximately 0.43% as proposed design is transformer less microgrid system.



(a)



(b)

Fig. 10. *The half phase inverter output waveform (a) phase and magnitude and (b)THD.*

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Simulation has analysis on the frequency domain, and It has found that inverter output phase angle is almost 0° at the fundamental frequency of 50 Hz, presenting in Fig.11. This proposed inverter phase angle and microgrid phase angle is almost same due to zero crossing, but the phase error is 3.45^0.

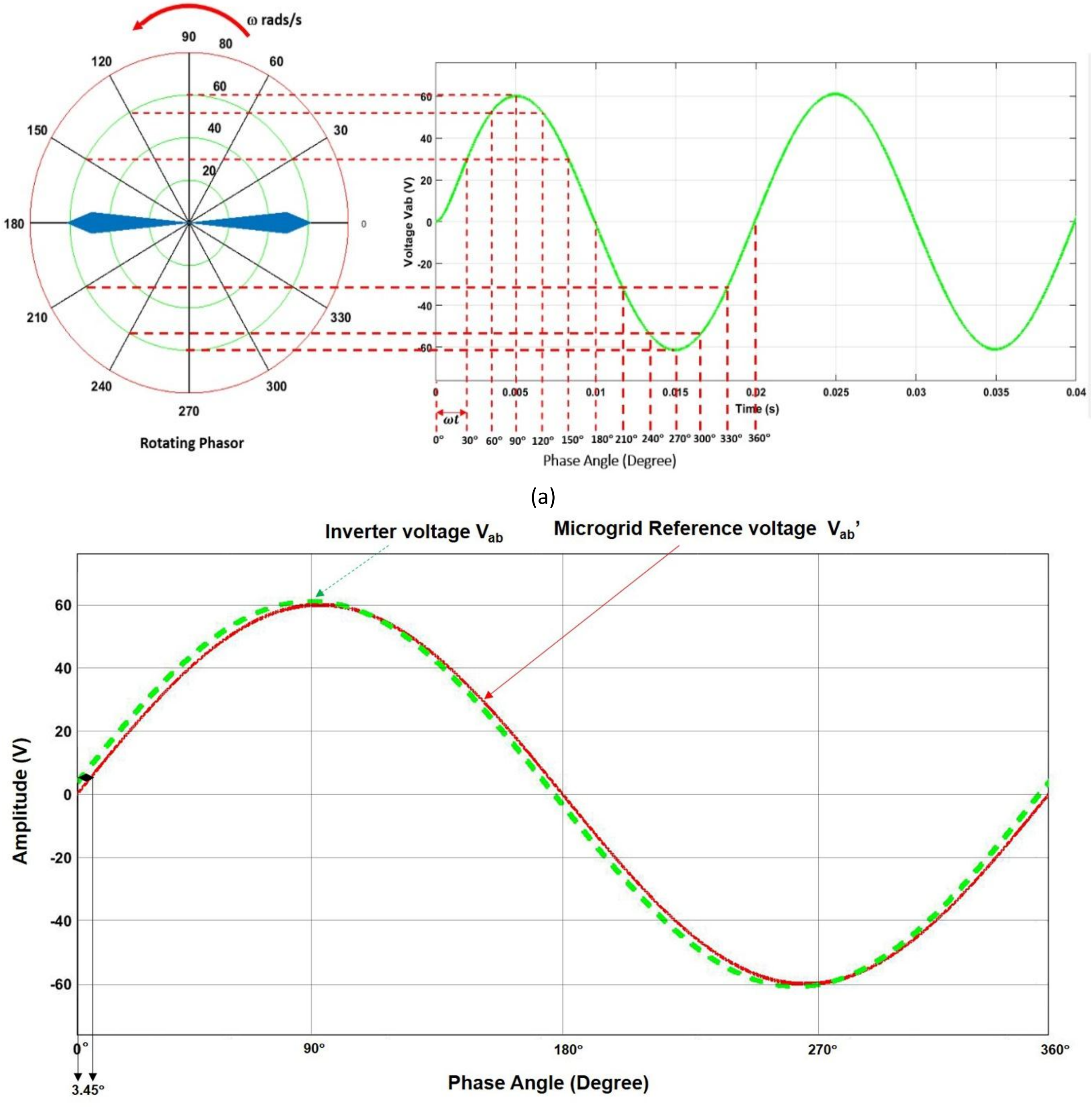

Fig. 11. *Phase Synchronization for (a) microgrid output voltage and (b)inverter and microgrid refrence voltage.*

4. Conclusions

PSI system has been proposed and researched in both theoretically and numerically which has solved the switching controller and output filter issue for PSI based microgrid inverter. Besides that, proposed Inverter has synchronized the switching frequency and phase. However, this design has unable to avoid reduction of switching loss, same as a microgrid phase by introducing PWM controller based switching phenomenon which increases the overall system efficiency. The overall system efficiency is 96.01%, and the phase angle is only 3.45^0; lower than the maximum allowable angle (Phase angle <50) as per IEEE standard. Designed PSI is appropriate for applications where the demandable source is AC voltage which needs to be higher than DC and economically feasible.

5. Acknowledgment

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