Pertanika J. Sci. & Technol. 25 (S): 145 - 156 (2017)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Synchronisation of Output Voltage Waveforms in Phase Synchronous inverter with LCL Filter for Smart Grid Systems

Tawfikur Rahman*, M. I. Ibrahimy and S. M. A. Motakabber

Department of Electrical and Computer Engineering, International Islamic University Malaysia (IIUM), 53100 Kuala Lumpur, Malaysia

ABSTRACT

A new smart grid system is widely used for energy supply system because it is simple, available, low cost, high efficiency and environmentally friendly. Conventionally, inverter techniques are utilised to convert input DC into output AC with the same frequency and phase. This process suffers the same problem which is a higher harmonic distortion, phase synchronisation, lower quality of waveform and long distance, among others. In this paper, three phase synchronous inverters (PSI) were used to direct synchronous PWM control, LCL filter, three phase RLC load, three phase Yg-Delta transformer, 5 km feeder with 2 MW load. PWM was used to generate the pulse signal for synchronisation. However, LCL filters were used to remove the noise in inverter output and transformer output side of the design. A balanced three phase load (10 kVAR) and also the input DC voltage 500 V were considered in this design. Three phase transformer (100kVA/260V/25kV) was used to increase the inverter output voltage and current with the fundamental frequency (50 Hz). The system conversion efficiency was 99.96% and phase synchronous error for each phase was approximately 4.5 degrees.

Keywords: Choke coil, controller, LCL filter, PSI, transformer

INTRODUCTION

A new smart grid system is an open system that connects distribution network systems for solar, wind power and so on (Zidar, Georgilakis, Hatziargyriou, Capuder, & Škrlec, 2016). The distribution network systems consist of local area network, power storage and distributed generators that can be operated on the main grid-connected modes. This system consists of two types of feeders such as sensitive and non-sensitive

ARTICLE INFO

Article history:
Received: 05 January 2017
Accepted: 17 January 2017

E-mail addresses:
tawfikurr@gmail.com (Tawfikur Rahman),
amotakabber@iium.edu.my (S. M. A. Motakabber),
ibrahimy@iium.edu.my (M. I. Ibrahimy)
*Corresponding Author

ISSN: 0128-7680

load feeder. Generally, it is used in the distribution network for domestic and small cottage industries in a rural area and the island. The sensitive-load feeders are used to continuously supply the power in grid network; therefore, every feeder connected with the system should have a minimum number of micro sources to fulfil the inner feeder load. The non-sensitive-load feeder is utilised to shut down if there is a power quality problem on the grid, utility or a disturbance (Rahman, Ibrahimy, Motakabber, & Mostafa, 2014; Zidaret al., 2016).

Grid energy systems such as solar and wind connect with the new smart grid system. Grid source, replaces itself and is usually available throughout an unremitting source (Zhang, Armstrong, & Elgendy, 2016). Sunlight is directly converted into DC by using solar panels and then convert it to AC (Hassaine, Olías, Quintero, & Barrado, 2014). In the case of wind systems, generally wind passes through directly through a big propeller blades to move the generator to produce the AC/DC electrical power. Likewise, energy sources are converted into electrical power to supply the grid systems with suitable techniques.

Inversion is a process that changes the input DC to output AC by means of a desired output current, voltage and frequency. An electrical power inverter circuit can perform this type of alteration. The terms voltage-sustained and current-sustained are used as a part of reference to power electrical inverter circuits. A voltage-sustained power electrical inverter is one within that the DC input voltage or current is fundamentally consistent and free of the load current strained. However, the phase synchronous inverter (PSI) brings up the load voltage through the strained current structure and is fixed. The grid system inverters can create three various types of output waveforms such as square wave, modified square wave or close to a sine wave and pure sine wave. The square wave inverter is a simple type of electrical inverter whose output is a rectangle wave shape. Due to sharply rising and falling edges, there are many higher order harmonic frequencies involved in this wave. Though this type of inverter is simple in construction, low cost and efficient, quality of its power is poor. However, this type of inverter is still in demand (Rahman et al., 2014). The modified square wave has better power quality and its output is composed of many square waves with different amplitude. Due to its sharp rising and falling edges, it contains a higher harmonic frequencies and close to a sine wave, which results in improved power quality and efficiency. Its circuit is more complex and expensive, but better quality of power compared with the square wave inverter. This type of inverter is suitable for small and medium systems (Rahman, Ibrahimy, Motakabber, & Mostafa, 2016). The pure sine wave inverter output voltage waveform looks like a sine wave, this wave shape is desirable for sensitive system and it provides a good power quality. There is some harmonic distortion to enable supply of clean energy and which makes it perfect for running electronic systems for household and industrial application with less noise. This type of inverter circuits is very complex and expensive as well as inefficient. However, it provides clean and good quality of power (Wen, Boroyevich, Burgos, Shen, & Mattavelli, 2016).

The three phases inverter is exceptionally appealing for commercial enterprise application systems because of its high current rating, high voltage rating, and high efficiency. In this inverter, the overall performance is impressive because the system produces less harmonic, switching loss and it also costs less. The increase in quantitative measure corresponds with the output voltage waveform. The SPWM control method is used to control the semiconductor switches and synchronise phases between inverter and the utility grid (Ahuja & Kumar, 2014). In the inversion system, filters are utilised in the inverter interface circuit to reduce harmonic. The LC is one kind of traditional filter that decreases the % THD. Indeed, several types of PWM control systems are utilised to reduce harmonic distortion and ensure proper phase synchronisation. Multilevel inverter is used in switching device because it reduces switching losses and improves system efficiency. Therefore, it is generally utilised as part of renewable energy application (Tayebi & Batarseh, 2016). As a result of the improved utilisation of the nonlinear loads, the limitation of harmonics becomes more difficult. The state-space comparisons are produced by analysing the single stage full bridge inverter. The fuzzy logic and PI controllers are utilised for the experimental simulation. The fuzzy logic controller is able to reduce the overall system's harmonic distortion whereas the general PI controller is not that efficient (Rahman et al., 2014).

MATERIALS AND METHOD

The PSI circuit has been designed by using MATLAB 2014a/SIMULINK/SIMPOWER. The logic circuit of the PSI was designed and simulated.

Phase Synchronous Inverter

The phase synchronous inverter is an electronic device that can be synchronised between invert phase and grid phase with appropriate transformer and filter. Figure 1 shows a three phase PSI circuit diagram that consists of two input terminals, three output terminals and six gate pulses.

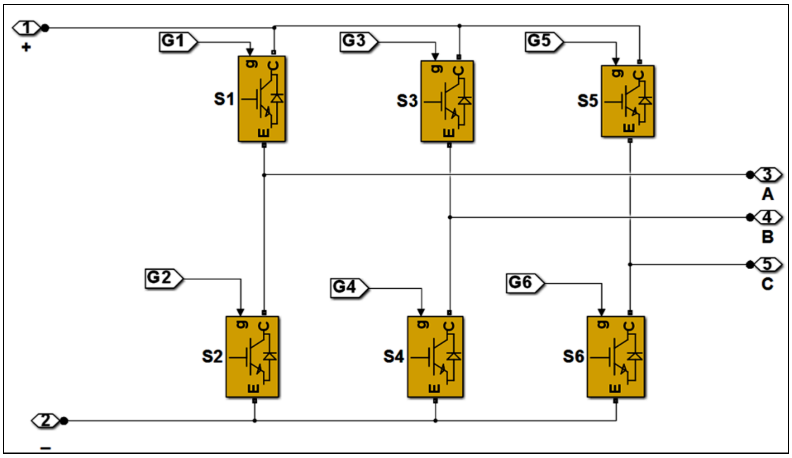

Figure 1. Three phase PSI circuit diagram

The driving input DC voltage ± 250V is chosen for the PSI circuit. The IGBT (internal resistance $1e^{-03}\Omega$ and snubber resistance $1e^{05}\Omega$) is used as the logic control switch for the PSI. The advantage of the IGBT as switch is that it can safely operate with high voltage and high frequency. In addition, the solid-state switch like IGBT works as an ideal switch. Therefore, during the operation, at ON condition the voltage across the device is zero volt and the OFF condition in the device is zero Amp. In this design, the IGBT is controlled by pulse width modulation (PWM) signal and therefore, IGBT switches remain either on or off state during its operation. As a result, there is no power loss in the IGBT switch and the efficiency of the circuit will be improved.

Design of A Synchronous Switching Topology

There are eight switching condition modes of process in a cycle to make a three-phase output voltage from the inverter; a group of switches are triggered at 120° phase apart, 0°, 120° and 240° respectively. A carrier based PWM method was used to control the three phase circuit switches. The PWM controller generates pulses for carrier based pulse width modulation converts using two level switching circuit as shown in Figure 2.

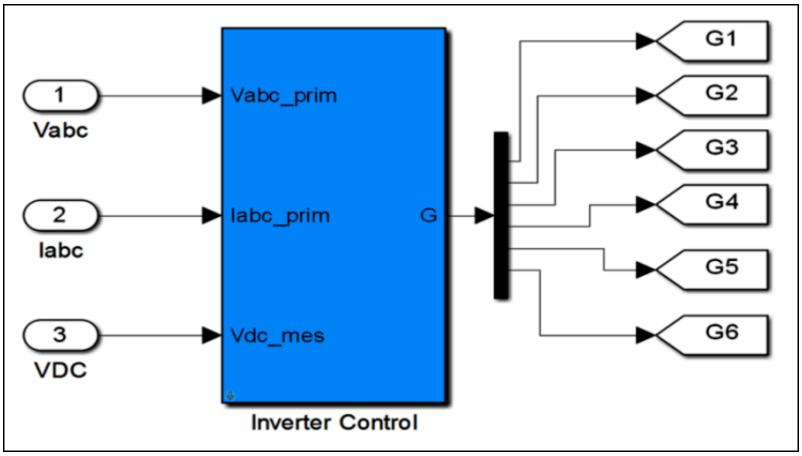

Figure 2. The inverters controller MATLAB block diagram

The PWM controller can control switching IGBT of the three-phase circuit. The input reference/sample signal from the new smart grid is used for phase synchronisation. When the input sample signal amplitude is greater than the carrier voltage amplitude, the switches show S1=S3=S5=1 or ON condition, consequently the other switches are S2=S4=S6=0 or OFF state shows in Table 1.

Table 1
Inverter switching condition

S1	S3	S5	V_{oa}	V_{ob}	V_{oc}
S2'	S4'	S5'			
0	0	0	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
0	0	1	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$
0	1	1	$-\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$
1	0	0	$+\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
1	0	1	$+\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$
1	1	0	$+\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$	$-\frac{V_{dc}}{2}$
1	1	1		$+\frac{V_{dc}}{2}$	$+\frac{V_{dc}}{2}$

Output LCL Filter Design

Different parameters must be considered in a LCL filter designing which are filter size, switching ripple current and current ripple etc. The capacitor resonance frequency may cause a resonance with the grid requirements of to the reactive power. So, active damping is a resistor in series added by the capacitor. On the other hand, the passive damping has been implemented, then active is also be useful. The subsequent parameters are required for the LCL filter design. Figure 3 shows the single phase LCL filter circuit.

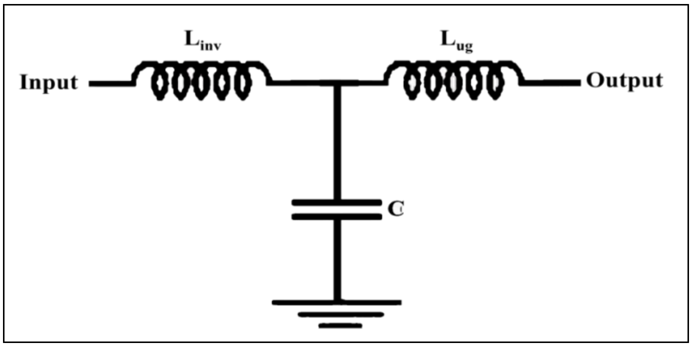

Figure 3. The single phase LCL filter circuit

The LCL filter value depends on a percentage of the base value (Rahman et al., 2016):

$$Z = \frac{Vn^2}{S_n} \tag{1}$$

$$Z = \frac{1}{Z \times \omega} \tag{2}$$

The inverter side inductance L_{inv} can limit the current ripple of the output side which is 10% of normal amplitude.

$$L_{inv} = \frac{V_{DC}}{16\ f_s \times \Delta I_L} \tag{3}$$

The grid side inductance L_{ug} can be calculated as:

$$L_{ug} = r \times L_{inv} \tag{4}$$

The control of the resonant frequency depends on the distance and one half of the switching frequency due to attenuation in the switching frequency of the inverter. The design of the LCL filter, resonant frequency can be calculated as:

$$f_{Res} = \frac{1}{2\pi}\sqrt{\frac{L_{inv} \times L_{ug}}{L_{inv} \times L_{ug} \times C_f}} \tag{5}$$

Where,

V_n is the phase to phase RMS voltage

V_{DC} is the input DC voltage

f_s is the fundamental frequency Harz

f_{sw} is the switching frequency Harz

f_{Res} is the resonance frequency Harz

Design of A Synchronous PSI System

Synchronous inverter was designed and simulated by using MATLAB2014a/Simulink/simpower block. The three-inverter design is completed based on six IGBT based inverter respectively. The two IGBT is called a half phase inverter circuit. Final design of the three-phase inverter circuit is constructed by combining three half phase inverter. Generally, a diode is used in reverse biased condition with each IGBT to protect the device (IGBT) from high voltage surge. If the switches are turned OFF the flywheel diodes provide an alternate path for the load current.

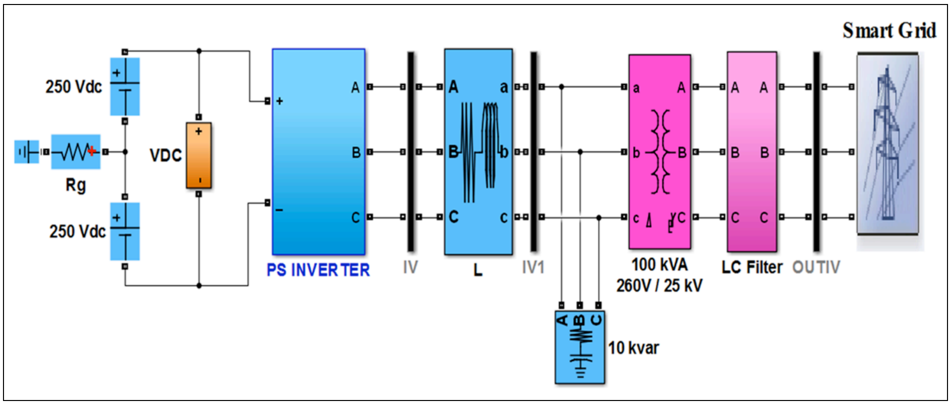

Figure 4. Block diagram of the phase synchronous system

Figure 4 shows a synchronous inverter block diagram for the PSI system which includes DC voltage source, electronic switches, synchronous controller, one output LCL filter with 10 kVAR three phase load, transformer and feeder. In this system, inverter input sources generally use DC voltage which is converted into AC voltage. The PSI controllers are controlled inverter switch for synchronising the inverter and micro-grid phase. The LCL filter reduces DC ripple current and decreases high frequency distortion resulting in lower switching loss. Three phase load depends on the load flow of the system. The step-up transformer two winding are coupled with inverter and new smart grid. The first winding (Δ) indicates a high voltage wye connection and second winding (Y) indicates low voltage wye connection. However, feeder is used to the lossless distributed LC line because it cannot represent correctly the frequency dependence of RLC parameter of the line.

RESULTS AND DISCUSSION

The phase synchronous inverter was simulated using MATLAB2014a. Figure 5 shows the phase synchronous inverter output voltage waveform without filtering. In this system, the controller used in the inverter gate sends signal to generate the pulse signal. A sampled pulse signal was used to synchronise the inverter output phase with the new smart grid phase. A 1.665 kHz carrier frequency with modulation index of 1 was utilised in a pulse controller to generate 50 Hz voltage wave. The magenta, red and blue colours represent the three-phase voltage V_a, V_b, V_c and V_{abc} respectively. From Figure 5, it is observed that the output voltage waveform of the inverter is a control signal and its output voltage is approximately ±500 V.

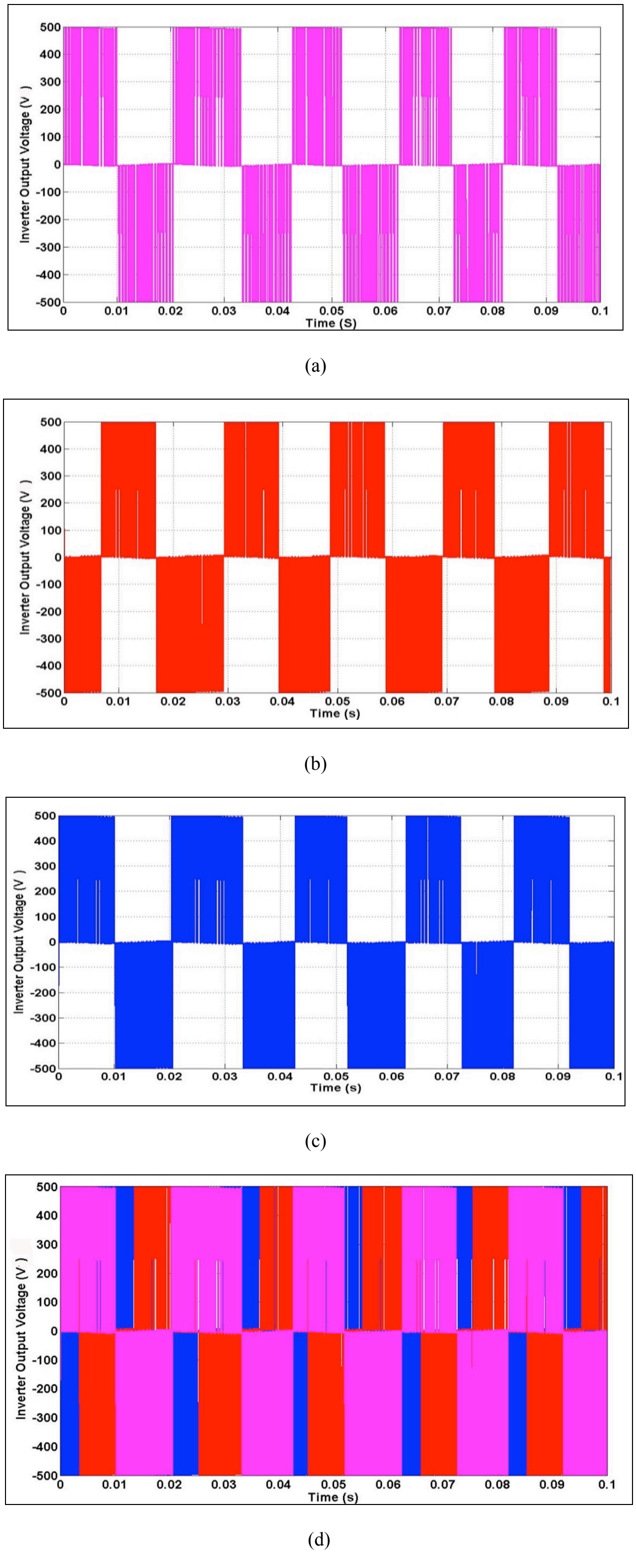

Figure 5. Inverter output voltage waveform for: (a) V_a; (b) V_b; (c) V_c; and (d) V_{abc} without filtering

Figure 6 shows the inverter output phase-to-phase current is around ±2 A, for the three phase RLC load of 10 kVAR, active power 100W, capacitive reactive power 10e3var, inductive reactive power 0var, normal phase to phase voltage 240 V and fundamental frequency 50 Hz.

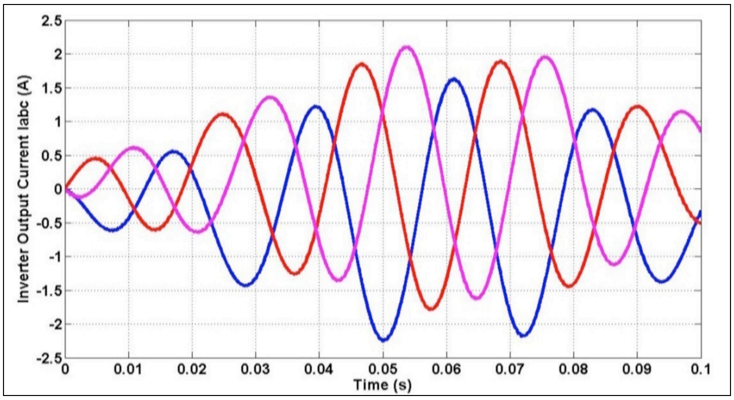

Figure 6. Inverter output current waveform without filter

Figure 7 and figure 8 show the inductor output phase-to-phase voltage and current output waveform which is around ±300V_{p-p} and ±2 A, for the three phase RLC branch resistance R=500e^{-6}×377/50/2 Ω and inductance L=500e^{-6}/2 H.

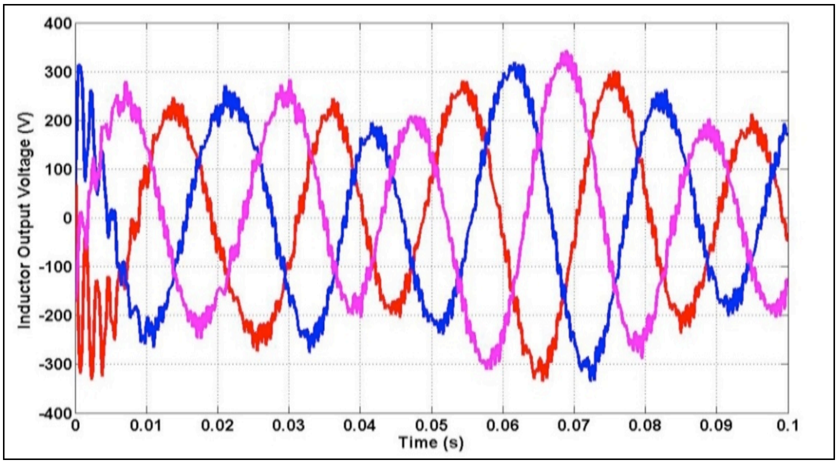

Figure 7. Inductor output voltage waveform without filter

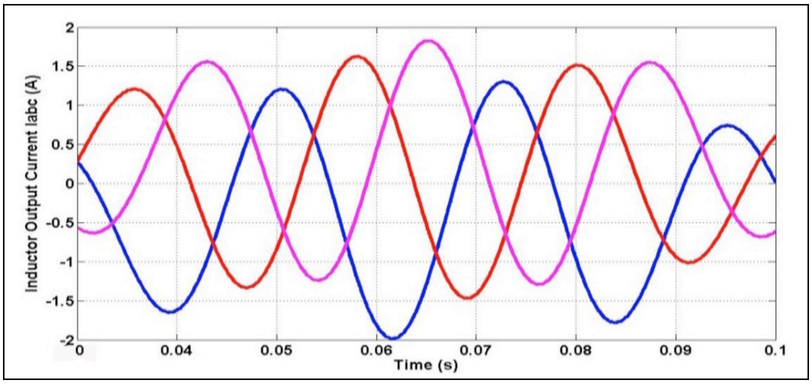

Figure 8. Inductor output current waveform without filter

The inverter output voltage pulses pass through a transformer primary winding. The secondary winding is connected to the LCL filter which produces higher harmonic frequencies and generates the pure sinusoidal wave as shown in Figure 9 and Figure 10. In this paper, the simulated results of the inverter with transformer are: normal power P_n=100e^3 VA, frequency f_n=50 Hz, p-p output voltage V_{abc}=±2e^{04} kV and the load current =±91.42 A. From the simulation results, the phase difference between the inverter voltage and grid voltage is 50 with THD of 0.04%.

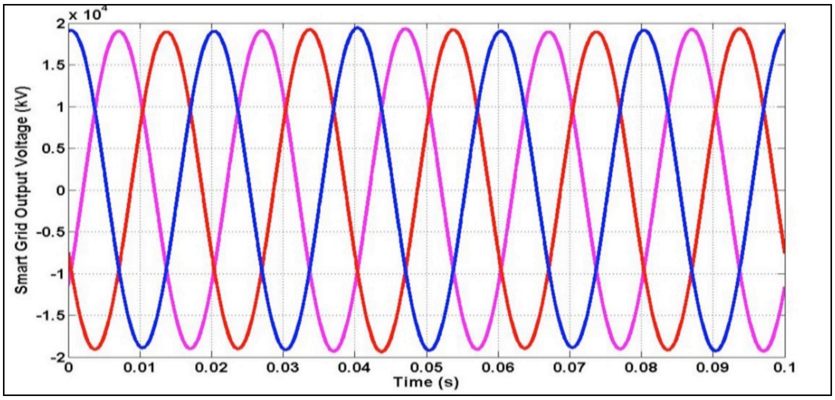

Figure 9. Smart grid output voltage waveform with filter

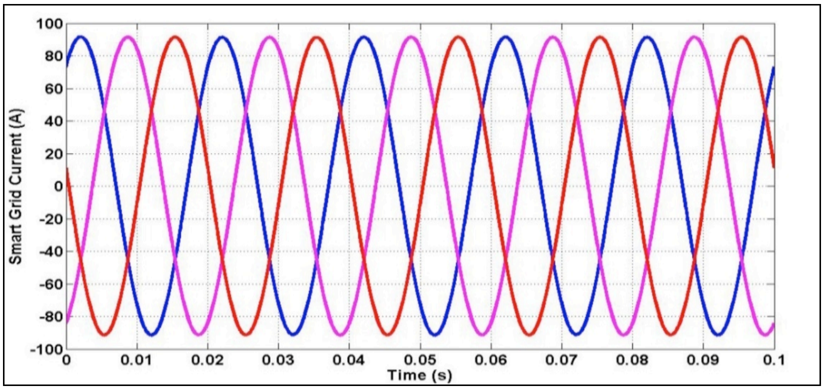

Figure 10. Smart grid output current waveform with filter

Figure 11 shows the result of the phase synchronisation inverter waveform. The signals V_{ab}, V_{bc} and V_{ca} represent the new smart grid sampling signal while the signals V_{ab}', V_{bc}' and V_{ca}' represent the phase synchronous inverter controller signal. Also, it can be seen that PSI phase and smart grid phase are almost synchronised. It can also be seen the phase angles among the phase voltages V_{ab}-V_{bc}, V_{bc}-V_{ca}, V_{ca}-V_{ab}, are 91.8°, 211.1± and 27.3° without filtering condition. On the other hand, the THD of each output voltage is 0.04% and the phase angles are 124.08°, 244.6± and 4.5° with filtering condition.

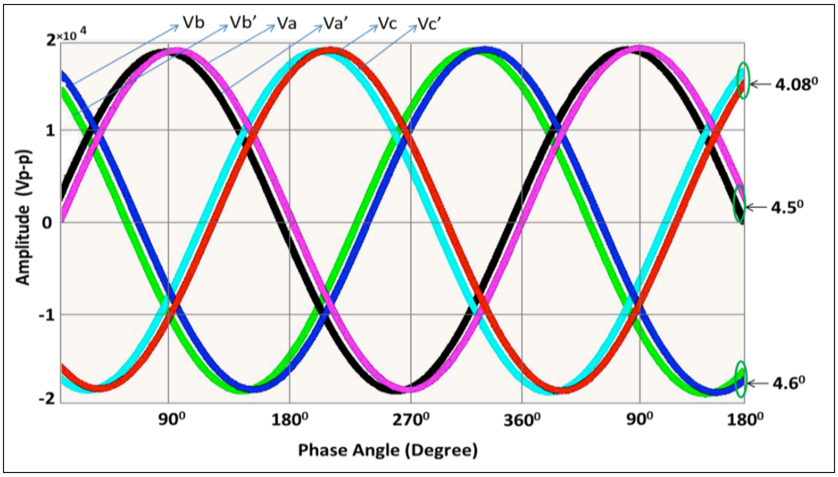

Figure 11. Phase Synchronisation inverter and smart grid phase synchronous waveform

CONCLUSION

In PSI based new smart grid inverter in interface circuit, impulse generator and output LCL filter are the main problems in this design. Due to the power loss of the circuit switching frequency, the reduction of the overall system efficiency occurred. Nevertheless, the design was unable to avoid the reduction of the switching loss, similar to smart grid phase by introducing a pulse controller based switching phenomenon which increases the overall system efficiency which is 99.96%. In this paper of the PSI system was aimed at synchronising the inverter with smart grid phase. The simulation result shows that the value of inverter phase angle is at an acceptable level of IEEE standard. Particularly, the phase angle ratio is closely synchronised at 4.5°, 4.08° and 4.6° which is lower than the maximum allowable angle as per requirements of IEEE standard (Phase angle <5°). The PSI system was proposed and researched both theoretically and numerically. As indicated by our prediction, the PSI is appropriate for applications where the AC voltage as an output needs to be higher than DC as an input and economically feasible.

ACKNOWLEDGEMENT

This research was supported by the Malaysian Ministry of Education through the Fundamental Research Grant Scheme under the project ID: FRGS15-190-0431.

REFERENCES

Ahuja, R. K., & Kumar, A. (2014). Analysis and control of three phase multilevel inverters with sinusoidal pwm feeding balanced loads using MATLAB. *International Journal of Engineering Research and General Science, 2*(4).

Hassaine, L., Olías, E., Quintero, J., & Barrado, A. (2014). Power control for grid connected applications based on the phase shifting of the inverter output voltage with respect to the grid voltage. *International Journal of Electrical Power &and Energy Systems, 57*, 250-260.

Rahman, T., Ibrahimy, M. I., Motakabber, S. M., & Mostafa, M. G. (2014). Three phase three layer phase synchronous inverter for microgrid system. *International Conference on Computer and Communication Engineering (ICCCE)* (pp. 44-47)

Rahman, T., Ibrahimy, M. I., Motakabber, S. M., & Mostafa, M. G. (2016). Simulation and evaluation of a phase synchronous inverter for micro-grid system. *International Postgraduate Conference on Engineering Research* (pp. 27-28).

Tayebi, S. M., Mu, X., & Batarseh, I. (2016, March). Improved three-phase micro-inverter using dynamic dead time optimization and phase-skipping control techniques. *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)* (pp. 1381-1386). IEEE.

Wen, B., Boroyevich, D., Burgos, R., Shen, Z., & Mattavelli, P. (2016). Impedance-based analysis of active frequency drift islanding detection for grid-tied inverter system. *IEEETransactions on Industry Applications, 52*(1), 332-341.

Zhang, W., Armstrong, M., & Elgendy, M. (2016). DC component detection in grid connected inverter systems, using a mid-ground low pass filter approach. *8th IET International Conference on Power Electronics, Machines and Drives* (pp. 1-6)

Zidar, M., Georgilakis, P. S., Hatziargyriou, N. D., Capuder, T., & Škrlec, D. (2016). Review of energy storage allocation in power distribution networks: applications, methods and future research. *IET Generation, Transmission & Distribution, 10*(3), 645-652.