VOLUME 14 NO. 2
DECEMBER 2017
ISSN 1675-7009

SCIENTIFIC RESEARCH JOURNAL

Institute of Research Management and Innovation

Scientific Research Journal is a journal by Institute of Research Management & Innovation (IRMI), Universiti Teknologi MARA, Bangunan Wawasan, Level 3, 40450 Shah Alam, Selangor Darul Ehsan, Malaysia. E-mail: irmiuitm@salam.uitm.edu.my

SCIENTIFIC RESEARCH JOURNAL

Institute of Research Management & Innovation (IRMI)

Vol. 14, No. 2 December 2017 ISSN 1675-7009

Design and Simulation of a PWM Based Phase Synchronous Inverter for Utility Grid Systems with 20km Feeder Line

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Received: 7 February 2017
Accepted: 9 October 2017

ABSTRACT

In recent years, the utility grid system is more essential for the power transmission and distribution system because it cannot produce harmful gases or no discharge waste in the environment. PWM based phase synchronous invert systems are generally utilised in the high efficiency energy supply, long distance and higher power quality. The inverter output voltage depends on the coupling transformer, input sources and invert controllers. An inverter using a three leg IGBT has been designed for utility grid and simulated by using MATLAB2014a. In this paper, both sides of the LCL filters are used for removing the DC ripple current, reducing the noise and synchronous the output phase between inverter and the utility grid. The PWM controller has created pulse signal to control the inverter, electronic switches and precisely synchronise with grid line frequency. In this system, the input DC voltage 500V, switching frequency 1.65 kHz, grid frequency 50Hz, 20 km feeder (resistance, inductance and capacitance per unit length, which are 0.1153, $1.05e^{-3}$ and $11.33e^{-09}$ ohms/km) with 30MW three phase load (active and inductive reactive power which are $30e^{6}$ W and $2e^{6}$ var) and also a balanced utility grid load of star configuration (0^{0}, 120^{0}, and 240^{0} degree) are considered in the design. On the other hand, three phase transformer consists of three signal phase transformers, normal power $100e^{3}$, magnetization resistance and inductance which are 500 pu and 416.67pu are considered in this design. The system conversion efficiency is 99.94% and 99.96%, while the total THD are 0.06% on inverter side and 0.04% on grid side.

Keywords: *PSI, controller, LCL filter, transformer and feeder*

INTRODUCTION

A utility grid system is limited as an open system of interconnected grid and micro-grid network systems likewise, fuel generator, solar cell, wind turbine, electrostatic generator, water turbine and so on, transfers it over a long and short distance, then take the energy down to the consumer over a distribution network (Zidar *et al.,* 2016). This system consists of commercial electric energy transmission and distribution system, energy storage and distributed generators that can operate on the national grid. Alternatively, these systems are using a sensitive and non-sensitive load feeder. The sensitive-load feeders are operated to supply continuous energy in the main grid network; so every feeder connected with the system should have a minimum number of micro sources to fulfil the inner feeder load. The non-sensitive-load feeders are connected when shut down in the system error or if there is a power quality problem with the grid networks (Banerjee *et al.,* 2016); (Rahman *et al.,* 2016).

Usually, there are different types of energy sources by using in the inverter input because it can be easily control, low cost, high efficiency and environment friendly. However, the number of renewable powered local area networks connected to the commercial utility grid has improved dramatically. These commercial systems have a wind turbine and solar modules by providing most of their energy, but still being interconnected to the utility grid. Utility grid connected systems, mostly operate commercial electric supply. In this technique, renewable energy produced in the wind turbines or solar cells that cannot be utilised directly is conducted to the utility grid. Nonetheless, the sunlight is directly converted into DC by using solar panels to convert AC (Rahman *et al.,* 2016). On the other hand, the wind system, generally wind passes through directly a big propeller blades to move the generator to produce the AC electrical power (Zhang *et al.,* 2016). Likewise, other energy sources are converted into electrical power to supply utility grids with the respective suitable techniques. Both processes generated less energy than is required for the additional energy from the utility grid.

Grid connected inversion system is a process that alterations DC to AC by means of a desired output voltage, frequency and phase. An electrical power inverter circuit can perform this type of alteration. The terms voltage-sustained is used as a part of reference to voltage electrical inverter circuits. A voltage-sustained power electrical inverter is one within that the DC input voltage is fundamentally consistent and free of the feeder current strained (Rahman *et al.,* 2014). Moreover, the PSI brings up the feeder voltage through the strained current structure is fixed by the feeder. The utility grid system inverters can create three various types of output waveforms such as square wave, close to a sine wave and pure sine wave. The square wave inverter is a simple type of power electrical inverter which output is a rectangle wave shape. Due to sharply rising and falling edges there are many noise involved in this wave. Though this type of inverter is simple in construction, low cost and high efficiency, but it offers poor power quality. When the power quality is not as a big issue, still this type of inverter used. The modified square wave has better power quality comparable to a pure square wave inverter. Its output is composed of many square waves with different amplitude. Due to reduction of the sharp rising and falling edges, it contains a less amount of noise and close to a sine wave, as a result the power quality and efficiency are improved. Its circuit is more complex and expensive, but better power quality compares to square wave inverter. This type of inverter is suitable for using small and medium systems (Choi *et al.,* 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. It has a small amount of noise regarding a very clean supply and 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, in addition, efficiency is poor. Its uses are highly preferred when needs a very clean and good power quality (Darwish *et al.,* 2010). The three phases, the inverter is turning out to be exceptionally appealing for commercial enterprise application systems because of their high current rating, high voltage rating, and high efficiency. In this inverter, the overall performance is very efficient because of the system produces less harmonic, switching loss and low cost. As the quantitative measure of level increases, the output voltage waveform is additionally increasing.

This paper proposes a new PWM based phase synchronous inverter topology appropriate for high voltage applications. PWM based phase synchronous inverters are characterised in discrete, powergui modes of process which allow lossless changing of the internal and snubber components by a suitable recirculation of net power. The IGBT electronic element does not connect in series with a current source, an inductor and an open circuit. On the other hand, snubber parameter is worked when use the powergui parameters to specify discretisation of the electrical circuit. The proposed design uses PWM technique is simply implemented without modification of the hardware. The commonly utilised over modulation systems are also easily implemented in the nominal time conception. In addition, providing a full description of the proposed design, simulation results in various operating principals are presented in this paper.

PWM BASED PHASE SYNCHRONOUS INVERTER

The PWM phase synchronous inverter is an electronic system that can be converted DC into AC voltage with appropriate transformer and filter. Figure 1 shows a PWM based PSI circuit block diagram that consists gate, input and output terminal. These systems are used in two input sources ($\pm 250V_{DC}$), one mutual point (0 point), ground resistance ($Rg=1\Omega$), three output terminals (V_A, V_B and V_C) and six IGBT switches with six gate pulses. The IGBT internal and snubber resistance ($Ron= 1e\text{-}^{03}\Omega$, $Rs =1e^{05}\Omega$) are used as the logic control switch for the PSI.

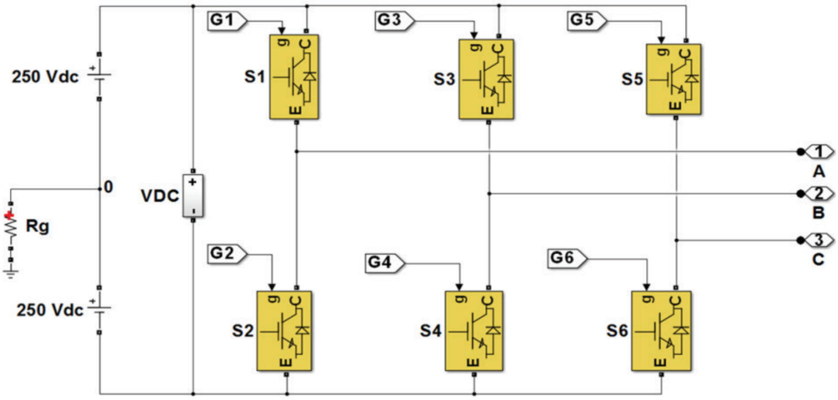
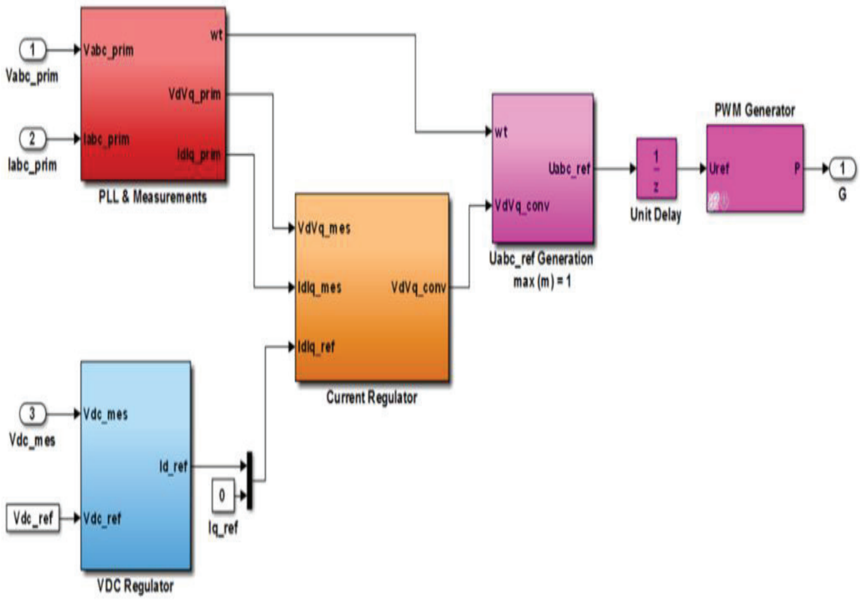


Figure 1: PWM Based PSI Circuit Block Diagram (source by author)

The advantages of the IGBT as switch, it can safely operate with 500V voltage, modulation one and 1.65 kHz switching frequency. However, at ON state the voltage across the device is zero volt and the OFF state the current in the device is zero Amp. In this design, the IGBTs is controlled by pulse width modulation (PWM) signal, therefore IGBT switches are remaining either ON or OFF states during its operation. As a result, there is no switching loss in the IGBT switch and the efficiency of the circuit will be improved.

DESIGN OF A PWM CONTROLLER

PWM controllers have been designed and simulated by using MATLAB2014a/ Simulink/ simpower block shows in Figure 2. The PWM design consists of VDC regulator, phase locked loop (PLL), abc to dqo park transformation, current regulators with feedforward and Uabc_reference generator are used correspondingly. There are eight switching state modes of method in a circle to make a three phase output voltage from the inverter. A group of switches is triggered at 120^0 phase apart, that is, 0^0, 120^0 and 240^0 respectively. A carrier based PWM method adopted two levels of topology. The Uref reference signal is generally sampled and compared by a symmetrical triangle carrier. Nonetheless, the carrier signal, less than the reference signal, the pulse signal for lower switching is low (0) and upper switching is higher (1). In this design, one reference signal is needed to create the two signal pulses and a second reference signal is needed to produce the two signal pulses of the second terminal. This signal pulses are internally created by phase-shifting the original reference signal by 120 degrees. For a three-phase system, three reference signals are essential to produce the six signal pulses. The reference signals are internally produced by the PWM generator. In this case, specify a voltage output frequency, phase and a modulation index.



Moreover, the PLL was utilised to synchronise on a set of adjustable frequency, sinusoidal signals. If the automatic gain control is acceptable, the phase error of the PLL regulator is scaled, allowing to the input signal magnitude and set regulator gains are Kp=180, Ki=3200 and Kd=1. In this design, the normal power (Pn=100e^3 Vrms phase to phase), V_{DC} regulator (gain Kp=7 and Ki=800), current regulator gain (Kp=0.3 and Ki=20) and fundamental frequency (50Hz) are considered for the control circuits.

OUTPUT LCL FILTER DESIGN

Different parameters are considered in an LCL filter designing which is filter size, switching ripple current and current ripple etc. In this system, LCL filters use both sides because inverter side LCL filters have been reduced, inverter DC ripple current and utility grid side filters are reduced higher harmonic distortion as shown in Figure 3. The capacitor resonance frequency may cause a resonance of the interacting with the grid requirements 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:

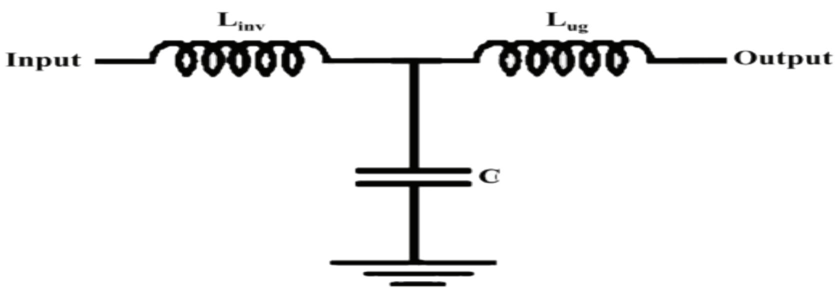


Figure 3: Single Phase LCL Filter Circuit

LCL filter value depends on a percentage of the base value (Rahman *et al.*, 2016) as the following equations:

$$Z = \frac{Vn^2}{S_n} \quad (1)$$

$$Z = \frac{1}{Z \times \omega} \quad (2)$$

The inverter side inductance Linv can be limit the current ripple of the output side which is 10% normal amplitude as in the following equations:

$$L_{inv} = \frac{V_{DC}}{16\, f_s \times \Delta I_L} \quad (3)$$

The grid side inductance Lug can be calculated as follows:

$$L_{ug} = r \times L_{inv} \qquad (4)$$

The control of the resonant frequency depends on a distance and one half of the switching frequency because some attenuation in the switching frequency of the inverter. The design of the LCL filter, resonant frequency can be calculated as in Equation 5:

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

Where,

Vn is the phase to phase RMS voltage
VDC 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 UTILITY GRID TRANSGORMER

Figure 4 shows the three phase transformer with two winding block diagram. This design consists of three single phase transformers and set the connection of the winding (Yn) and access the neutral point of the Wye. The main problem of the transformer are the fluxes are not identified, the initial values are automatically adjusted, therefore, the simulation starts in steady state.

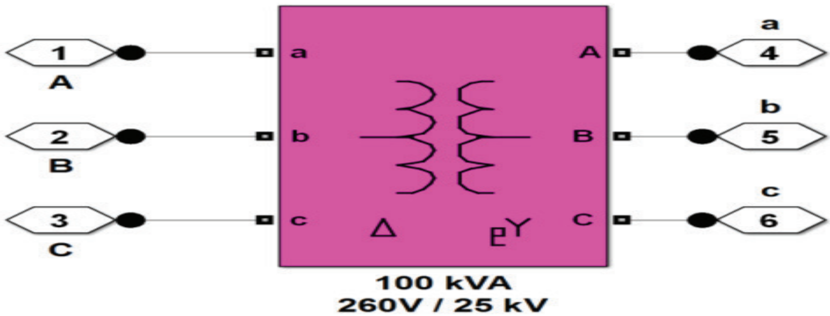


Figure 4: Matlab Block Diagram of the Utility Grid Transformer (source by author)

On the other hand, the leakage resistance and inductance of each winding are set in pu based on the winding nominal voltage (V1 or V2) and on the nominal power of the transformer (Pn). In this design, the primary winding parameters (V1=260Vrms ph-ph, R1=0.002028Ω and L1=0.00017H), the secondary winding parameters (V2=25000Vrms ph-ph, R2=6.25Ω and L2=0.5H), magnetisation resistance (Rm=3.125e^{+06} Ω), magnetisation inductance (Lm=8289.3h), power (Pn=100e^{3}VA) and utility grid frequency (50Hz) are considered in the circuits.

DESIGN OF THREE PHASE FEEDER LINE

Figure 5 shows the 20km three phase feeder line block diagram. This system consists 6km feeder with 2MW three phase load, 14km feeder with 30MW and 2Mvar three phase load, 47MVA transformer, grounding transformer and 120kv/2500MVA three phase source.

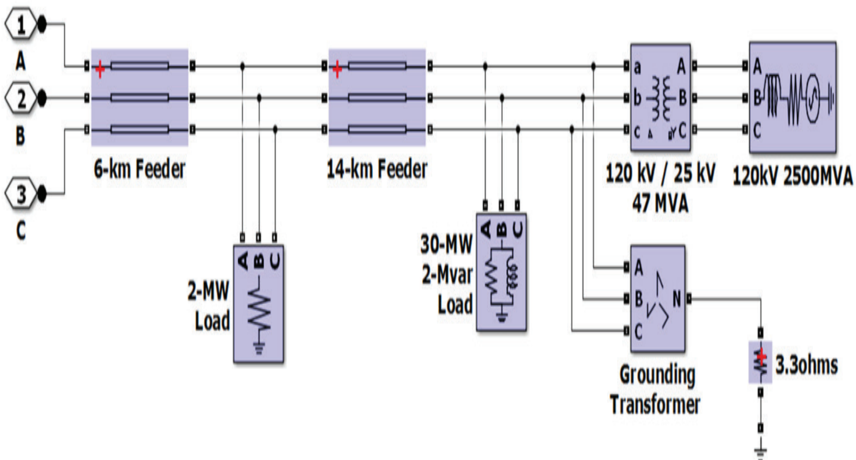


Figure 5: The 20km Three Phase Feeder Line (source by author)

In this design, number of phase (N=3), frequency for RLC specification (50Hz), resistance per length [[N×N matrix] or [r1, r0, r0m]= (0.1153, 0.413 Ω/km)], inductance per length [[N×N matrix] or [l1 l0 l0m]= (1.05e^{-3}, 3.32e^{-3} H/km)], capacitance per length [[N×N matrix] or [c1, c0, c0m]= (11.33e^{-009}, 5.01e^{-009} F/km)], line length (D=6km and 14km), normal phase to phase voltage (Vn=25e^{3}Vrms), active power (p=2e^{6}W and 30e^{6}W), inductive reactive power (QL=2e^{6}var) are measured in the circuits. On the other hand, capacitive reactive power is 0 because negative var.

RESULTS AND DISCUSSION

The simulation has been done using MATLAB2014a/Simulink/simpower block for a PWM based utility grid with transformer connected inverter. In this system, the input voltage ± 250V is converted into ± 172.8Vp-p AC. The three phase RLC load is measured to sustain unity power factor by simplifying the analysis.

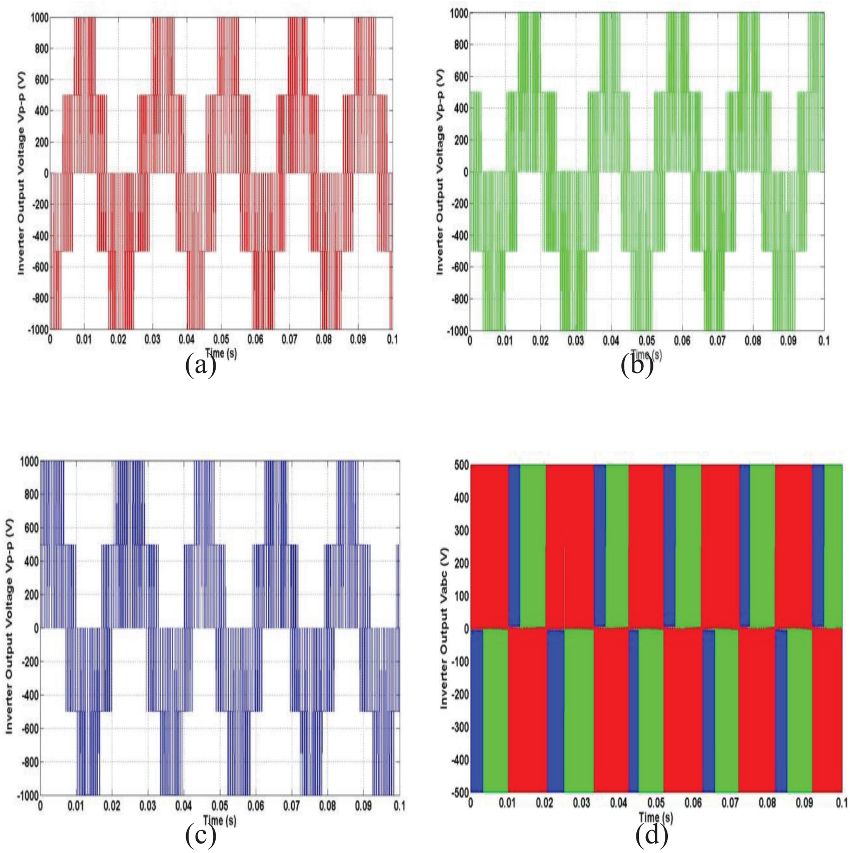


Figure 6: PWM Based Inverter Output Voltage Waveform for (a) V_{ab}, (b) V_{bc}, (c) V_{ca} and (d) V_{abc} without Filtering (source by author)

To generate PWM circuits, the switching frequency is 1.65Hz, the cut-off frequency is 33, sampling time 1e-05s and the sampling per cycle is 2000. Figure 6 shows the PWM based inverter output voltage without filtering. From the figure, a PWM based inverter output voltage is V_{ab}=V_{bc}=V_{ca}=1000V and fundamental frequency 50Hz respectively. Figure 6 shows the PWM based inverter output phase-to-phase current is around ±2 A, for the three phase RLC load of 10 kvar and fundamental frequency 50Hz.

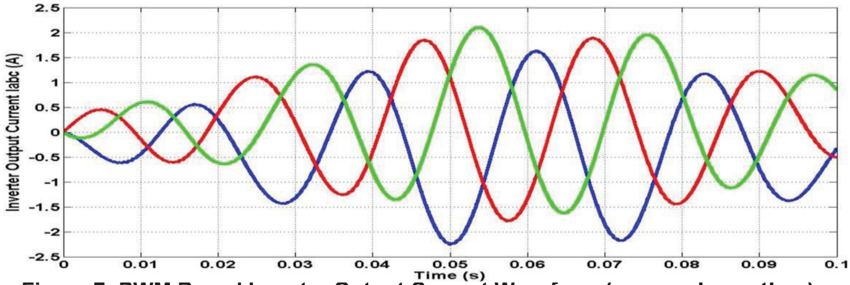
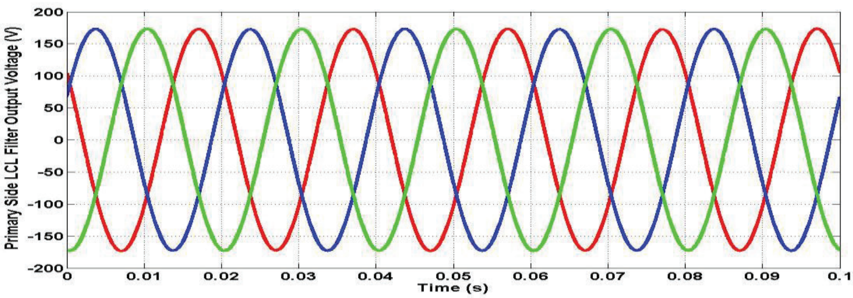


Figure 7: PWM Based Inverter Output Current Waveform (source by author)

Figure 8 and Figure 9 show the inverter side of the LCL filter phase-to-phase voltage and current output waveform which is around ±172.8Vp-p and ±2 A, for the three phase RLC load of 10 kvar, 100kVA/260/25kV transformer and fundamental frequency 50Hz.



(source by author)

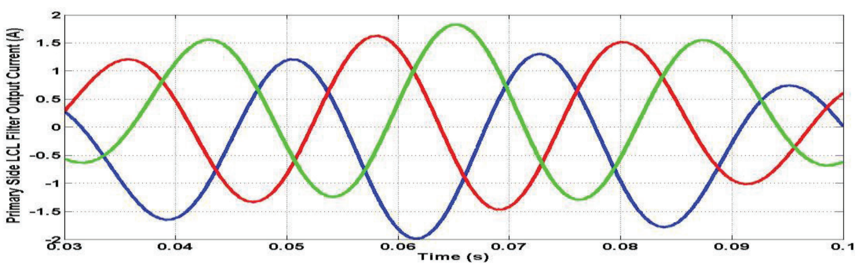


Figure 9: The Inverter Side of the LCL Filter Output Current Waveform with Filter
(source by author)

In this system, the voltage ±172.8V_{AC} converted into ± 2×104 kV AC. The LCL filter output voltage pulses pass through a transformer primary winding. The secondary winding are connected in the utility grid LCL filter which fundamentals the higher harmonic frequencies and generates the pure sinusoidal wave as shown in Figure 10 and Figure 11.

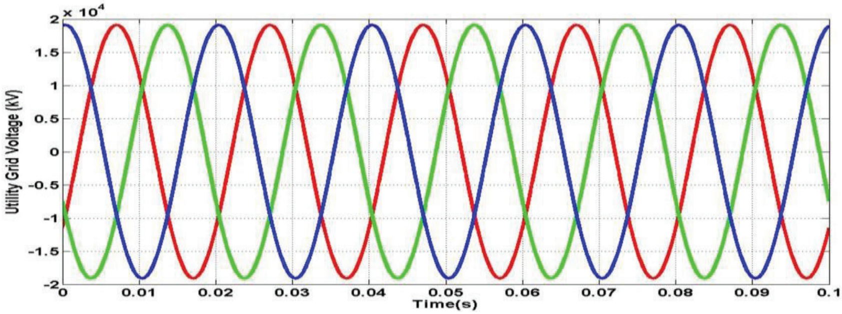


Figure 10: Utility Grid Voltage Waveform with Filter (source by author)

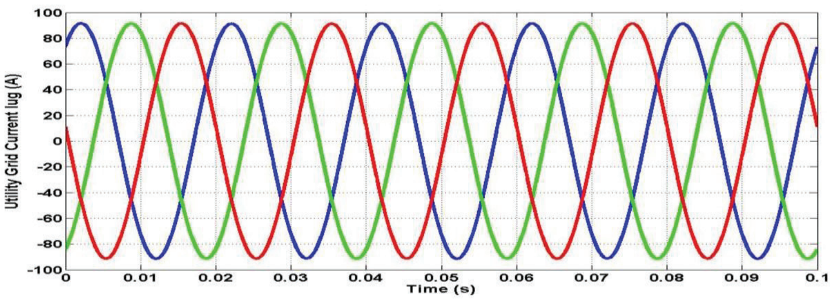
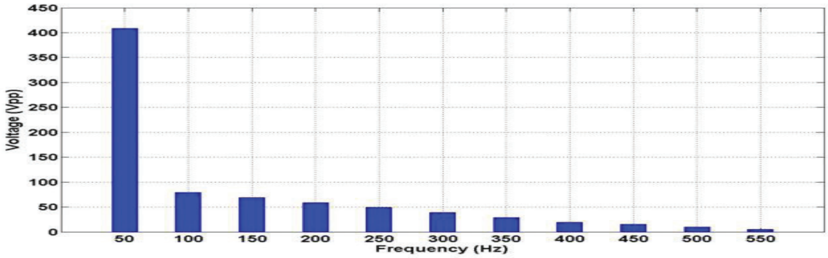
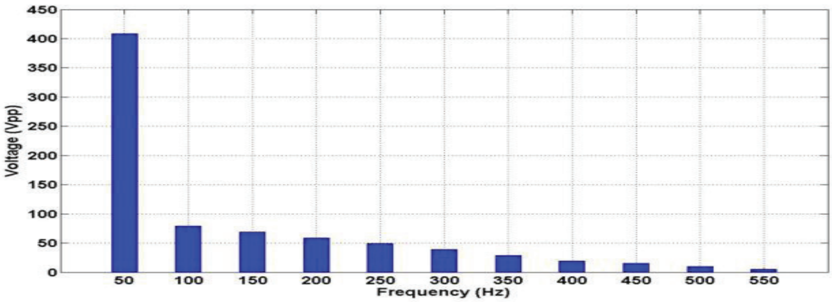


Figure 11: Utility Grid Current Waveform with Filter (source by author)

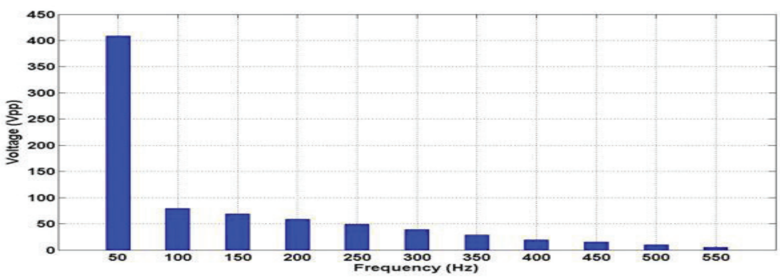
The simulated results shows the utility grid voltage and current is ±2e[04]kV and ±91.42 A phase to phase. Figure 12 shows the FFT analysis of the inverter output voltage without filtering. From the figure, it is found that the p-p line voltages, V_{ab}, V_{bc}, and V_{ca} are about ±409.4Vpp, ±398.9Vpp and ±408.9Vpp, and THD almost 34.5%.



(a)



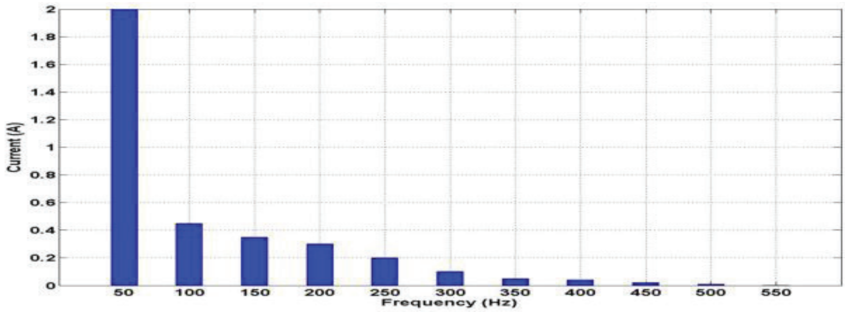
(b)



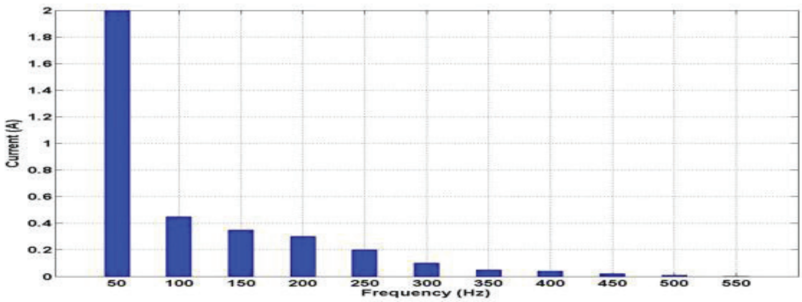
(c)

Figure 12: FFT for 3φ Inverter Output Voltage without Filtering V_{ab}, V_{bc} and V_{ca} (source by author)

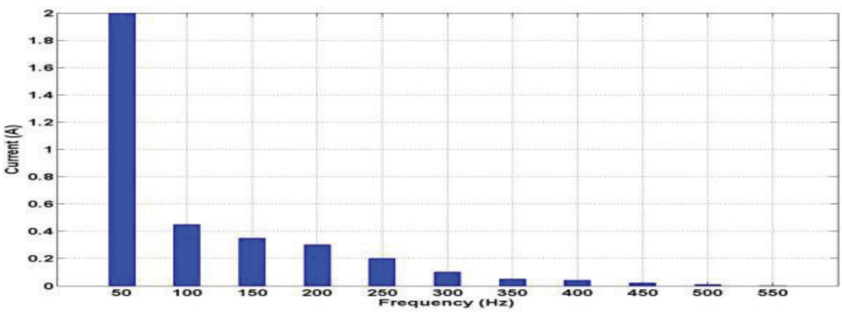
Figure 13 shows the FFT analysis of the inverter output current without filtering. From the figure, it is found that the p-p line current, I_{ab}, I_{bc}, and I_{ca} are about ±2A, ±1.9A and ±1.88A, and THD almost 35.37%.



(a)



(b)



(c)

Figure 13: FFT for 3φ Inverter Output Voltage without Filtering I_{ab}, I_{bc} and I_{ca} (source by author)

Figure 14 shows the FFT analysis of the inverter side LCL output voltage with filtering. From the figure, it is found that the p-p line voltage, $V_{ab} = V_{bc} = V_{ca} = \pm 173$Vpp and THD almost 0.06 %.

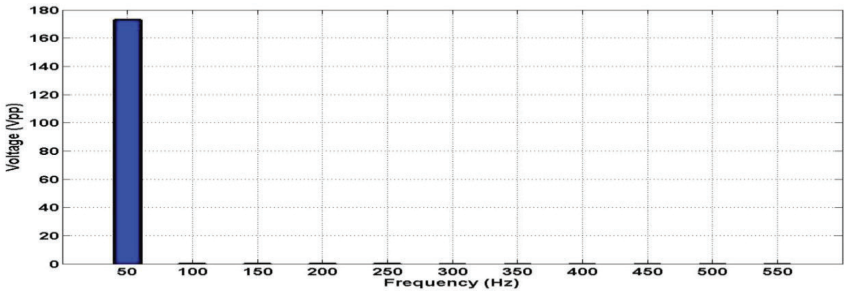


Figure 14: FFT for the Inverter Side Output Voltage with Filtering (source by author)

Figure 15 shows the FFT analysis of the utility grid voltage with filtering. From the figure it is found that the p-p line voltage, $V_{ab} = V_{bc} = V_{ca} = \pm 1.1911e^{04}$ kV and THD almost 0.04 %.

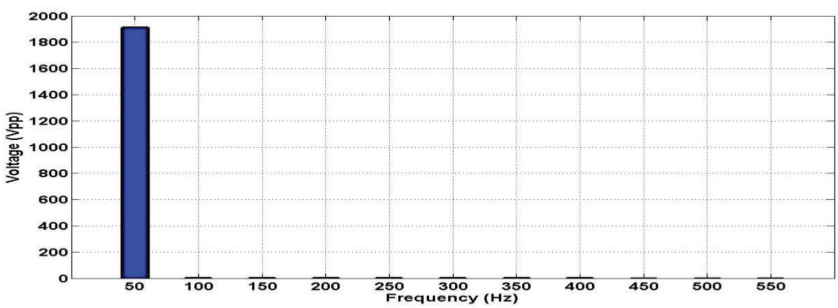


Figure 15: FFT for the Utility Grid Voltage with Filtering (source by author)

CONCLUSION

In PWM based PSI with LCL filter in interface circuit, mainly in pulse 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. But, the design became unable to avoid the reduction of the switching loss, same as utility grid phase by introducing a pulse controller based switching phenomenon which increases the overall system efficiency which is 99.96% and 99.94%. From the simulation results, the PSI system to reduce the switching loss and high frequency distortion. By using LCL filter both sides of the inverter and utility grid, the capacitor is $5.53e^{-06}$F and $1.02e^{-05}$F, the inductance is 1.84H and 0.996H which are reduced ripple current and also decrease the switching frequency which is 1.6 kHz. Therefore, this decreases the switching losses of the system to reduce the higher frequency harmonic distortion. Due to a PWM of the utility grid system with the connected 20km feeder line, simulation results show that the value of injecting current is at an acceptable level of IEEE standard. In other word, the THD ratio is limited to 0.04 % and 0.06%, which is lower than maximum permissible distortion as per requirements of IEEE standard (THD <5%). As the previous filter parameters of the system are reduced, more transferred power from the inverter to the utility grid load is gained.

ACKNOWLEDGEMENT

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

REFERENCES

[1] T. Rahman, M. I. Ibrahimy, S. M. Motakabber & M. G. Mostafa, 2016. Simulation and Evaluation of A Phase Synchronous Inverter for Micro-Grid System. In *The International Postgraduate Conference on Engineering Research*, pp 27-28.

[2] M. Zidar, P. S. Georgilakis, N. D. Hatziargyriou, T. Capuder & D. Škrlec, 2016. Review of Energy Storage Allocation In Power Distribution Networks: Applications, Methods And Future Research. *IET Generation, Transmission & Distribution, 10*(3), pp 645-652. DOI: 10.1049/iet-gtd.2015.0447.

[3] B. Banerjee, D. Jayaweera & S. Islam, 2016. Micro Grid Planning and Operation. In Smart Power Systems and Renewable Energy System Integration, pp 29-47. Springer International Publishing. DOI: http://dx.doi.org/10.1007/978-3-319-30427-4.

[4] T. Rahman, M. I. Ibrahimy, S. M. Motakabber & M. G. Mostafa, 2014, September. Three Phase Three Layer Phase Synchronous Inverter for Microgrid System. In *2014 International Conference on Computer and Communication Engineering*, pp 44-47. DOI: 10.1109/ICCCE.2014.25.

[5] W. Zhang, M. Armstrong & M. Elgendy, 2016. DC Component Detection in Grid Connected Inverter Systems, Using a Mid-Ground Low Pass Filter Approach. In *8th IET International Conference on Power Electronics, Machines and Drives* (PEMD, 2016), Glaslow, UK. DOI: 10.1049/cp.2016.0207.

[6] A. Darwish, Y. Wang, D. Holliday & S. Finney, 2016, June. Operation and Control Design of New Three-Phase Inverters with Reduced Number of Switches. In *International Symposium on Power Electronics, Electrical Drives, Automation and Motion* (SPEEDAM), pp 178-183. DOI: 10.1109/SPEEDAM.2016.7525993.

[7] W. Choi, C. Morris & B. Sarlioglu, 2016, February. Modeling Three-Phase Grid-Connected Inverter System Using Complex Vector in Synchronous Dq Reference Frame and Analysis on the Influence of Tuning Parameters of Synchronous Frame PI Controller. In *2016 IEEE Power and Energy Conference at Illinois* (PECI), pp 1-8. DOI: 10.1109/PECI.2016.7459235.

MS ISO/IEC 17021:2006
QS 12022007 CB 06
ISO 9001:2008 Certificate No. KLR 0404089

ISSN 1675-7009
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