Microcontroller Based Energy Controller for Grid Integrated DC Source in a PV System

Preprint · June 2016

DOI: 10.13140/RG.2.2.33002.70083

1 author:

Pubudu Sanjeewani
Griffith University

Microcontroller Based Energy Controller for Grid Integrated DC Source in a PV System

Sanjeewani T.G.P[#1], Wijeyarathne W.M.S.M.M[*2], Dharmasena G.T.S[*3], Ireshika M.A.S.T [#4]
[#]*Department of Electrical and Information Engineering, Faculty of Engineering, University of Ruhuna Galle, Sri Lanka.*
[1]sanjeewanipb@gmail.com
[2]menu.sri13@gmail.com
[3]gtsajith@gmail.com
[4]ireshika@eie.ruh.ac.lk

***Abstract* - It is a fact that most of the grid connected Photo Voltaic (PV) systems at present operate at maximum power points and inject power in an uncontrolled way. Therefore, it has become an urgent requirement in today's world to find a solution to this matter. A controlling algorithm capable of supporting instantaneous power balance, frequency control and thus maintaining the power quality of low voltage grid connected PV systems should be given attention in this regard. This report deals with designing a control algorithm for a single-phase grid-connected PV system in order to control the active and reactive power injected to the low voltage grid enhancing the power quality. In this project, a Voltage Source Inverter (VSI) fed from a PV source synchronized with a low voltage grid by using Phase Lock Loop (PLL) technology is used and it has to be developed further by adding an energy controller to produce a quality power output. The proposed energy controlling algorithm will be useful for the future smart grid system and also for building integrated PV based active generator systems and demand side management [1].**

***Keywords* - Voltage Source Inverter, Phase Locked Loop, Synchronization, PWM, Energy Controller**

I. INTRODUCTION

One of the prominent sources for renewable energy sources is the PV system. PV systems can perform double functions of active power generation and reactive power compensation. For this purpose, the proper power factor should be selected according to active power and reactive power demand of the grid. The existing PV systems can be modified to supply reactive power to the electrical grid when there is little or no solar radiation which will be useful for compensing the reactive power at peak hours when the main grid needs an amount of reactive power higher than average consumption.

This work proposes an algorithm for controlling active and reactive power for a grid tied single phase VSI. The major concern deals with the aspects of controlling both bidirectional active and reactive power fed from a DC source to the low voltage grid and vice versa At present, although there are VSIs which can be synchronized with the low voltage grids they are required to be developed in such a way that active and reactive power are controlled independently according to the load requirement. If there is not any controlling mechanism integrated with a low voltage grid tied VSI to handle the power injection, the quality of the power will also be very poor and some adverse effects like islanding effect can be taken place. Therefore, the introduction of a mechanism that can support instantaneous power balance, frequency control and maintaining the power quality with controllable power injection has grabbed the attention of most of the utility operators. When concerning a low voltage grid, there are three conditions under which a grid may operate. They are, the normal condition, harmonic condition, and non-harmonic condition. When designing the energy controller for the low voltage grid, these three conditions should be given special attention and care must be taken to avoid an unfavorable situation from the best of we can. There is also an adverse effect of the harmonics. When implementing the VSI it also needed to avoid harmonics as much as possible in order to minimize the total harmonic distortion. Also a grid is frequently subjected to the surges. Therefore, special attention should be given in order to eradicate such situations. The architecture of the implemented energy controller is shown in FIGURE 1.

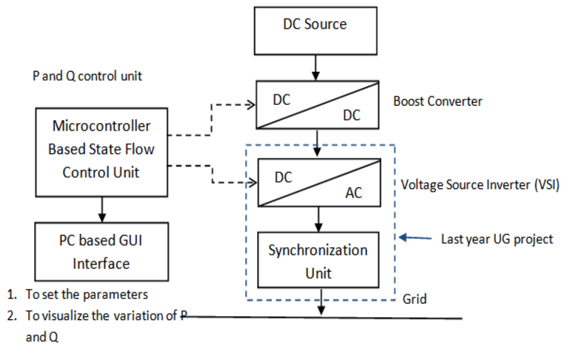

FIGURE 1: Architecture of the energy controller

To get maximum utilization of the power, we can couple them with the main grid system. This can be accomplished by a properly designed VSI with necessary filtering techniques. This project involves the production of a single phase VSI which is fed by a renewable energy source like solar energy and synchronizing the inverter with a low voltage grid.

I. DESIGN ANALYSIS

A device that converts DC power into AC power at desired output voltage and frequency is called an Inverter. A VSI is used for the design because it works better when interfacing with the renewable energy sources. Pulse Width Modulation (PWM) is the switching technique that has used along with the inverter. Here, the input DC voltage is constant in magnitude and the output frequency and the voltage is controllable. The objective of this project consists of basically three goals. First one is, designing the single phase VSI and then the second one is, synchronization of the inverter with the low voltage grid using PLL technique. The third goal is the design and implementation of the energy controlling algorithm. According to the requirement, the design of the inverter consists of 6 major circuit blocks as shown below.

1. Power supply circuit
2. Micro-controller unit (Arduino Mega 2560)
3. Isolator circuit (Optocoupler Driven)
4. MOSFET gate driver circuit
5. Full bridge MOSFET circuit
6. Filter circuit

The arrangement of these components can be illustrated as shown in the block diagram below.

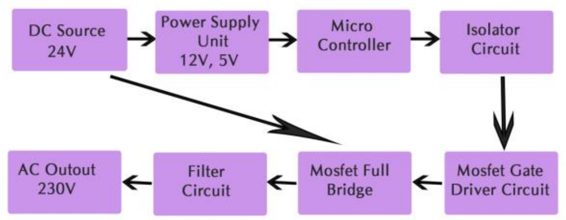

FIGURE 2: Block diagram representing the arrangement of components of the VSI

A 24V DC battery is used as the DC input to the VSI. The DC power required for other circuitry is also obtained from the same DC source. For that purpose, 12V and 5V DC outputs are required and this power requirement is fulfilled using a power supply unit. A microcontroller is used in order to generate the relevant PWM signal. This signal is fed to the MOSFET driver circuit through an isolator circuit. The MOSFET driver circuit drives the MOSFET full bridge and the output of the MOSFET full bridge is filtered in order to obtain pure sinusoidal output.

A. Power Supply Circuit

The power supply unit is used in order to distribute necessary voltage values to the circuits in the system. It is required to supply 5V, 12V and 9V for the relevant circuits. For that purpose, we have used LM series voltage regulators.

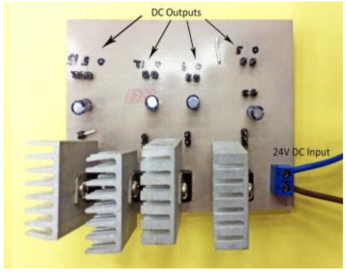

FIGURE 3: Practically implemented power supply unit

B. Micro-Controller Unit (Arduino Mega 2560)

Arduino Mega 2560 is used as the microcontroller board in the project for PWM generation and controlling purposes. The main function of the microcontroller is to generate the PWM signal which is required to switch the MOSFET full bridge.

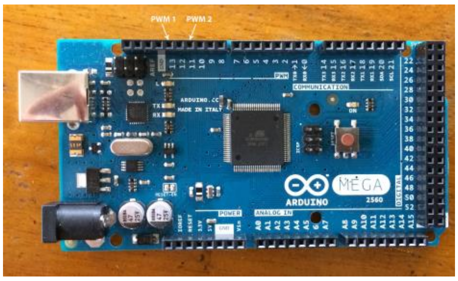

FIGURE 4: Arduino mega 2560 microcontroller unit

C. Isolator Circuit(Optocoupler Driven)

After generating a sinusoidal PWM signal using microcontroller circuit, this PWM signal should be fed to the MOSFET Bridge. Direct contact between the microcontroller and the MOSFET full bridge will be not safe. Therefore, in order to ensure a safe operation between these two devices, an isolator circuit built using TLP251 optocouplers is used.

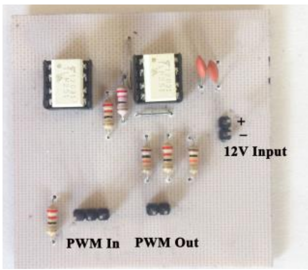

FIGURE 5: Practically implemented optocoupler isolator unit

D. MOSFET Gate Driver Circuit

Switching of a MOSFET requires a supply voltage to gate of minimum 10V with respect to source. The output of the isolator circuit is 12V. Therefore, it should be large enough to drive the MOSFET full bridge. In many situations, we are required to use a MOSFETs configured as high-side and low-side switches. One such situation is in bridge circuits. In half-bridge circuits, there are one high-side MOSFET and one low-side MOSFET. In full-bridge circuits, there are two high-side MOSFETs and two low-side MOSFETs. In such situations, there is a need to use high-side drive circuitry alongside low-side drive circuitry. The most common way of driving MOSFETs in such cases is to use high-low side MOSFET drivers. Undoubtedly, the most popular such driver chip is the IR2110 and it is used in this project as well.

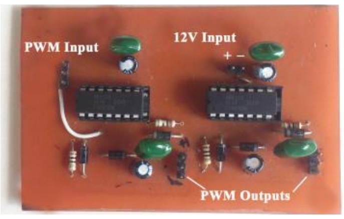

FIGURE 6: Practically implemented MOSFET gate driver unit

E. Bridge MOSFET Circuit

It is the full bridge topology that is used in our design. The type of power electronic switching devices used is the MOSFETs. Each leg of the MOSFET full bridge comprises of a pair of MOSFETs that work at same state while switched using bipolar switching technique. Power MOSFETs have the capability of operating at somewhat higher frequencies ranging from few kHz to several tens of kHz. But, they are having a limited power ratings; usually to 1000V, 50A. The type of the switching device used in the project work is IRFP460 MOSFET. The reasons for selecting this type of switching device are the low voltage, high current and high frequency switching which is about 40 kHz in this device. IRFP460 also possesses ratings of 500V, 20A at ambient temperature. This rating is more than enough to be operated at a healthy condition as we uses only 24V for the drain supply. But, the desired value of ac output voltage is 230V. For this reason, a step up transformer is used at the MOSFET bridge output. A boost converter can also be used to provide a drain voltage of about 315V where it is still operating at safe condition. This is because; the breakdown voltage of MOSFET is about 500V.

Arduino Mega 2560 microcontroller unit is used to generate the sinusoidal PWM signal which is required to drive the MOSFET bridge as well as the boost converter connected to the output of the PV source.

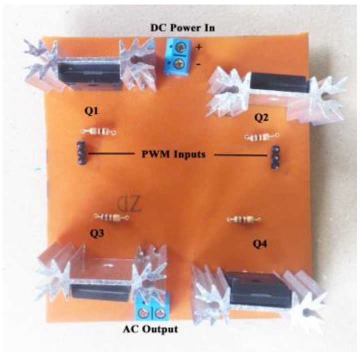

FIGURE 7: Practically implemented MOSFET full bridge

F. Filter Circuit

The direct output of a MOSFET full bridge contains harmonics. Hence, we are unable to obtain a pure sinusoidal waveform as the inverter output. Therefore, in order to obtain a pure sinusoidal output we are required to design a filter circuit. For our purpose, we have designed a low pass LCL filter circuit to obtain a pure sinusoidal signal of 50Hz. Since, a 31 kHz PWM switching signal is used low order harmonics will no longer appear in the inverter output. Therefore, it is little easy for the designing of the filter.

FIGURE 8: Practically implemented LCL circuit

G. DC to DC Converter Design

In order to ensure the quality of output power of the PV source and to control the DC voltage produced by the PV source, it is required to connect the PV source output to a DC to DC converter. It is the output of the DC to DC converter that should be fed to the VSI which is connected with the low voltage grid simultaneously. Further, for the purpose of controlling both active and reactive power injected from inverter to the low voltage grid and the power injected from low voltage grid side to the inverter, the circuitry should have the capability to flow power bi directionally. Therefore, in order to fulfil these requirements, a DC to DC converter is designed.

Boost converter consists of three major units as,

1) PWM Generation Unit: In order to generate the PWM signal, Arduino Mega 2560 is used as the microcontroller unit. PWM signal output from the arduino is a simple square pulse signal which has the capability of changing the pulse width.

2) Isolator Circuit (Optocoupler Circuit): Once a sinusoidal PWM signal is produced from the microcontroller circuit, the task becomes the connecting that signal to the switching MOSFETs. But, in order to ensure the safe operation of the devices, it is not recommended to have a direct contact between those two devices. At this point, the electrical isolator comes in to action. Therefore, we have designed an isolator circuit using TLP251 optocouplers.

3) Boost Converter: Boost converter consists of capacitor, inductor and a MOSFET as a switching device.

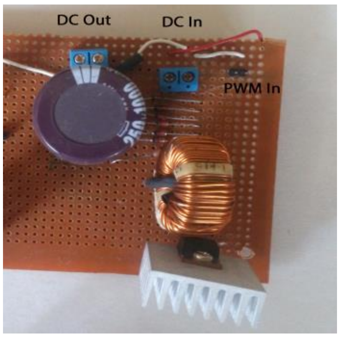

FIGURE 9: Practically implemented circuit of the boost converter

H. Designing a VSI Monitoring System

The project comprises of two major sections as the inverter side and the low voltage grid side. Since, voltage and frequency of the grid fluctuates frequently, the frequency and voltage of the inverter side should be adjusted in such a way that it matches the grid voltage and grid frequency. Software is designed in order to fulfil this requirement.

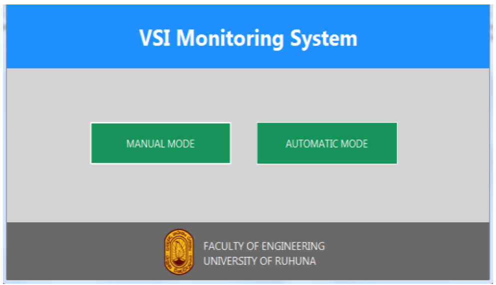

FIGURE 10: The interface of the VSI monitoring system

GUI (Graphical User Interface) is implemented to operate in two modes as, manual mode and automatic mode.

1. Manual Mode: In manual mode, interface is designed to input values for the frequency, voltage and power in order to get desired values at the inverter output. For example, when we in put a frequency value between 45 - 60 Hz, it will adjust the inverter output frequency to that value entered through GUI. Voltage can be changed within plus or minus 10% margin.

FIGURE 11: Interface of the VSI monitoring system for manual mode

2. Automatic Mode: In automatic mode, GUI automatically displays the frequency, voltage and phase difference values in the low voltage grid side and inverter side after synchronization is achieved.

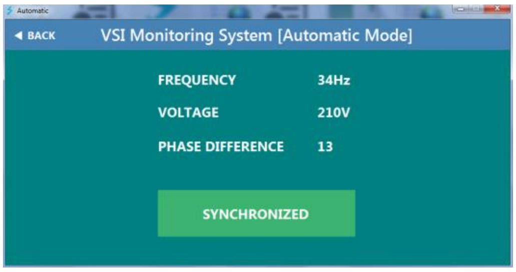

FIGURE 12: Interface of the VSI monitoring system for automatic mode

I. Synchronization using PLL Technique

In this context, the term, 'Synchronization' refers to the action of equating the voltage, frequency and phase angle of the inverter output with those of the grid. There are several synchronization methods like traditional zero crossing detection and phase detector based PLL algorithms.

Among several PLL synchronization techniques, PD based PLL method is used in our project to achieve proper synchronization between inverter and low voltage grid. For single-phase applications, the estimation of the amplitude, phase and frequency of the input signal precisely even under disturbances such as non-harmonic distortions has become the basic requirement. This could be easily achieved using PD based PLL method and thus it has become the choice of our project.

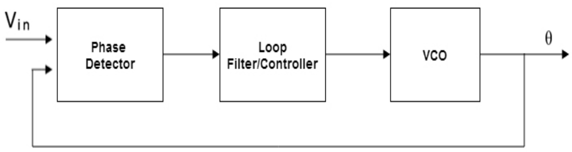

FIGURE 13: Block diagram for PD based PLL

In this context, VCO output signal refers to the inverter output signal and for the PD the CD 4046 IC. LF or the controller is the arduino 2560 microcontroller. The circuit involves a comparison of the phase of the input signal with the phase of the signal derived from its output oscillator thus adjusting the frequency of the oscillator to keep the phases matched. PD output signal is used to control the oscillator in a feedback loop. Frequency is the time derivative of phase. The action of keeping both the input and output phase in lock step implies keeping the input and output frequencies in lock step. As a result, it can track an input frequency or generate a frequency which is a multiple of the input frequency. Therefore, the PD based PLL is implemented in this project due to its better performance even under disturbances of the grid.

Synchronization is achieved when following three conditions of the inverter output are matched with those of the grid. They are the voltage, frequency and phase angle. Therefore, in order to achieve synchronization between inverter output signal and grid, it is required to implement the following circuits.

1) Voltage Detection: Voltage synchronization is achieved by sensing the grid voltage and inverter voltage through a 240/6 V step down transformer and then passing the transformer output through a voltage divider circuit which is connected to an arduino.

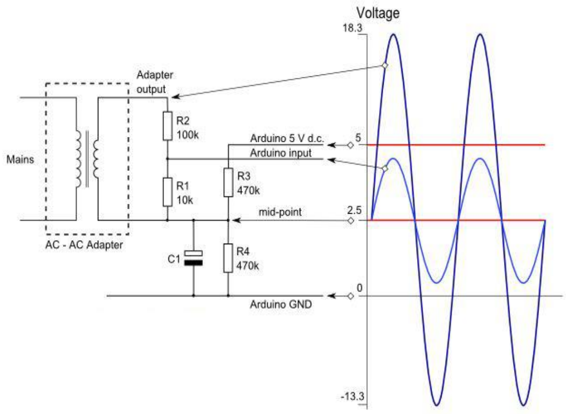

FIGURE 14: Block diagram of the voltage sensor

Resistors R1 and R2 form a voltage divider that scales down the power adapter AC voltage. Resistors R3 and R4 provide the voltage bias. Capacitor C1 provides a low impedance path to ground for the AC signal. Capacitance value between 1μF and 10μF is satisfactory for this purpose. We have used a 10μF capacitor in the voltage sensor in our project. As we are required to obtain a peak to peak voltage less than 5V in the sine wave which is input to the arduino, this set up is used. The output value from this circuit is input to the microcontroller and through an analog read and a suitable calibration voltage is calculated.

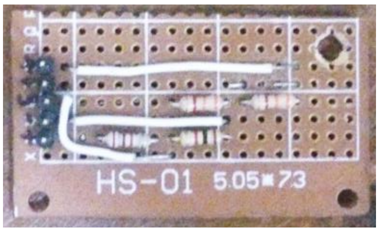

FIGURE 15: Practically implemented voltage sensor

We have implemented two such voltage sensors to detect voltages at the grid and the inverter output. During synchronization, both inverter and grid voltages become equal. A programme is written in arduino to increase or decrease the output voltage at the inverter by changing the duty of boost converter if it detects a difference between these voltages in such a way that these voltages are matched.

2) Frequency Detection: For frequency synchronization, we have used two main circuits to detect frequencies at grid and the inverter and to detect the phase difference between the two waves. As the first step, we are required to convert sine waves in to a square pulse. For that purpose, we use two comparator circuits using LM324 op amp.

The basic op-amp comparator produces a positive or negative voltage output by comparing its input voltage against some pre-set DC reference voltage. Since the inverting terminal is grounded the output wave is a square pulse which has a positive value during the positive half cycle of the sine wave and a negative value during the negative half cycle of the sine wave.

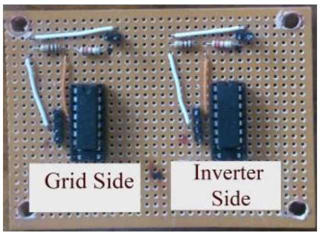

FIGURE 16: Practically implemented circuit for frequency detection

Two comparator circuits are implemented to convert the two sinusoidal signals from grid and the inverter. Those square waves are used to detect frequencies by counting the zero crossings using the microcontroller.

3) Phase Detection: For phase detection, a circuit made with CD4046 IC is used. The square pulses generated from grid sine wave and inverter sine wave are input to pin 14 and pin 3 respectively. The output is obtained from pin 2. The output is a square pulse whose duty is varied according to the phase difference of the two signals. When phase difference is 180 degrees, pulse width is maximum and phase difference will be zero if pulse width is at minimum. In this way, the PWM signal is input to the arduino and the pulse width is detected in order to detect the phase difference between the two signals.

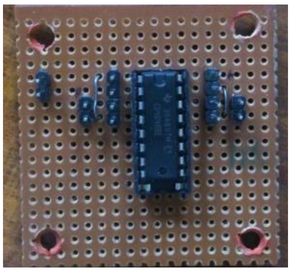

FIGURE 17: Practically implemented circuit for phase detection

J. Active and Reactive Power controlling

Load angle controlling method of power controlling is used for controlling power in this project. The implemented control strategy would be cost effective and simple. The implemented energy controller controls active power by changing the load angle and the reactive power by changing the inverter output voltage magnitude.

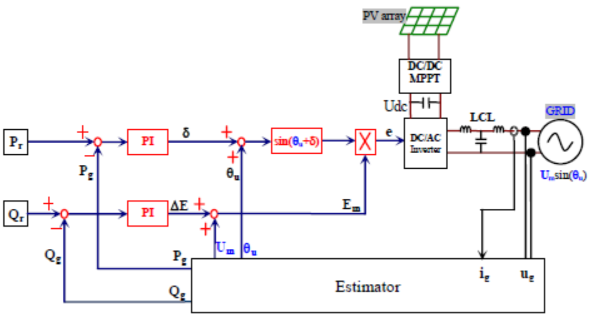

FIGURE 18: Control structure for a single phase grid connected PV system

FIGURE 18 is an illustration of the implemented control structure of the single-phase inverter connected to the low voltage grid in this project. It consists of a PV generator, a DC/DC converter, a single phase inverter and an active and reactive power controller. The control circuit is comprised of two parts as the active power controller and the reactive power controller. The first one controls the active power injected into the grid by the load angle and the second one controls the reactive power through the inverter output voltage magnitude E. The implemented control structure shown in FIGURE 18 compenses the reactive power injected into the grid (Qg) and compares it with its reference (Qr) thus originating an reactive power error. This error is passed through a PI controller and it is added to grid voltage amplitude (Um~const) resulting the inverter output voltage amplitude (Em) [2]. The controller produces the active power generated by the inverter (Pg) and compares it with a reference signal (Pr) thus generating an active power error. This error passes through another PI controller originating reference load angle (δ). The load angle gets added to grid voltage phase angle (θu) thus generating inverter output voltage phase angle (δ + θu). The inverter output voltage amplitude (Em) is multiplied by sin (δ + θu) resulting the instantaneous value of the inverter output voltage (e), the DC/AC inverter reference signal [2]. The grid voltage:

$$u = Umsin(\omega t) = Umsin(\theta u) \qquad (1)$$

and

$$\delta \sim P \qquad (2)$$

and

$$\Delta E \sim Q \qquad (3)$$

Inverter output voltage:

$$e = Emsin(\delta + \theta u) \qquad (4)$$

where:

$$Em = Um + \Delta E \qquad (5)$$

As it is seen from equation (2) and (3), active power is proportional to the load angle (δ) while reactive power is proportional to the difference between inverter output voltage and the fundamental component of utility grid voltage (ΔE). Hence, active power can be controlled by changing the load angle and the reactive power can be controlled by changing the inverter output voltage magnitude.

In order to implement active power controlling, several loads are connected to the inverter output. For example, when a 3W bulb is connected across the inverter output, it draws active power from the inverter thus increasing the load angle. If another load is connected across the inverter output which should also be supplied with same capacity as for the previous load, the load angle will decrease further. In order to keep the frequency unchanged, the source (inverter in this case) should supply more power to the load. Therefore, if active power controlling is achieved, the frequency of the system would slightly deviate from the desired value when increasing the number of loads and it would come to the desired value after some time. This would happen when the inverter starts supplying power to the load once the active power requirement is increased.

In order to implement reactive power controlling, a load drawing reactive power, for example a fan is connected across the inverter output. Thus, it would increase the difference between inverter output voltage and the fundamental component of utility grid voltage (ΔE) as reactive power is proportional to E. Thus, the inverter should supply more power to the load to reset the voltage difference. Therefore, if reactive power controlling is achieved, it would increase E and after some time, it would reset the initial voltage difference between inverter and the grid.

This control strategy would be advantageous in many ways due to its simplicity related to the computational requirements of the control circuit and hardware implementation allowing controlling not only an active power needs to be injected but also a reactive component.

III. RESULTS

We have tested the inverter, the boost converter etc. in the Department Laboratory. The following figures are some screen shots of the results we have obtained from the oscilloscope. FIGURE 19 shows the output waveform of the inverter.

FIGURE 19: Output waveform of the VSI

When observing FIGURE 19, it could be seen that a pure sinusoidal waveform is obtained at the inverter output.

In FIGURE 20, 21 and 22, it denotes SPWM waveforms obtained for different pulse widths.

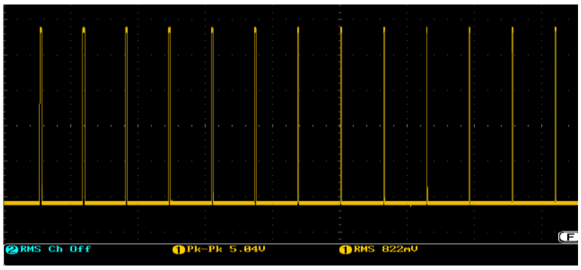

FIGURE 20: SPWM waveform for pulse width 1

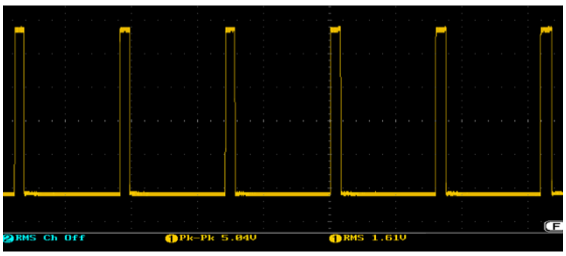

FIGURE 21: SPWM waveform for pulse width 2

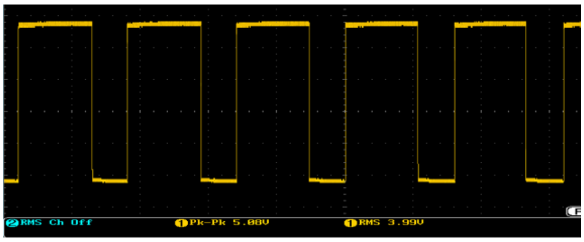

FIGURE 22: SPWM waveform for pulse width 3

In FIGURE 23, it denotes the SPWM waveform and the complement of the SPWM waveform.

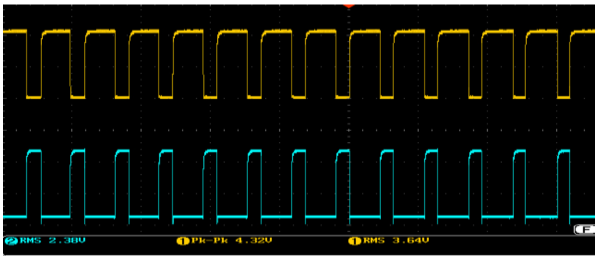

FIGURE 23: SPWM waveform and the complement of the SPWM waveform

FIGURE 24 denotes the sinusoidal signal input to the comparator circuit with output square waveform obtained from the comparator circuit which used for synchronization purpose.

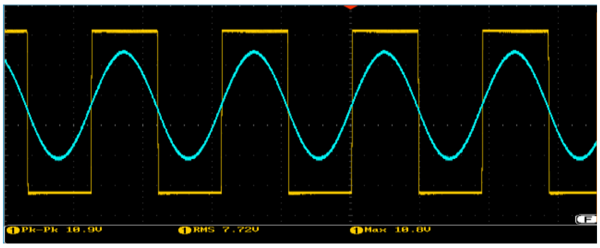

FIGURE 24: Sinusoidal signal input to the comparator circuit with square waveform output from comparator circuit which is used for synchronization

The waveform denoted in blue colour in FIGURE 24 is the input sinusoidal signal to the comparator circuit while the yellow colour square waveform is the output waveform from the comparator circuit.

The observed waveforms at inverter output, in utility grid and at CD4046 IC output are shown in FIGURE 25.

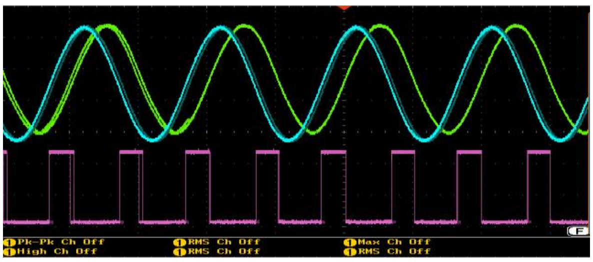

FIGURE 25: Inverter output waveform, grid waveform and CD4046 IC generated square waveform

The blue colour sinusoidal waveform in FIGURE 25 denotes the inverter output signal and the green colour sinusoidal waveform denotes the low voltage grid signal.

The purple colour square waveform situated below is the square waveform generated from CD4046 IC. When observing the square waveform, it could be seen that there exist a phase difference between inverter output and utility grid signal. Inverter output waveform, grid waveform and CD4046 IC generated square waveform observed during an instant where the system has gained synchronization are shown in FIGURE 26.

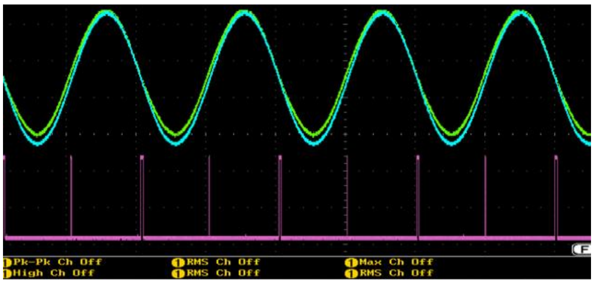

FIGURE 26: Inverter output waveform, grid waveform and CD4046 IC generated square waveform during synchronization

When observing the square waveform in FIGURE 26, it can be seen that the pulse width of the waveform is at minimum. Therefore, it can be concluded that at this instant, there does not exist any phase difference between the two waveforms. Also it can be seen that the sine waves coin side. Thus, at this instant, the grid and the inverter output signal have achieved synchronization.

IV. CONCLUSIONS

In this way, we could implement a single phase full bridge inverter having an output voltage of 230V and a frequency of 50Hz. Also we could develop a method to synchronize the inverter output with low voltage grid. By taking all these into account, we can identify a VSI as a very useful device to convert DC voltages of renewable energy sources to AC utility voltage for domestic usage. Not only that, PLL method of synchronizing can be identified as the most appropriate synchronization technique that can be used when connecting an inverter with a low voltage grid. Furthermore, the voltage controlling method of power controlling can be stated as one of the optimum methods of controlling active and reactive power injected into the low voltage grid and vice versa. This inverter control strategy is not only capable to control the active power, but also dynamically reconfigured to change the magnitude of the reactive power injected into the grid. Thus, the voltage controlling method can be ranked in the foremost place when compared with other energy controlling methods like current controlling method and the method of frequency droop characteristics.

Acknowledgment

We are very much thankful to Dr. P. D. C. Perera, Dean of Faculty of Engineering, University of Ruhuna, who gave us the opportunity to initialize the undergraduate project and we are so indebted to Dr. S.H.K.K. Gunawickrama, Head of the Electrical and Information Engineering department for providing us a clear guidance about the way of selecting the suitable projects, report writing skills, and presentation skills as well as the allocation of required equipment and premises. Also our sincere gratitude goes to Mr. E.H. Jayatunga, the module coordinator of the undergraduate project for his guidance to carry out the research work and to be familiarizing with it. We would be very much thankful for Mrs. M.A.S.T. Ireshika, the project supervisor of our project for giving us necessary instruction and guidance in order to make our project a success. Also, we are so grateful to Mr. K.M.S.Y. Konara, as our core supervisor of the project who provides his valuable time for our project work to achieve our target in success and his valuable thoughts and guidance in both subjective and documentary part when carrying out the work. Further our sincere graduate is extended to all the academic and non-academic staff of the Department of Electrical and Information Engineering for their incomparable services to achieve our target. Last but not the least, we would like to thank everyone who helped us a lot in gathering different information, data and guiding us from time to time in making this project despite of their busy schedules, they gave us their support in making this project.

References

[1] Aimie Nazmin Azmi, Mohan Lal Kolhe, Photovoltaic Based Active Generator: Energy Control System Using State flow Analysis.

[2] Tran Cong Binh, Mai Tuan Dat, Ngo Manh Dung, Phan Quang An, Pham Dinh Truc, Nguyen Huu Phuc, Active and reactive power controller for single-phase grid- connected photovoltaic systems, Feb. 2009.

[3] Xiangdong Zong, Peter W. Lehn, Reactive Power Control of Single Phase Grid Tied, IEEE Trans.

[4] Nader Anani, Omar Al-Kharji AlAli, Mahmoud Al-Qutayri, Saleh AL-Araji, (2012): Synchronization of a renewable energy inverter with the grid,American Institute of Physics.

[5] Guan-Chyun Hsieh, James C. Hung, Phase locked loop techniques, IEEE Trans. Industrial Electronics, vol. 43,pp. 6, 1996.