Solar Grid-Tied Inverter, with Battery Back-up, for Efficient Solar Energy Harvesting

Danish Hameed, Saad Hamayoon, Asad Ali Malik
School of Electrical Engineering and Computer Sciences
National University of Sciences and Technology
Islamabad, Pakistan
e-mail: {12beedhameed, 12beeshamayoon, 12beeaamalik}@seecs.edu.pk

Osama Aslam Ansari
Department of Electrical Engineering
University of Saskatchewan
Saskatoon, Canada
e-mail: oa.ansari@usask.ca

Abstract—**Solar Grid-Tied Inverter system is an electricity generating system that is connected to the utility grid. This paper discusses the design of a Grid-Tied Inverter (GTI). The first stage is Maximum Power Point Tracking (MPPT) which is implemented using perturb and observe algorithm. Then push-pull converter is used to convert DC output from MPPT stage to 330V dc. This DC voltage is then converted into AC voltage using full-wave inverter topology employing unipolar SPWM technique. Then synchronization is achieved between grid and photovoltaic system. Finally, power flow control mechanism controls the power flow from GTI system to the grid and the house load.**

Keywords-grid-tied inverter; SPWM; power flow; MPPT

I. INTRODUCTION

Solar energy is gaining importance day by day while world population and consequently, power demand is increasing. To cater the ever increasing power demand, solar energy could prove to be really effective, especially in countries like Pakistan, where we have longer hours of sunshine and summer takes up major part of the calendar. Moreover, the production of electricity through fossil fuels has increased air pollution globally to an alarming extent. Carbon Dioxide and oxides of sulphur and nitrogen, commonly called SO_x and NO_x respectively, are inadvertent products of combustion process. On the other hand, solar energy is clean and renewable and abundantly available to us in the form of sunlight.

Earth intercepts a large amount of power from the sun, 173,000 terawatts. That's 10,000 times more power than the world population uses. It's up to us to devise efficient mechanisms to utilize this intercepted power. One way is to use solar panels to convert the energy of photons into electrical energy and after storing some of it as back-up power, supply the rest of it to the power grid. The different stages of a grid connected photovoltaic system will be discussed here.

II. MAXIMUM POWER POINT TRACKING

Maximum power point tracking is a technique used to improve the efficiency of PV (photo voltaic) systems by extracting maximum power available from them at all times irrespective of the temperature and irradiance conditions.

The PV systems when connected directly to the load result in poor efficiency of the system, so MPPT is required to improve the efficiency of the systems. MPPT is not a mechanical system, it is based on the maximum power transfer theorem and it matches the source (PV systems) and load impedance electronically by using dc/dc converter.

There are different techniques to track maximum power point. The most popular techniques available for MPPT are Perturb and Observe and Incremental Conductance.

The technique employed is Perturb and Observe method because this technique is simpler and efficient whereas Incremental Conductance method is not simpler because of its complicated judgment procedure.

The general working of the algorithm is displayed in the flowchart below (Fig. 1):

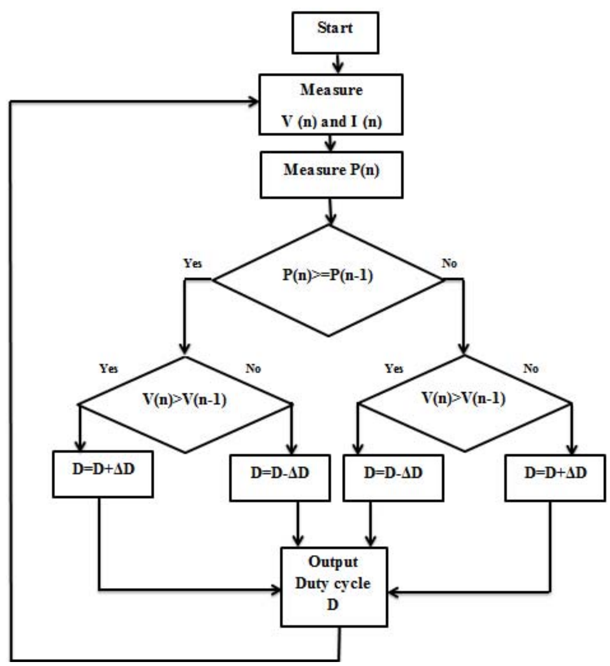

Figure 1. Perturb and observe algorithm.

The method is based on the power difference of n^{th} and $(n\text{-}1)^{th}$ iterations. If the difference is positive i.e. power has increased then the perturbation is continued in the same direction. If the difference is negative i.e. power has decreased then the perturbation is done in the reverse direction.

There are many types of dc/dc converter available for MPPT but most commonly used are Buck, Boost, Buck-Boost, and Cuk converter.

Cuk converter is used in this design. Cuk converter can both buck and boost the voltage and it requires a low gate drive. Cuk converter uses capacitor as the primary source of storing and transferring energy from input to output. This causes energy transfer to occur during both on and off gated switch intervals.

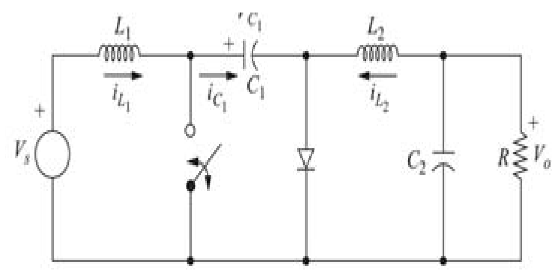

Figure 2. Cuk converter [1].

III. Inverter Stage

A. Idea of Design

A conventional inverter converts DC supply to AC supply with the help of switching signals. The switching or control signal may be a Pulse Width Modulation PWM signal or in case of the requirement of a pure sinusoidal wave, can be Sinusoidal Pulse Width Modulation SPWM signal. An inverter design consists of a power circuit part and a control circuit part. The power circuit consists of four switches, in case of a single phase inverter and six switches in case of a three phase inverter. The control circuit of an inverter is rather more important and controlling mechanism determines the output generated by the inverter.

Using SPWM control signals, the switching technique may be unipolar or bi-polar. The unipolar switching technique generates an output waveform that is completely positive for the positive half cycle and is completely negative for the negative half cycle. But in case of bipolar switching technique, both the half cycles consist of positive and negative signals. The unipolar technique produces dominant harmonics at $2m_f \pm 1$, $2m_f \pm 3$ as compared to the bi-polar technique which produces these harmonics at m_f, $m_f \pm 2$, $m_f \pm 4$, where m_f is the frequency modulation index which is basically the ratio of switching frequency and the desired AC signal frequency. Since the unipolar technique produces harmonics at higher frequencies, it is easier to extract pure sinusoidal wave from the inverter output and the proposal design will employ the unipolar switching technique.

The control circuitry is either built from analog components like op-amps, comparators, etc. or from digital micro-controller or even a combination of both but the proposed design will solely use a micro-controller for generating the required control signals.

A grid-tied inverter is different from a conventional inverter or a variable speed controller in the sense that its output needs to follow some rules or requirements in order to get connected with the power grid. The following requirements are a must and need to be fulfilled before getting connected with the grid [2]:

- The voltage magnitude of the inverter output must be equal to that of the grid.
- The phase of the inverter output must match with that of the grid.
- The frequency of the inverter output must be equal to the grid frequency.
- Phase sequence must be the same.

The fourth requirement is significant for three phase systems only. Since the proposed grid-tied inverter system is single phase, the last requirement is not of the essence.

After getting connected with the power grid, the next step is to make the power flow from inverter to the grid. The flow of real as well as reactive power is important for maintaining the required voltage levels. Real and reactive power flow from GTI to the grid is governed by the following two equations [3]:

$$Real\ Power,\ P = \frac{|V_{inv}||V_{grid}|}{Z_t} sin\theta \quad (1)$$

$$Reactive\ Power,\ Q = \frac{|V_{inv}|^2}{Z_t} - \frac{|V_{inv}||V_{grid}|}{Z_t} cos\theta \quad (2)$$

where,

V_{inv} = Inverter output voltage
V_{grid} = Grid voltage
Z_t = Impedance of the linking line
θ = Angle between V_{inv} and V_{grid}

From equation 1, it is clear that the value of $\sin\theta$ can be positive as well as negative. The direction of real power flow will be from inverter to the grid if V_{inv} leads V_{grid} and will be opposite otherwise.

B. Proposed Design

The proposed design's power circuit is the conventional inverter circuit with four MOSFETs being used as switches while the control circuit consists of a digital micro-controller that generates control signals not only for synchronization but for power flow as well. A total of four gate signals are generated for the four MOSFETs. When G1 is turned on and G2 is provided SPWM while keeping G3 and G4 OFF, during one half cycle, a positive output voltage is generated across the load. Similarly, when G3 is turned on and G4 is provided SPWM while keeping G1 and G2 OFF during other half cycle, a negative voltage is generated across the load. Same output can be obtained by generating only two SPWM gate signals and supplying one of them to G1 and G2, and the other one to G3 and G4 but this would increase the switching losses which may be reduced by generating four gate signals and applying to the gates in the right sequence, as discussed above. The output of the inverter, before filtering it out to obtain pure sinusoidal wave, is shown in Fig. 4. [4]

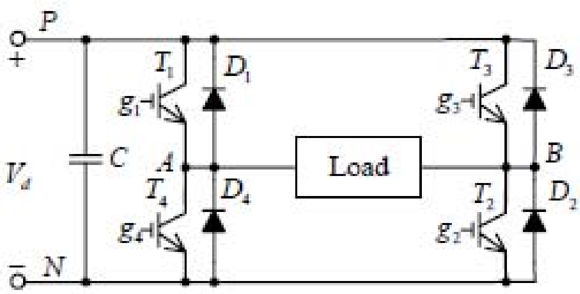

Figure 3. Full wave inverter topology [1].

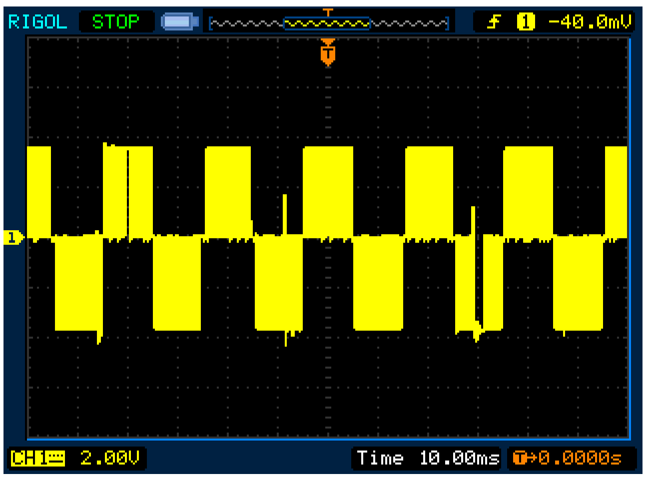

Figure 4. Inverter output before filter

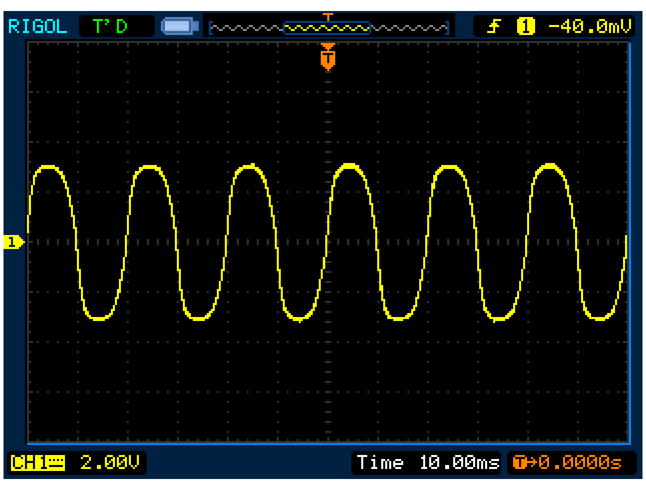

Figure 5. Inverter output after filter.

IV. SYNCHRONIZATION

A. *Monitoring of Voltage and Frequency*

Since the output voltage and frequency of the GTI should be in accordance with the grid voltage and frequency, therefore grid voltage and frequency are continuously monitored. The grid voltage is measured using op-amp as difference amplifier to step down the AC voltage from 220 volts to less than 5 volts. This low voltage is fed to the micro-controller that computes the grid voltage using gain of the difference amplifier. Likewise, the grid frequency is measured by using zero-crossing detection technique that employs an opto-coupler to generate a momentary pulse at zero crossing. These pulses are fed to the controller's external interrupt pin to determine the frequency.

B. *Voltage Matching*

For synchronization, the output voltage, phase and frequency of GTI have to be adjustable so that grid voltage, phase and frequency may be followed. The technique employed here is simple and intuitive, and does not involve a PLL circuit. In order to reduce the output voltage, the values in the sine table for SPWM generation are all divided by a certain factor (greater than 1). Thus the ON time of switches decreases and consequently, output voltage reduces. Same technique may be employed to increase the output voltage.

C. *Frequency Matching*

In order to vary the output frequency, the number of values in the sine table are varied. For instance, to increase the output frequency, sine table is reduced to fewer values. This decreases the time required to complete a sinusoidal cycle and thus, output frequency is increased. Same procedure may be adopted to decrease the output frequency.

D. *Phase Matching*

Instead of using a phase shifter circuit for varying the phase of output voltage, the proposed design manipulates the sine table for phase matching and therefore, does not include any additional circuitry for this purpose. Since the sine table is in the form of an array, the phase of output voltage may be varied by starting to read the array from an index other than zero. Starting to read the index from a non-zero value, for instance 10, would result in a certain phase delay of the output voltage and in this way, phase matching may be achieved.

V. POWER FLOW

Synchronization is achieved as soon as the magnitude, phase and frequency of output voltage are matched with the corresponding parameters of the grid voltage. In this situation, there is no power flow from GTI to the grid as shown in figure 9. The next step is getting the power to flow from GTI to the grid. This may be achieved by increasing the voltage magnitude a bit and getting the phase of inverter output to lead the grid voltage in order for both the real and reactive powers to flow into the grid, as per the given equations. Increment of output voltage and getting it to lead the grid voltage are achieved with the help of methods described in the synchronization part.

VI. RESULTS

A MATLAB simulation is designed to illustrate the power flow by varying the phase of output voltage. The Simulink circuit diagram consists of two AC supplies, one simulated as GTI output and the other one as grid supply. Equal resistive load is connected to each of the two AC supplies and an inductor is connected between them to cater for the impedance of matching line. The power flow through the inductor is studied to demonstrate the power flow from inverter to the grid.

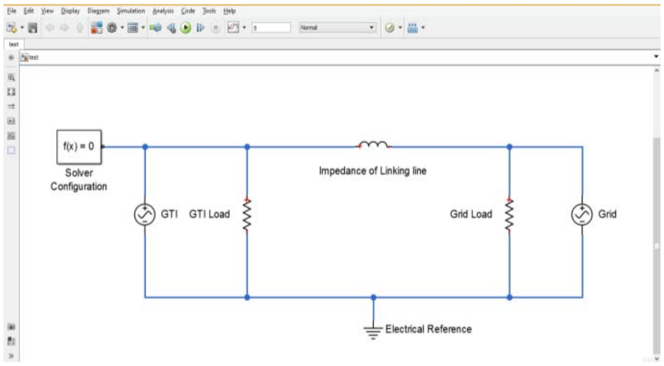

Figure 6. Simulink circuit to demonstrate power flow.

Initially, the voltage, frequency and phase of both supplies is matched. The power delivered by GTI, grid and power through inductor are shown in figures 7, 8 and 9 respectively.

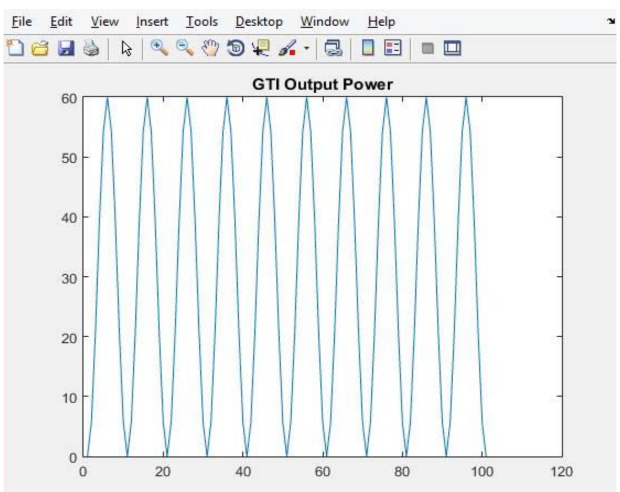

Figure 7. GTI output power.

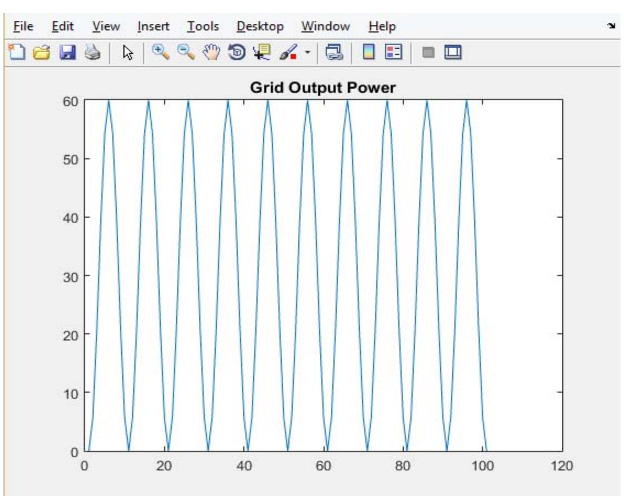

Figure 8. Grid output power.

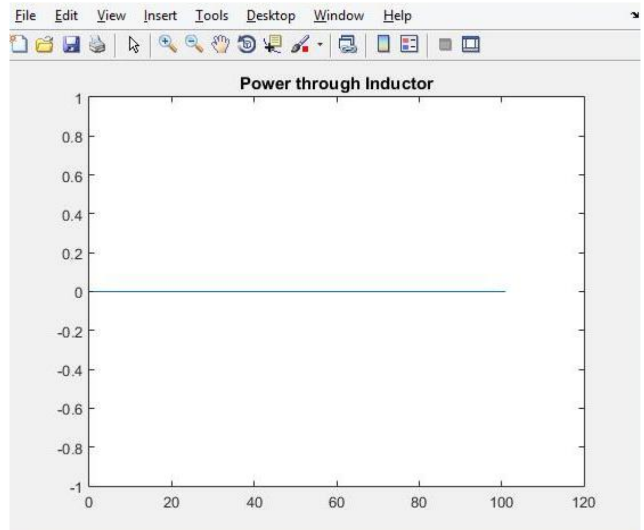

Figure 9. Power through inductor.

Now the phase of GTI is made to lead that of the grid by 5 degrees and the results are shown in figures 10,11 and 12.

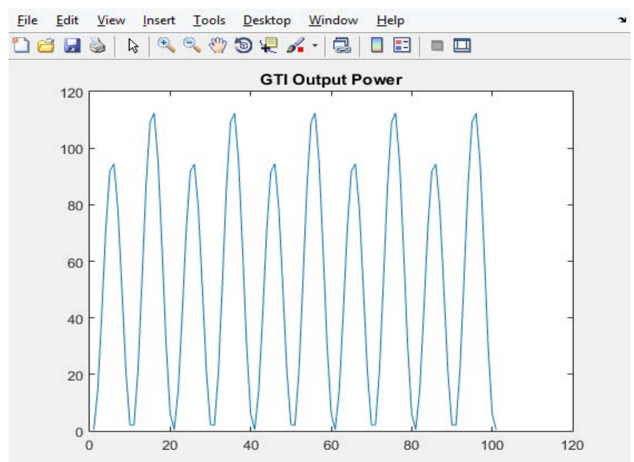

Figure 10. GTI output power.

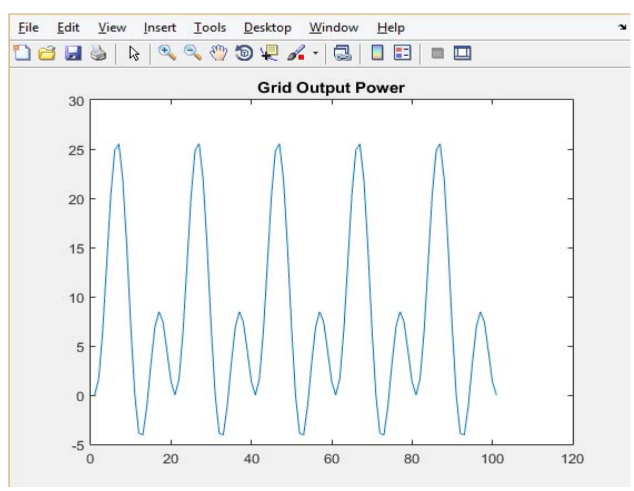

Figure 11. Grid output power.

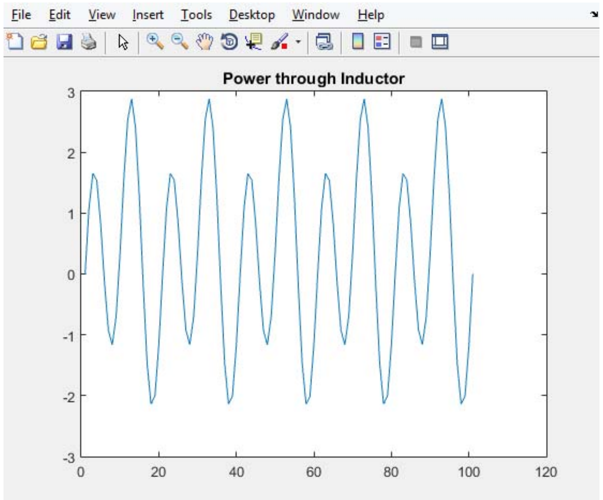

Figure 12. Power through inductor.

From figure 12, it can be seen that amplitude of positive cycle of power is greater than that of the negative cycle, which shows net power flow from GTI towards the grid.

ACKNOWLEDGMENT

This research work has been carried out under the supervision of our faculty advisor Dr. Farid Gul. Whereas, industrial support has been provided by National Institute of Electronics (NIE).

REFERENCES

[1] Power Electronics: Circuits, Devices and Applications, 3/E by M. H. Rashid, Prentice Hall, 2004J. Clerk Maxwell, A Treatise on Electricity and Magnetism, 3rd ed., vol. 2. Oxford: Clarendon, 1892, pp.68–73.

[2] Electric Machinery Fundamentals by Stephen J. Chapman, 4th Edition, McGraw-Hill, 2005K. Elissa, "Title of paper if known," unpublished.

[3] M. A. Salam, Fundamentals of Power Systems, Alpha Science Oxford, UK International Ltd., 2009.

[4] T. Kwang and S. Masri, "Grid Tie Photovoltaic Inverter for Residential Application," Modern Applied Science, vol. 5, No. 4, Aug. 2011, pp. 3-4, doi:10.5539/mas.v5n4p200.