Abstract—Grid connected solar system uses to have converter circuits followed by two levels: A DC/DC boosters and PWM Inverter. This combination of converters leads to decrement of Quality and efficiency of electric power. This paper proposes a single phase thirteen-level photo voltaic inverter for grid connected solar system with a novel pulse width modulated control scheme. The fast variations of solar radiation can be compensated by digital proportional-integral controller. The inverter offers less total harmonic distortion and good power factor. This inverter topology uses two reference signals instead of one reference signal to generate PWM signals for the switches. Both the reference signals \( V_{ref1} \) and \( V_{ref2} \) are identical to each other, except for an offset value equivalent to the amplitude of the carrier signal \( V_c \). Because the inverter is used in a Photo Voltaic system, a proportional–integral current control scheme is employed to keep the output current sinusoidal and to have high dynamic performance under rapidly changing atmospheric conditions and to maintain the power factor at near unity. PV arrays are connected to the inverter via a dc–dc boost converter. The proposed system offers improved performance over five level inverters.

Keywords: Solar System, Photo Voltaic Cell, Multilevel Inverter and PI Controller.

I. INTRODUCTION

Due to the energy shortage, the integration of renewable energy sources to the electricity grid becomes an interesting research topic nowadays. The number of renewable energy sources and distributed generators is increasing very fast which also brings some threats to the power grid. In order to maintain or even to improve the power supply reliability and quality of the power system with distributed generation, it is necessary to have some new strategies for the operation and management of the electricity grid. Modern power electronic technology is an important part in distributed generation and the integration of the renewable energy to the power grid. It is widely used in the grid based system.

According to the latest report of IEA PVPS on installed PV power, during 2010 there was a total of 35 GW capacities that could grow by 2050 to 3000 GW corresponding to an 11% of global electricity generation. Particularly in USA PV installation grew by 92% compared to 2009, for a total of approximately 900 MW. Preliminary market segment data show that commercial-scale projects constituted over 50 % of the market, residential systems about 25 %, and utility-scale projects the remainder. The top 7 states accounted for 76% of the market in 2010.

The Figure 1.1 shows the growing trend of grid-Tied PV capacity by market segment from 2006 to 2010.

Since the output power of micro-sources (photovoltaic, wind energy etc.) is it is necessary to use some specific control strategies or to have some energy storage system (battery, super-capacitor etc.) in order to compensate for the fluctuations. One traditional way is to use different kind of converters to integrate the micro sources, energy storage and different types of loads into a common DC bus the basic structure is shown in Figure 1.2.

Figure 1.1 Grid tied PV capacity

Figure 1.2 Connection of grid, micro-sources, energy storage systems and load
Some problems with this kind of structure are as follows:
- There are lots of power electronics converters in the system so the harmonics components would be very high, which increases the cost and size of the harmonics filter.
- If the voltage level is very high, the switching stress of the power electronic device would increase.
- The efficiency would be low due to the power losses in different converters.

To overcome the above shortcomings, a modular power electronics technology named multilevel inverter, which is very appropriate for the integrating renewable energy source is proposed. The core idea of the multilevel inverter is to achieve the desired ac voltage from several levels of dc voltages. Theoretically, the number of levels for the multilevel inverter can be chosen arbitrarily, so the output voltage of the inverter can reach high level even without the use of transformer. In addition, due to the step characteristic, the output voltage can be almost sinusoidal which, in turn, decrease the size of the filter. There are three commonly used topologies for the multilevel inverter called diode-clamped inverter (neutral-point clamped), capacitor-clamped (flying capacitor), and cascaded multilevel inverter. Among these topologies, the cascaded H-bridges (CHB) multilevel inverter is seen as the most suitable topology for the integration of the renewable energy since the separate DC sources that it requires can be directly fed by PV arrays, wind turbine or fuel cells. In addition, in order to compensate the fluctuation of the output power of the PV arrays and wind turbines, several energy storage devices can also be incorporated into the system. Furthermore, since the number of DC sources can be chosen arbitrarily, it is convenient to increase the level of the output voltage and output power. One proposed topology for the cascaded H-bridge multilevel inverter with renewable energy sources is shown in. Note that the number of inverters for each kind of renewable energy sources can be increased.

II. PHOTO VOLTAIC CELL

The ability to generate electrical power by means of converting solar irradiation is called Photovoltaic. Photovoltaic is the field of technology and research related to the devices which directly convert sunlight into electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic effect involves the creation of voltage in a material upon exposure to electromagnetic radiation.

A number of solar cells electrically connected to each other and mounted in a single support structure or frame is called a ‘photovoltaic module’. Modules are designed to supply electricity at a certain voltage, such as a common 12 volt system. The current produced is directly dependent on the intensity of light reaching the module. Several modules can be wired together to form an array. Photovoltaic modules and arrays produce direct-current electricity. They can be connected in both series and parallel electrical arrangements to produce any required voltage and current combination.

The electrical output of a single cell is dependent on the design of the device and the semiconductor material(s) chosen, but is usually insufficient for most applications. In order to provide the appropriate quantity of electrical power, a number of cells must be electrically connected. There are two basic connection methods: series connection, in which the top contact of each cell is connected to the back contact of the next cell in the sequence, and parallel connection, in which all the top contacts are connected together, as are all the bottom contacts. In both cases, this results in just two electrical connection points for the group of cells.

2.1. SERIES CONNECTION:

Figure shows the series connection of three individual cells as an example and the resultant group of connected cells is commonly referred to as a series string. The current output of the string is equivalent to the current of a single cell, but the voltage output is increased, being an addition of the voltages from all the cells in the string (i.e. in this case, the voltage output is equal to 3Vcell).

It is important to have well matched cells in the series string, particularly with respect to current. If one cell produces a significantly lower current than the other cells (under the same illumination conditions), then the string will operate at that lower current level and the remaining cells will not be operating at their maximum power points.
2.2. PARALLEL CONNECTION:

Figure shows the parallel connection of three individual cells as an example. In this case, the current from the cell group is equivalent to the addition of the current from each cell (in this case, 3 I cell), but the voltage remains equivalent to that of a single cell. As before, it is important to have the cells well matched in order to gain maximum output, but this time the voltage is the important parameter since all cells must be at the same operating voltage. If the voltage at the maximum power point is substantially different for one of the cells, then this will force all the cells to operate off their maximum power point, with the poorer cell being pushed towards its open-circuit voltage value and the better cells to voltages below the maximum power point voltage. In all cases, the power level will be reduced below the optimum.

2.3. SYSTEM DESIGN:

There are two main system configurations—stand-alone and grid-connected. As its name implies, the stand-alone PV system operates independently of any other power supply and it usually supplies electricity to a dedicated load or loads. It may include a storage facility (e.g. battery bank) to allow electricity to be provided during the night or at times of poor sunlight levels. Stand-alone systems are also often referred to as autonomous systems since their operation is independent of other power sources. By contrast, the grid-connected PV system operates in parallel with the conventional electricity distribution system. It can be used to feed electricity into the grid distribution system or to power loads which can also be fed from the grid. It is also possible to add one or more alternative power supplies (e.g. diesel generator, wind turbine) to the system to meet some of the load requirements. These systems are then known as ‘hybrid’ systems. Hybrid systems can be used in both stand-alone and grid-connected applications but are more common in the former because, provided the power supplies have been chosen to be complementary, they allow reduction of the storage requirement without increased loss of load probability. Figures below illustrate the schematic diagrams of the three main system types.

2.4. MAXIMUM POWER POINT TACKING:

The power output of the PV module changes with the amount of solar irradiance and with the variation of temperature. In Figures we could observe the non-linear response characteristic of any PV cell. There exists a single maxima point of the power that corresponds to a specific voltage and current. Since we know the efficiency of a solar cell is around 15% to 17%, is it desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and irradiance levels.

There are many algorithms used to find the maximum power point. Ideally the power tracking is done automatically to adjust to the varying weather conditions. Fig shows how the maximum power point varies due to irradiance. Many papers have been written comparing the efficiency, effectiveness, easiness of the many MPPT algorithms. There are static methods where a specific voltage is chosen for the system to operate in and the solar array is forced to match the voltage referenced.

2.5. PERTURB AND OBSERVE:

Perturbation and Observation method also known as Hill Climbing is one of the most popular algorithms. As the name implies the method will perturb the system by either increasing or decreasing the array’s operating voltage point and comparing the result to the one obtained in the previous perturbation cycle. If the perturbation leads to an increase or decrease in array power, the subsequent perturbation is made in the same or opposite direction. In this manner, the peak power tracker continuously seeks the peak power condition.
With this algorithm the voltage $V$ is constantly perturbed with every step calculation meaning $V$ will oscillate around the ideal $V_{mpp}$ in the manner showcased in Figure 2.6. In order to keep the power variation small the perturbation size is also kept small, this introduces an obvious drawback the time required to reach the peak power point is large. If the variation is large, then the oscillation around the $V_{mpp}$ will be larger, causing power loss. The value of the optimal step size is unique to each system. For simulation purposes the variation in duty cycle is set at 0.01%, but it is editable by the user. The starting value of the duty cycle is set at 50%.

The algorithm reacts as if the increase in power is due to the perturbation, therefore the system will continue the perturbation in the same direction sometimes causing the system to operate far away from the maximum power point.

The algorithm for this method is summarized in Figure 2.7.

**2.5. INCREMENTAL CONDUCTANCE:**

The Incremental conductance method eliminates the drawbacks of the Perturb and Observe method. It uses the advantage that the derivate of the power with respect to the voltage at the maximum power point is zero. Furthermore the derivative at the left of the MPP is greater than zero and less than zero to the right of the MPP (see Figure 2.8). The following set of equations describes the incremental conductance algorithm.

$$P = V \times I \quad \text{(2.1)}$$

Deriving Equation (2.1) with respect to $V$:

$$\frac{dP}{dV} = \frac{d(V \times I)}{dV}$$

$$= I + V \frac{dI}{dV} \quad \text{(2.2)}$$

Since it is known that:

$$\frac{dP}{dV} = 0 \quad \text{(2.3)}$$

At the MPP, combining Equation (2.2) and Equation (2.3) and substituting

$$\frac{I}{V} = G \quad \text{(2.4)}$$

If the incremental changes $dV$ and $dI$ are approximated by comparing the most recent measured and approximated to

$$dV(k) \approx V(k) - V(k - 1)$$

$$dV(k) \approx \Delta V$$

and

$$dI(k) \approx I(k) - I(k - 1)$$

$$dI(k) \approx \Delta I$$

Finally the algorithm can be summed up in the following set of equations

$$\frac{dP}{dV} > 0 \Rightarrow G > \Delta G \quad \text{(2.5)}$$
The incremental conductance can determine that the MPPT has reached the MPP and stop perturbing the operating point. If this condition is not met, the direction in which the MPPT operating point must be perturbed can be calculated using the relationships described in above Equations 2.6 and 2.7.

\[
\frac{dP}{dV} = 0 \Rightarrow G = \Delta G \quad \text{(2.6)}
\]
\[
\frac{dP}{dV} < 0 \Rightarrow G < \Delta G \quad \text{(2.7)}
\]

III. MULTILEVEL INVERTER AND PWM TECHNIQUE

3.1. PULSE WIDTH MODULATOR:

First you generate a triangle waveform as shown in the diagram below. You compare this with a d.c voltage, which you adjust to control the ratio of on to off time that you require. When the triangle is above the ‘demand’ voltage, the output goes high. When the triangle is below the demand voltage, the output goes low.

When the demand speed it in the middle (A) you get a 50:50 output, as in black. Half the time the output is high and half the time it is low. Fortunately, there is an IC (Integrated circuit) called a comparator: these come usually 4 sections in a single package. One can be used as the oscillator to produce the triangular waveform and another to do the comparing, so a complete oscillator and modulator can be done with half an IC and maybe 7 other bits.

A more efficient technique employs pulse width modulation (PWM) to produce the constant current through the coil. A PWM signal is not constant. Rather, the signal is on for part of its period, and off for the rest. The duty cycle, D, refers to the percentage of the period for which the signal is on. The duty cycle can be anywhere from 0, the signal is always off, to 1, where the signal is constantly on. A 50% D results in a perfect square wave. (Figure 3.2)

A solenoid is a length of wire wound in a coil. Because of this configuration, the solenoid has, in addition to its resistance, R, a certain inductance, L. When a voltage, V, is applied across an inductive element, the current, I, produced in that element does not jump up to its constant value, but gradually rises to its maximum over a period of time called the rise time (Figure 3.3). Conversely, it does not disappear instantaneously, even if V is removed abruptly, but decreases back to zero in the same amount of time as the rise time.
Therefore, when a low frequency PWM voltage is applied across a solenoid, the current through it will be increasing and decreasing as V turns on and off. If D is shorter than the rise time, I will never achieve its maximum value, and will be discontinuous since it will go back to zero during V’s off period. In contrast, if D is larger than the rise time, I will never fall back to zero, so it will be continuous, and have a DC average value. The current will not be constant, however, but will have a ripple.

At high frequencies, V turns on and off very quickly, regardless of D, such that the current does not have time to decrease very far before the voltage is turned back on. The resulting current through the solenoid is therefore considered to be constant. By adjusting the D, the amount of output current can be controlled. With a small D, the current will not have much time to rise before the high frequency PWM voltage takes effect and the current stays constant. With a large D, the current will be able to rise higher before it becomes constant.

3.2. Multilevel Inverter PWM Modulation Strategies:

Pulse width modulation (PWM) strategies used in a conventional inverter can be modified to use in multilevel converters. The advent of the multilevel converter PWM modulation methodologies can be classified according to switching frequency as illustrated in Figure 4.5. The three multilevel PWM methods most discussed in the literature have been multilevel carrier-based PWM, selective harmonic elimination, and multilevel space vector PWM; all are extensions of traditional two-level PWM strategies to several levels. Other multilevel PWM methods have been used to a much lesser extent by researchers; therefore, only the three major techniques will be discussed in this chapter.

3.3. PWM Controller strategies

This controller offers a basic “Hi Speed” and “Low Speed” setting and has the option to use a “Progressive” increase between Low and Hi speed. Low Speed is set with a trim pot inside the controller box. Normally when installing the controller, this speed will be set depending on the minimum speed/load needed for the motor. Normally the controller keeps the motor at this Lo Speed except when Progressive is used and when Hi Speed is commanded (see below). Low Speed can vary anywhere from 0% PWM to 100%. Progressive control is commanded by a 0-5 volt input signal. This starts to increase PWM% from the low speed setting as the 0-5 volt signal climbs. This signal can be generated from a throttle position sensor, a Mass Air Flow sensor, a Manifold Absolute Pressure sensor or any other way the user wants to create a 0-5 volt signal. This function could
be set to increase fuel pump power as turbo boost starts to climb (MAP sensor). Or, if controlling a water injection pump, Low Speed could be set at zero PWM% and as the TPS signal climbs it could increase PWM%, effectively increasing water flow to the engine as engine load increases.

This controller could even be used as a secondary injector driver (several injectors could be driven in a batch mode, hi impedance only), with Progressive control (0-100%) you could control their output for fuel or water with the 0-5 volt signal. Progressive control adds enormous flexibility to the use of this controller. Hi Speed is that same as hard wiring the motor to a steady 12 volt DC source. The controller is providing 100% PWM, steady 12 volt DC power. Hi Speed is selected three different ways on this controller: 1) Hi Speed is automatically selected for about one second when power goes on. This gives the motor full torque at the start. If needed this time can be increased (the value of C1 would need to be increased). 2) High Speed can also be selected by applying 12 volts to the High Speed signal wire. This gives Hi Speed regardless of the Progressive signal. When the Progressive signal gets to approximately 4.5 volts, the circuit achieves 100% PWM – Hi Speed.

IV. PI CONTROLLER

The general block diagram of the PI speed controller is shown below.

![Figure 5.1 Block diagram of PI controller](image)

The output of the speed controller (torque command) at n-th instant is expressed as follows:

\[ T_e(n) = T_e(n-1) + K_p \omega_r(n) + K_i \omega_r(n) \]

Where \( T_e(n) \) is the torque output of the controller at the n-th instant, and \( K_p \) and \( K_i \) the proportional and integral gain constants, respectively.

A limit of the torque command is imposed as

\[ T_e(n+1) = \begin{cases} T_{e\text{max}} & \text{for } T_e(n+1) \geq T_{e\text{max}} \\ -T_{e\text{max}} & \text{for } T_e(n+1) \leq -T_{e\text{max}} \end{cases} \]

The gains of PI controller shown can be selected by many methods such as trial and error method, Ziegler–Nichols method and evolutionary techniques-based searching. The numerical values of these controller gains depend on the ratings of the motor.

V. SIMULATION RESULTS

![Figure 5.1 Inverter 13-level output voltage for M=0.2](image)

![Figure 5.2 Inverter 13-level output voltage for M=0.8](image)

![Figure 5.3 Inverter 13-level output voltage for M=1.2](image)

![Figure 5.4 THD of 5-level inverter output voltage](image)

![Figure 8.8 THD of 13-level inverter output voltage](image)
VI. CONCLUSION

As renewable energy systems become more widespread, rooftop PV systems are more likely to be found in a grid connected scheme. Modeling an accurate PV cell has always presented a challenge, more so when the PV module is used to simulate PV arrays and PV Panels. This research addresses both issues by simulating a comprehensive model in SIMULINK that takes into consideration the most important elements in a PV cell, array or panel. When the PV array is used as a source of power supply it is necessary to use the MPPT to get the maximum power point from the PV array. This paper presented a single-phase 13 level inverter for synchronized grid PV system. It utilizes two reference signals and a carrier signals to generate PWM switching signals. The circuit topology, modulation law, and operational principle of the proposed inverter were analyzed in detail. The PI controller is to optimize the operation of inverter. Simulation results indicate that the THD of the 13-level inverter is much lesser than that of the conventional 5-level inverter.

VII. REFERENCES