CHAPTER I

INTRODUCTION

Researchers in the field of photovoltaics are faced with the task of making solar energy more efficient. There exists a variety of avenues in making this type of technology more productive. For example, one branch of research deals with the solid state properties of the materials used in solar cells. This type of research focuses primarily on the properties of thin film silicon and finding methods to manufacture high quality silicon at lower manufacturing costs. This research is motivated by the fact that high quality semiconductor materials can have a significant effect on the energy efficiency of the solar panels themselves.

A photovoltaic (PV) system may be a combination of several components such as a battery system, DC/AC conversion circuits, and other power conditioning devices in addition to the solar panels themselves. The research I am presenting in this body of work concentrates more on the electronic means of enhancing energy efficiency in a PV system as well as describing energy storage and power grid integration techniques. This branch of power electronics is generally called power conditioning and in the present case is used to describe the management of electrical energy to effectively charge batteries, draw maximum power from the solar panels, or provide a high quality AC output.

If a PV system is constructed with rudimentary electronics, it is possible for nearly all of the power generated by the solar panels to be wastefully dissipated as heat in the system components. In order to prevent the waste of potentially useful electrical energy, it is worthwhile to investigate modern and sophisticated means of managing electrical power in PV systems. Furthermore, since solar energy systems are relatively expensive in comparison to other energy sources, it would be advisable to maximize energy efficiency so that the energy provided in relation to the system cost is optimized. Most importantly, since the energy provided by clean energy sources, such as solar energy, can potentially supplant the use of traditional energy sources that pollute, it is environmentally wise to enhance the power output of renewable energy sources.

In addition to enhancing efficiency, power conditioning is also used to facilitate energy storage. For example, some battery charging systems may require power conditioning circuitry to provide a desired current to charge batteries effectively. For this type of system, the use of an electronic circuit called a DC/DC converter is required to control the current supplied by the photovoltaic array to the battery. To prevent battery damage, the charging current supplied to the battery by the DC/DC converter is determined by the battery's state of charge. In other less sophisticated systems, circuitry may manage battery charging by simply connecting or disconnecting the solar panels from the battery depending on the state of charge of the battery. I have provided a block diagram of a typical battery charging system using a DC/DC converter circuit.

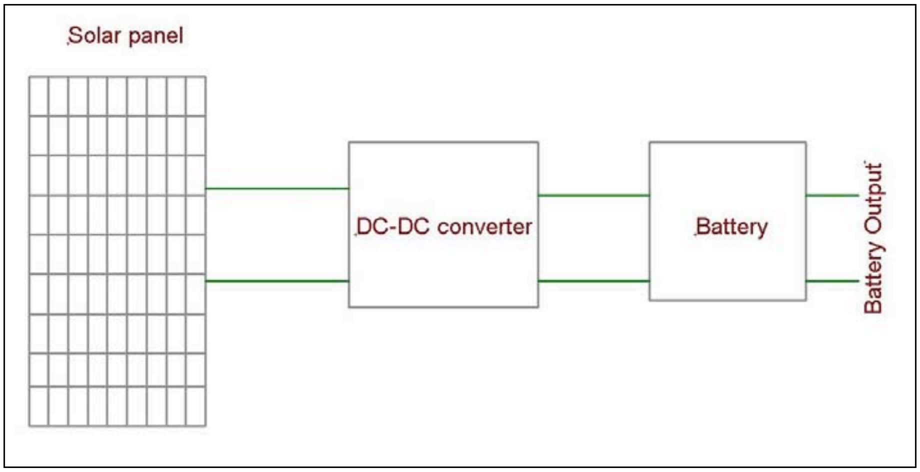

Figure 1.1 Block diagram of a battery charging system.

DC/DC converters are also useful in circuitry designed to draw maximum power from solar panels in what are called maximum power point trackers (MPPT). In the absence of a MPPT and depending on the load connected directly to solar panels, a great deal of the solar panel's electrical power may be dissipated in the form of heat. In the interest of maximizing energy efficiency, MPPTs are connected between the solar panels and load to ensure that the solar panels are producing their maximum power despite variations in light intensity and/or other factors that may vary within the system. MPPTs may be used in the presence or absence of battery charging systems but are more often used in grid-connected systems that have no batteries.

Considering that solar panels and batteries both supply DC voltages and most electronic devices require AC to power them, circuitry is usually required to convert this DC voltage into an AC voltage by what are called inverters. Once the DC voltage is converted into a 60 Hz waveform with proper amplitude, the AC voltage can then be introduced into a power grid. The presence of the inverter makes it possible to use solar energy to power almost any electronic device that runs on AC power. The following diagram demonstrates how an inverter may be used.

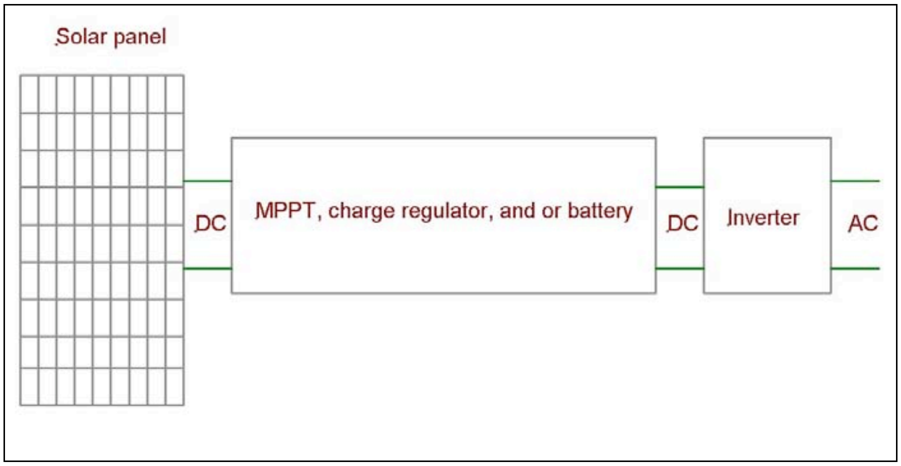

Figure 1.2 Block diagram of solar system using an inverter.

Electronics can play a large role in enhancing the efficiency of a PV system. Furthermore, the use of appropriate electrical techniques enables solar generated electricity to be integrated into a power grid that may power a home or business. Aside from improving the quality of the solar panels themselves and the materials they require, power electronics can provide another means of improving energy efficiency in PV systems.

CHAPTER II

DC/DC CONVERTERS

As mentioned earlier, DC/DC converters are used in several circuits such as battery chargers and maximum power point trackers (MPPT). Since solar panels are only capable of producing a DC voltage, the DC/DC converter becomes quite useful by providing the flexibility to adjust the DC voltage or current at any point in the circuit. DC/DC converters are often preferred in modern electronics since they are smaller, lightweight, provide a high quality output, and more efficient than the traditional linear power regulator [1].

Linear regulators often have poor energy efficiency despite their ability to provide a high quality DC voltage. This occurs because the linear regulator essentially acts as a variable voltage divider that functions to keep a constant output voltage. Considering that the voltage divider is constantly dissipating power as heat in its resistive elements, the linear regulator becomes highly inefficient. Consequently, the greater power efficiency of DC/DC converters is especially desired in solar applications where maximum power efficiency is a primary goal. Additionally, DC/DC converters can be more flexible than linear power regulators since they can step the output voltage higher or lower than the input voltage unlike linear regulators that can only provide an output voltage that is less than the input [1].

The primary purpose of the DC/DC converter is converting an input DC voltage into a different DC voltage at its output. The device must also be able to maintain a constant and/or controllable output DC voltage despite variations in the input voltage. This is achieved by using a switching topology to convert an average input voltage into another average output voltage. The presence of the input voltage will essentially be switched *on* and *off* so that the average output voltage is different. To provide a stable average output voltage, the operation of the switches must be periodic and controllable [1].

During operation of the DC/DC converter, energy will typically be stored in inductors and capacitors as it is transferred to its output. Furthermore, the switching element used is almost always a transistor, which can be manipulated by a control circuit to provide the periodic switching of the transistors. Several transistor types are available for switching use including the bipolar junction transistor (BJT) and field effect transistor (FET) [1].

Using the BJT as an example, the transistor can be viewed as having a control terminal (base) which controls a proportional current through the other two terminals (collector and emitter). This property can be exploited by using a small amount of current at the base terminal to control a much larger current through the collector and emitter. To turn the transistor *on*, the base current will be increased until the voltage drop from collector to emitter is nearly zero. In this condition, the transistor is said to be saturated because it cannot pass anymore current. To turn the transistor *off*, the base current will be brought close to zero causing the collector-emitter current to also become very small.

Although a variety of DC/DC converter types exists, they all work by storing energy in an inductor(s) and capacitor(s) and the flow of energy between the two types of components is controlled with switching transistors [2]. These switching circuits can achieve high power efficiency because a transistor is capable of dissipating very little power in both *on* and *off* states [1]. In the *on* state, there is a small voltage drop across the transistor due to low resistance, and in the *off* state very little current will flow. Furthermore, since most switching regulators operate at high frequencies (tens of kHz to a few MHz), components used such as capacitors, inductors, and transformers can be smaller in size and will consequently have a lower cost [1].

To optimize battery charging, power transfer, and the output voltage of a PV system, a DC/DC converter can be used to convert one voltage or current into a different voltage or current at the DC/DC converter output. This conversion can occur in several places such as between solar panels and a battery, between a solar panel and an inverter, and between a battery and inverter. DC/DC converters are also used to regulate a DC output in response to variations at the DC/DC converter input or output load [1]. This ability of a DC/DC converter to respond to changes will be exploited in what is known as maximum power point trackers and is usually seen at the output of the solar panels [3]. Supplementary to other features, the DC/DC converter can be built with a transformer to provide electrical isolation as a safety benefit to anyone touching the equipment. If a transformer is utilized in the DC/DC converter circuit, it is usually put at the input in series with the switching element [1].

The fundamental basis of a switching regulator's operation is its ability to output another average DC voltage by simply switching the presence of the input voltage in and out. The simplest switching regulator is a DC chopper and is shown in figure 2.1.

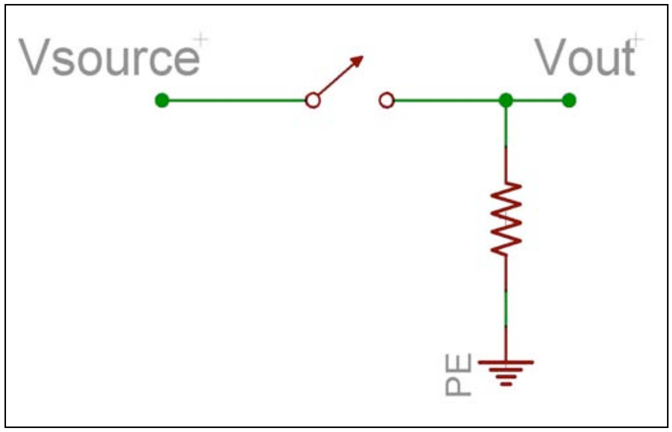

Figure 2.1 DC chopper.

The DC chopper provides an output voltage that can vary in average value by simply oscillating the switch between its *on* and *off* states. If the switch operates periodically, the average output voltage can be expressed by equation (2.1) [1]. Although the DC chopper is impractical due to its squarewave-like output, it illustrates one of the main principles in switching regulators. In the following equations V_S represents the voltage source input and V_{out} denotes the *average* output voltage. The duty ratio D is defined as the ratio of switch *on* time to the period of the switching frequency.

$$V_{out} = DV_S \qquad \text{where} \quad D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} \tag{2.1}$$

Moving to a more practical DC/DC converter example, figure 2.2 depicts the basic boost converter designed to step up the incoming voltage. For simplicity and as in the previous example, the switch shown represents a transistor that operates in either the *on* or *off* state and the transistor control voltage is also omitted from the illustration.

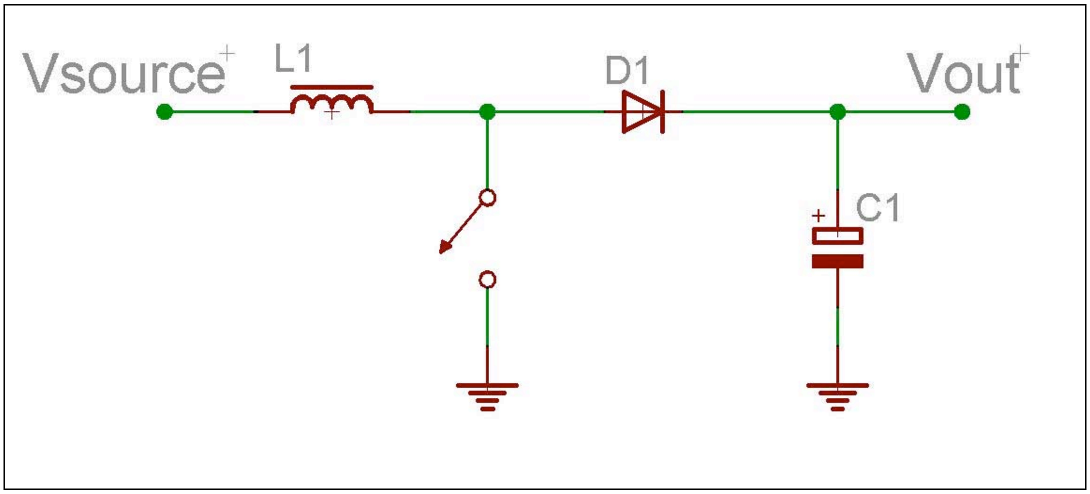

Figure 2.2 A basic boost converter.

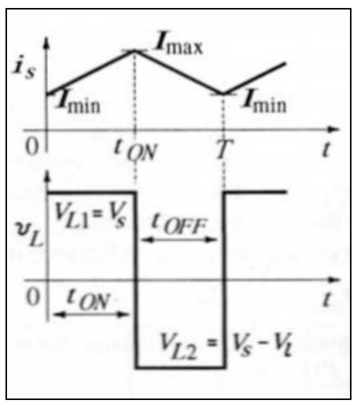

Figure 2.3 Switch current vs. time (top) & inductor voltage vs. time (bottom). [4]

To describe the operation of this circuit, the assumption will be made that the switch has been open for a long enough time and the capacitor labeled *C1* has been charged up to the source voltage minus a diode voltage drop. Once the switch is closed, current will flow through the inductor *L1* and switch and the rate of change of the current through the inductor and switch will obey equation (2.2) [2].

$$\frac{di}{dt} = \frac{V_L}{L} \tag{2.2}$$

Referring to the bottom of figure 2.3, when the switch is closed, V_L will equal input voltage V_S and the current will rise linearly through the inductor. The inductor then serves to store energy in the form of a magnetic field and will serve the auxiliary purpose of preventing a potentially destructive surge of current from passing through the transistor switch [2]. The energy stored can be expressed as a function of current in equation (2.3).

$$E(i) = \frac{1}{2} L i^2 \tag{2.3}$$

As current flows through the inductor and switch, the rectification diode will prevent the voltage stored in the capacitor from discharging to ground via the closed switch. During this time, current will be supplied to the load by the fully charged capacitor. Since a capacitor's discharge time constant depends on the capacitor's value and can be described as $t = XC$ (where X is the impedance of the load), the capacitor's value must be large enough to prevent excessive discharge ripple in the output voltage. The threshold value to prevent excessive discharge and ripple will primarily depend on the switching frequency and load impedance [1].

The inductor will release the stored energy when the switch is then opened. At this time, the inductor current will flow through the diode to charge up the output capacitor. As the inductor releases its energy, the current through it will decrease and *di/dt* will become negative.

$$\text{During discharge:} \quad \frac{di}{dt} = \frac{-V_L}{L} \tag{2.4}$$

For our example, the current through the inductor will always be positive while *di/dt* will vary between positive and negative values. Considering the current in the inductor is always in one direction and never zero, the DC/DC converter is said to operate in *continuous current mode* [1].

In pulse width modulation (PWM) circuits, the switch changes between its *on* and *off* states at a constant frequency and can be expressed using the duty ratio equation. Using the fact that in steady state operation the value of I_{min} provided by the source is equal after each period T (see figure 2.3), the average value of V_L can be found in the following calculation [4]:

$$V_{L(avg)} = \frac{1}{T}\int_0^T V_L\,dt = \frac{1}{T}\int_0^T L\frac{di}{dt}dt = \frac{L}{T}\int_{I(\min)}^{I(\min)} di = 0 \tag{2.5}$$

Since the average voltage is zero, the area under the bottom waveform of figure 2.3 over one period must be zero. This can be expressed in equation (2.6).

$$V_{in}t_{on} + V_L t_{off} = 0 \tag{2.6}$$

Since $V_S + V_L = V_{out}$, we can solve for V_L and insert the result into equation (2.6). After some algebra, it can be shown that $V_{out} = V_S(1 + \frac{t_{on}}{t_{off}})$. Going further by using the relationship for duty ratio, the expression for output voltage can be calculated yielding equation (2.7). Ideally, since $0 < D < 1$, V_{out} will always be larger than the input V_S, hence the name boost converter.

Boost converter output voltage: $$V_{out} = \frac{V_S}{1-D} \tag{2.7}$$

A variety of DC/DC converter types exists relying on the same principles outlined for the boost (step-up) converter. Some other basic types of DC/DC converters not mentioned so far are the buck (step-down) converter, buck-boost (step-up or step-down) converter and it should be mentioned that each type of converter can be constructed using a transformer at the input in series with the switching element. The added safety benefit of the transformer based switching regulator comes in the electrical isolation provided between the primary and secondary sides of the transformer. The isolation allows one side of the circuit to not be connected to ground and will consequently prevent anyone touching this part of the circuit from becoming a current return path to ground.

The converters discussed in my research are controlled by pulse width modulation (PWM), which involves feeding the output voltage of the DC/DC converter into a control loop [1]. The loop then responds to the present output voltage by adjusting the duty ratio of the transistor switches to provide the desired DC output voltage set within the control loop. This control loop will enable the DC/DC converter to output a constant or controllable DC voltage despite variations in the input voltage or load conditions. This scheme uses negative feedback and is especially useful in photovoltaic applications where a solar panel's output may vary during shading and a large range of light intensities. Figure 2.4 shows a typical control technique for any DC/DC converter.

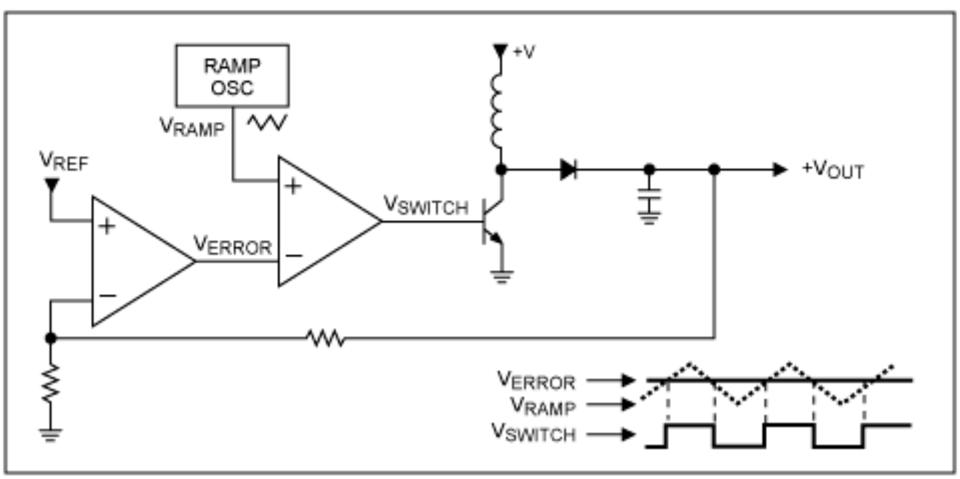

Figure 2.4 Boost converter using pulse width modulation. [2]

Considering that the voltage V_{REF} is the only controllable voltage in the control loop, the desired output of the DC/DC converter is variable and can be set by V_{REF}. The leftmost op-amp in figure 2.4 acts as a differential amplifier with large voltage gain. This op-amp will amplify the voltage difference ($V_{REF} – V_{OUT}$), which I will now refer to as the error voltage (V_{ERROR}). The second op-amp operates as a comparator where V_{ERROR} is compared to a constant amplitude and frequency waveform labeled V_{RAMP}, typically a sawtooth wave, generated by an oscillator. This comparator then outputs the PWM signal (V_{SWITCH}) that drives the base of the switching transistor with a control current [2]. The duty ratio of this PWM signal will depend on V_{REF} and will have the same frequency as the sawtooth waveform. The waveforms on the bottom of figure 2.4 can provide visual clarification.

Switching regulators are favored in photovoltaics because of energy efficiencies that can be higher than 95% [3]. This implies that nearly all of the power at the DC/DC converter input will be transferred to its output. This property of high-energy efficiency will be utilized in maximum power point trackers. Furthermore, DC/DC converters are able to provide controllable and stable output voltages despite variations in input voltage and load conditions. Since solar panels are subjected to volatile conditions that are manifested in weather and electrical conditions, DC/DC converters are a useful tool in providing consistency in places where a PV system needs it. For example, many systems incorporate batteries that require specific recharging currents to maximize battery life [1]. To complicate matters, the charging current should be varied and optimized depending on the batteries’ state of charge and temperature. At this point a DC/DC converter can be used to provide that specific charging current required; furthermore, the converter can be adjusted by changing V_{ref} to provide the appropriate charging current.

Fortunately, a variety of DC/DC converters are available in packaged integrated circuits (ICs). However in large PV systems, if the current generated by the solar panels is too great, ICs may not be an option due to their limited ability to dissipate significant amounts of power effectively.

CHAPTER III

MAXIMUM POWER POINT TRACKERS

At a given temperature and illumination level, solar cells supply maximum power at one particular voltage and current output called the maximum power point. In the interest of optimizing the power output of the PV system, the load should be operated at this maximum power point. However, the maximum power point can vary greatly as the illumination level and temperature of the solar cells change. In addition, the characteristics of the load may vary as well. To ensure ideal power transfer at the maximum power point, a dynamic system called a maximum power point tracker (MPPT) should be inserted between the solar panels and the load. This circuit will then respond to any variations at its input and output by ensuring that maximum power transfer is achieved [3].

The MPPT is most commonly constructed out of DC/DC converters that use pulse width modulation (PWM) to vary the duty ratio as well as current and voltage sensors at its input. In order to calculate the power at the MPPT's input, the current and voltage measured by the sensors are multiplied in a digital circuit. Considering the high power efficiency of the DC/DC converter, nearly all of the power at the input is transferred to the load [5].

The MPPT typically uses an iterative process to find the maximum power point. This type of operation dynamically varies the duty ratio one direction (increase or increase in duty ratio) while calculating the power at its input. If the variation produces an increase in power at the MPPT input, the duty ratio is further increased in the same direction. If the power at the input decreases, the duty ratio is adjusted in the reverse direction. It should be mentioned that several other methods not mentioned here do exist [5].

Before delving into a detailed explanation of how maximum power point trackers operate, it is imperative to gain an understanding of the current-voltage relation in a typical solar cell. Solar cells are constructed by joining p-type and n-type materials usually made of silicon doped with various impurities to create a p-n junction. The construction of the solar cell can be seen in figure 3.1. When the p-n junction is established, an electric field will be created as the charge carriers created by the doping material disperse [6].

Since the p-n junction is exposed to sunlight, free charge carriers are created via the photoelectric effect and are separated by the electric field established at the p-n junction. The separation of charge carriers, electrons and holes, creates a potential difference across the solar cell. When a load is connected across a solar cell, the charge carriers are free to flow as current through the load [6]. When individual cells are connected in parallel and series, various configurations can create solar modules, panels, and arrays. Each term generally refers to the scale of integration where the array contains the largest number of individual solar cells.

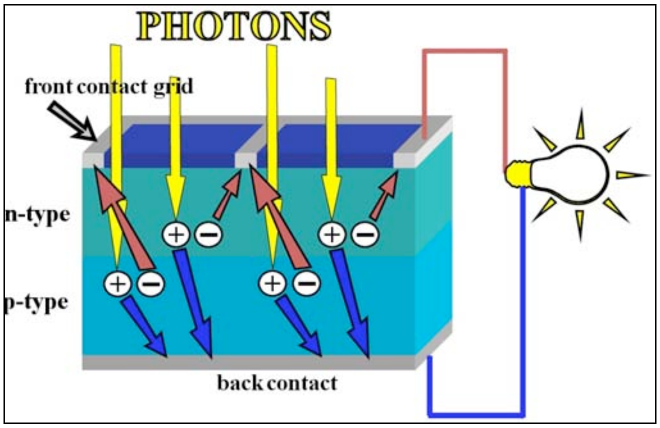

Figure 3.1 Illustration of a solar cell's construction. [7]

Since the solar cell is simply a p-n junction, the current-voltage relation of the cell is similar to that of a diode. However, because a diode's p-n junction isn't exposed to light the photocurrent must also be taken into in the solar cell *I-V* relation [1]. This can be expressed as follows:

$$I\text{-}V \text{ characteristic of solar cell:} \qquad I = I_{ph} - I_o(e^{\frac{qV}{kT}} - 1) \tag{3.1}$$

The first term represents the photocurrent which is generated by the incoming light on the p-n junction. It should be noted that the photocurrent, I_{ph} , is directly proportional to the light intensity. The equivalent circuit shown in Figure 3.2 can model the behavior of an ideal solar cell [6]. The symbol on the left represents a current source.

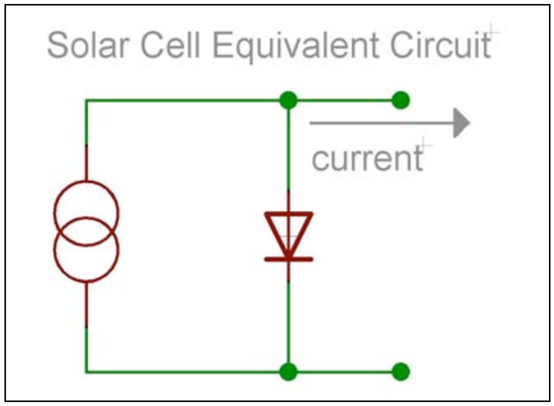

Figure 3.2 The equivalent circuit of a solar cell.

A solar cell behaves much like a current source in parallel with a diode. When the terminals at the output of the solar cell are shorted, no current will flow through the internal diode but will all flow to the output. In this short circuit condition, the short circuit current I_{sc} will be provided at the output and the output voltage will be zero. When the terminals are connected to a load with finite resistance, some but not all of the current will flow through the diode. Lastly, if the load connected approaches the open circuit condition, all the current will flow through the internal diode, the output current will be zero, and the output voltage will be V_{oc} [1].

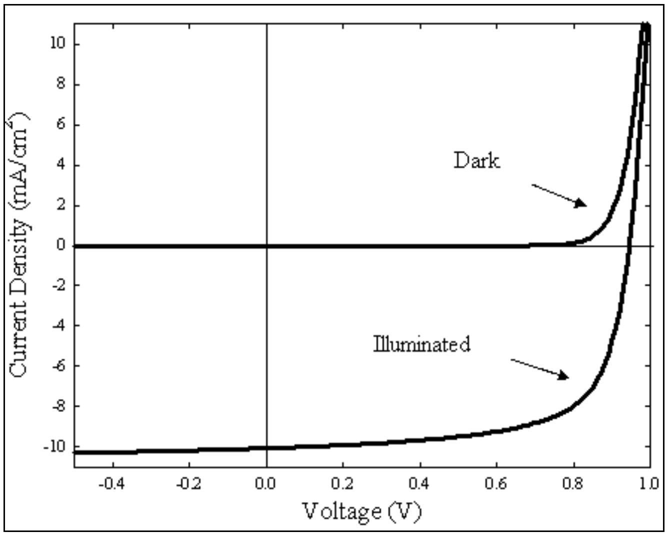

Figure 3.3 *I-V* characteristics of solar cell under illumination and darkness. [8]

A graphical representation of the *I-V* characteristic is shown in Figure 3.3. It can be seen that as the illumination intensity rises, the curve is shifted increasingly downward. This downward shift of the graph occurs because the photocurrent I_{ph} is in the opposite direction of the current produced in a conventional diode. This can also be understood by noting that the two terms in equation (3.1) are opposite in magnitude. In photovoltaics, the portion of the graph resulting from illumination is what is of interest. To simplify analysis and to make the power provided by the solar cell(s) positive in magnitude, the illuminated portion of the graph in figure 3.3 is conventionally inverted upside-down [1]. This can be seen by comparing the illuminated *I-V* curve of figure 3.3 and the customarily inverted *I-V* curve of figure 3.4.

Although a solar cell can be operated anywhere on its current vs. voltage curve, it is desired to operate the array so that maximum power output results. Considering the *I-V* characteristic of a solar cell, the power is maximized at a unique point on the *I-V* curve (see figure 3.4) under a specific illumination level and temperature. As the illumination level varies, the *I-V* curve will for the most part be shifted up or down and will consequently create different maximum power points for each illumination level. This shifting of the *I-V* curve can best be understood by realizing that the photocurrent term I_{ph} in equation (3.1) will shift the curve vertically along the current axis as I_{ph} is varied. The maximum power point P_{MPP} is located on the knee of the *I-V* curve and is indicated at a voltage of V_{MPP} and current of I_{MPP} in figure 3.4 [1]. This illustration shows both the *I-V* and power curves on one graph. Note how the maximum power point is located at the knee of the *I-V* curve.

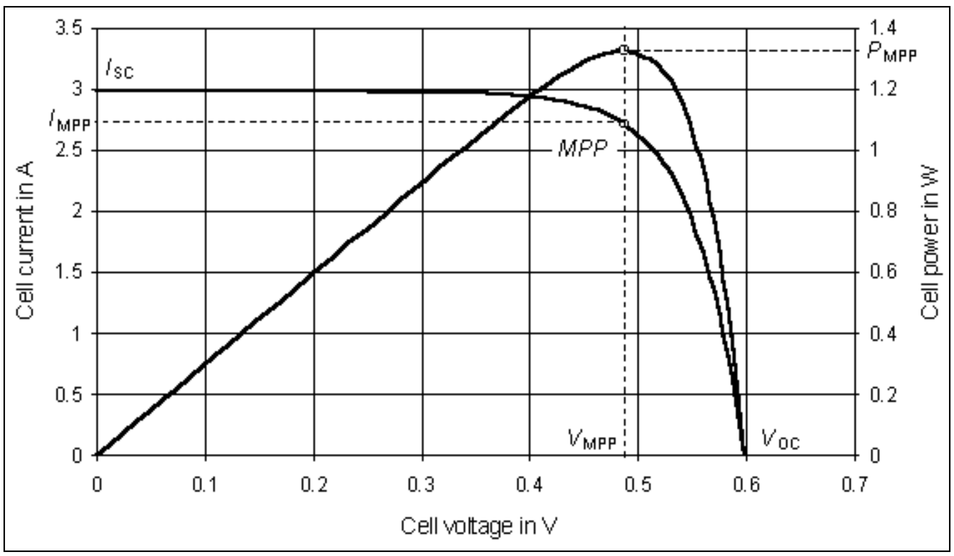

Figure 3.4 *I-V* and power curves of a typical solar cell. [9]

Depending on the current and voltage requirements of the load connected, a load will operate with a specific power consumption on the power curve with relatively little flexibility. Most likely, the load will not be operating at the maximum power point and it may be necessary to enhance power efficiency with a MPPT. The MPPT will be inserted between the PV array and the load and will serve to regulate the current and voltage supplied from the PV array to the load. The power output is effected because any changes in the current or voltage supplied from the PV array will correspondingly change the power delivered to the load. This is best understood by looking at the relationship of the *I-V* and power curves of the solar cell in figure 3.4 [3].

As mentioned earlier, the MPPT is essentially a DC/DC converter that varies the duty ratio in order to deliver maximum power to the load. This occurs because any changes in the duty ratio will correspondingly change the current draw of the MPPT which will also change the operation of the MPPT on the *I-V* curve. It should be noted that the current draw of the MPPT is proportional to the duty ratio $\left(\frac{t_{on}}{T}\right)$ because as t_{on} is increased, the input current in correspondingly increased. Depending on the configuration, the PWM feedback loop may employ voltage and current sensors along with a microcontroller to calculate the power present at the MPPT input. From there, the PWM control loop will vary the duty ratio accordingly to maximize the power at the input. Owing to the high power transfer efficiency of the DC/DC converter, an optimized power at the input translates to an optimized power at the output [3]. A block diagram of the MPPT can be seen in Figure 3.5.

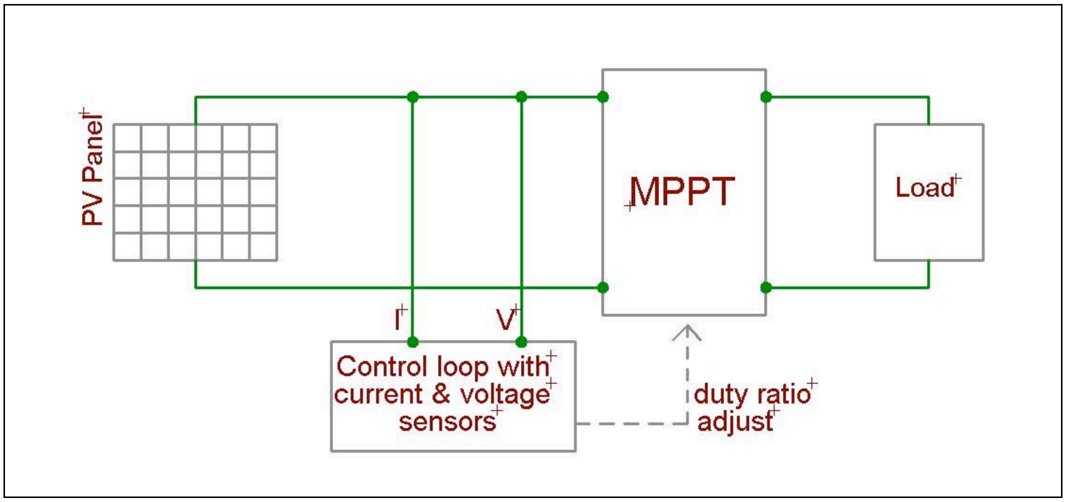

Figure 3.5 MPPT with PWM control loop utilizing current and voltage sensors.

An MPPT can be controlled in a variety of ways. The closed-loop control method involves varying the duty ratio by an incremental increase or decrease. The current and voltage sensors, which are part of some digital system in the PWM feedback loop, will assess if the power at the MPPT input increased or decreased. If an increase in power occurs, the MPPT increases or decreases the duty ratio in the same direction. Once a decrease in power is encountered, the system will step the duty ratio back in the reverse direction. To prevent an oscillatory action where the MPPT is constantly adjusting back and forth, the digital controls will employ a dead zone where if dP/dD is close to zero within a set range, the MPPT operation will remain static [10].

Since this circuitry will inevitably cause a rise in parts cost and will make the system considerably more complicated, it must be decided on a case-by-case basis whether the benefits outweigh the obstacles [3]. An MPPT is best used in grid-connected systems but can also be used in conjunction with battery chargers in stand alone systems where no grid-connection is used. Although the MPPT can enhance system efficiency, some power will inevitably be lost in the DC/DC converter. This loss should also be taken into account when justifying use of the MPPT [3].

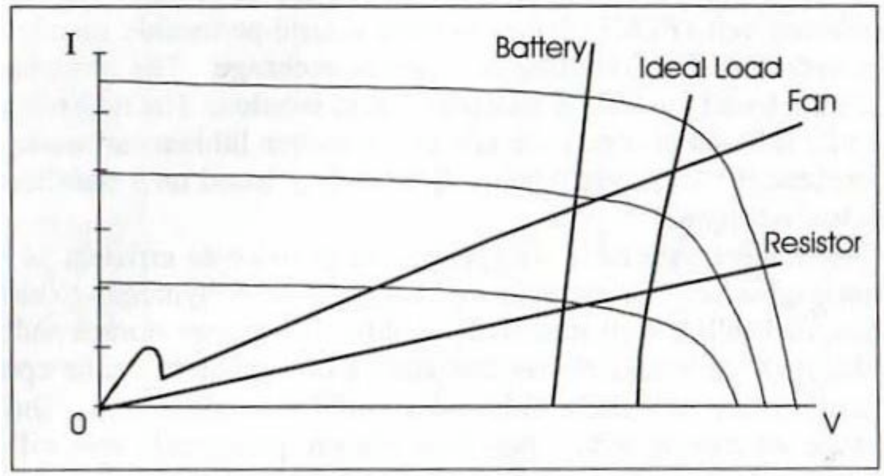

Figure 3.6 *I-V* characteristics of several common loads along with solar cell output at different illumination levels. [3]

Figure 3.6 shows the solar cell output at varying illumination levels as well as the characteristic *I-V* curves of common loads. Since the maximum power point of the solar cell occurs at the knee of each curve, it can be seen that each illumination level will provide a different maximum power point. If each of these loads were directly connected to the solar array, it would operate at the point of intersection between the solar array *I-V* curve and the load curve. Furthermore, if each of the non-ideal loads shown in Figure 3.6 were connected directly to the load, none would operate at the maximum power point for *all* illumination levels. In addition to responding to variations in input voltage, the MPPT must respond to the dynamic impedance of the load to optimize power output [3].

Using figure 3.7, the situation can be analyzed graphically. In the illustration the dotted inverse function curves represent constant power curves and in the case of power optimization, it makes sense to consider the ones that intersect with the maximum power points [3]. The functions of the constant power curves can be found be rearranging the expression $P_{max}=IV$ into equation (3.2).

$$\text{Constant power curve:} \quad I(V) = \frac{P_{\max}}{V} \tag{3.2}$$

Given that the solar array is operating under certain conditions, the MPPT will vary the duty ratio until it is operating at the maximum power point associated with the PV array's particular illumination level and temperature. For example, if load 2 was connected directly to the PV array under the illumination of the lower *I-V* curve, it would operate at point A. In order to extract maximum power, load 2 would be connected to the MPPT that is operating at the maximum power point. Owing to the high power transfer efficiency of the MPPT, nearly all of the power at the MPPT input will be delivered to load 2. As a result, load 2's *I-V* characteristic would intersect the maximum power curve of that particular illumination level at point A_{max} [3].

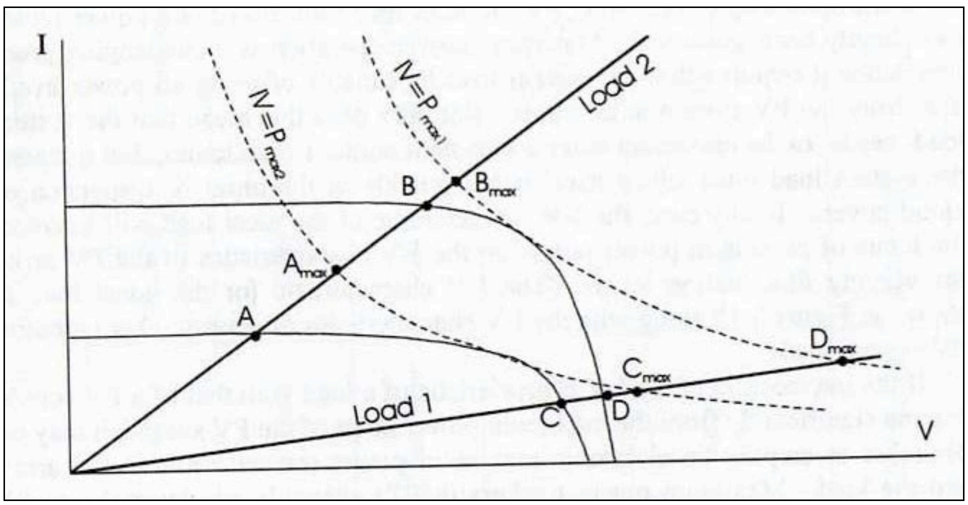

Figure 3.7 MPPT operation. [3]

Another control method relies on the fact that despite varying illumination levels, the ratio of V_{MPP}/V_{OC} remains approximately constant. This property allows the use of equation (3.3) to estimate the output voltage needed at the array to maximize power output.

$$V_{MPP} = kV_{OC} \tag{3.3}$$

The constant *k* typically has a value of approximately $k=0.75$. This method requires the solar array to be open circuited periodically so that V_{OC} can be measured. Another alternative that avoids opening the circuit involves continuously measuring V_{OC} of an unloaded cell that operates under similar temperature and illumination conditions as the rest of array [10]. Once V_{OC} is measured, the PWM feedback loop of the MPPT responds to vary the current draw at the input of the MPPT so that the solar panel operates at V_{MPP}. In this case, the DC/DC converter operating as the MPPT functions to vary the current draw at its input by adjusting the duty ratio. Once again, the duty ratio will be used to vary operating conditions.

Before describing how MPPTs typically interface with the various types of other components in solar systems, I will first describe how battery chargers and inverters operate.

CHAPTER IV

BATTERY CHARGERS

Systems utilizing batteries are usually seen in what are called stand alone PV systems. This type of configuration is not connected to any type of grid and is usually seen in isolated and rural areas. The utilization of the battery allows energy to be stored during times of daylight and to be used during nighttime or under insufficient illumination. The advantages offered by battery systems are typically not needed in grid connected systems since a grid connected solar system can inject extra power back into the grid [1]. On the other hand, stand alone systems have no grid to inject excess power into so the energy must be stored in a battery.

In most PV systems that utilize batteries, multiple batteries are connected in series and/or parallel depending on the voltage and current requirements of the load. Generally, if there are higher voltage requirements, the batteries will be connected in series. Conversely, if there are high current capacity demands, the batteries are connected in parallel. Owing to the extended life and lasting energy storage of lead acid batteries, they are currently the most common choice of battery for PV system energy storage [6]. Regardless of the battery type used, all rechargeable batteries are recharged by supplying current to the battery terminals.

In many cases, the cost of the batteries can be significant. Therefore battery charging control is needed so that the life of the batteries is extended as long as possible. Manufacturers of batteries usually indicate the nominal number of discharge cycles a battery may go through in its lifetime. This number of charging cycles has a direct relationship with the depth of discharge from its fully charged condition [1]. The more often a battery is deeply discharged and brought close to complete discharge, the shorter the lifespan of the battery becomes. Using this fact, battery chargers are usually designed to keep the battery as close to full charge as possible.

The idea of keeping the battery close to full charge should not be taken too far. For if the battery receives charging current *after* it has been fully charged, chemical reactions in the battery will cause internal gas to be produced within the battery [11]. This internal gassing may end up harming or destroying the battery. The battery charger must then be designed to stop charging current once the battery becomes fully charged.

Battery chargers come in a variety of forms each with its own level of sophistication. The two more primitive chargers are called series charge regulators and shunt charge regulators. Both of these systems essentially connect or disconnect the solar array from the battery depending on the state of charge in the battery. The more sophisticated type uses a DC/DC converter that is capable of supplying varying amounts of current to the battery depending on the battery's state of charge [1].

The DC/DC converter charger generally uses temperature and voltage sensors at the battery terminals to deduce the state of charge of the battery. If the battery is fully charged or close to full charge, the charger will eliminate or provide a small trickle charging current. If the battery is somewhat charged, a moderate charging current will be supplied. If the sensors determine that the battery is close to complete discharge, the load is disconnected to prevent further discharge and a strong charging current will be supplied. The DC/DC converter charger is the most flexible because it can provide a controllable amount of charging current to the battery [6].

The DC/DC converter charger also requires hysteresis to be introduced into the system. Hysteresis occurs when a system's future state depends on its history and previous state. For a battery charging system, this implies that the magnitude of the charging current will depend on the previous state of charge of the battery. This feature is used to prevent an oscillatory type of action where the charger is constantly switching between a smaller and a larger charging current or between two states [3].

The simpler series charge regulator is shown figure 4.1. In the illustration, the switches represent relays or transistors that are switched *on* or *off* by the charge controller. It operates by opening switch 1 and closing switch 2 when a predefined battery voltage has been reached. As the battery discharges through the load, its voltage will fall below another predefined discharge limit. When this happens switch 2 disconnects the battery from the load to prevent deep discharging and at the same time switch 1 connects the solar panels to the battery. Although most systems operate the switches exclusively in the *on* or *off* positions, sometimes the transistor of switch 1 will operate as a variable resistor. The main problem with this system is that power is constantly being dissipated in the switches. This problem is especially accentuated when switch 1 acts as a variable resistor that will constantly dissipate power [1].

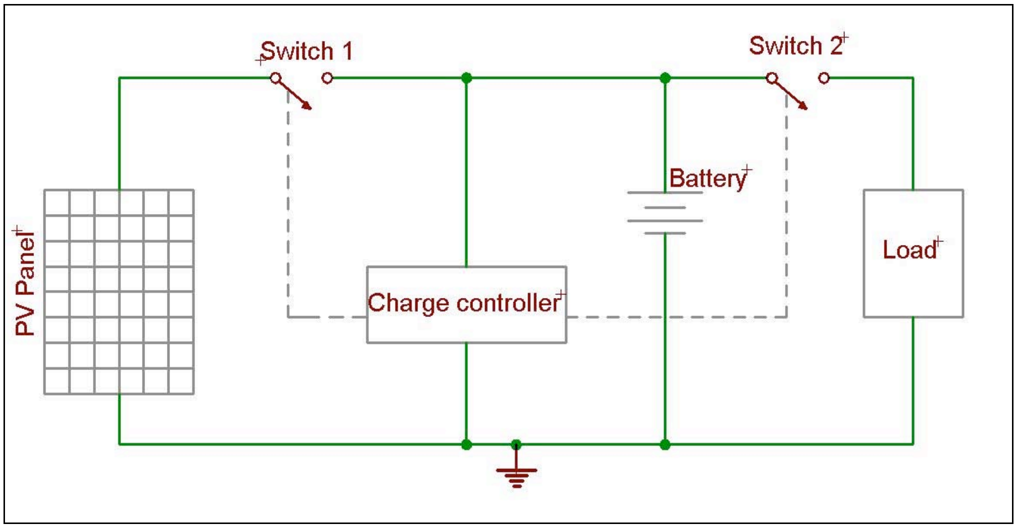

Figure 4.1 Series charge regulator.

The shunt regulator shown in figure 4.2 is limited to use in small photovoltaic systems that generate less than 20 Amperes. This limitation exists because switch 1 dissipates large amounts of power that can generate significant heat. The shunt regulator operates by disconnecting the load via switch 2 when the battery voltage has fallen below the discharge limit. Switch 1 can act as a variable resistor allowing a programmable amount of current to be shunted to ground while the rest goes towards battery charging. The blocking diode protects the system from damage by preventing the battery from discharging into the solar panels. Just as with the series charge regulator, large amounts of power will be dissipated in the switches. This will significantly reduce power efficiency and will necessitate the use of large heat sinks [1].

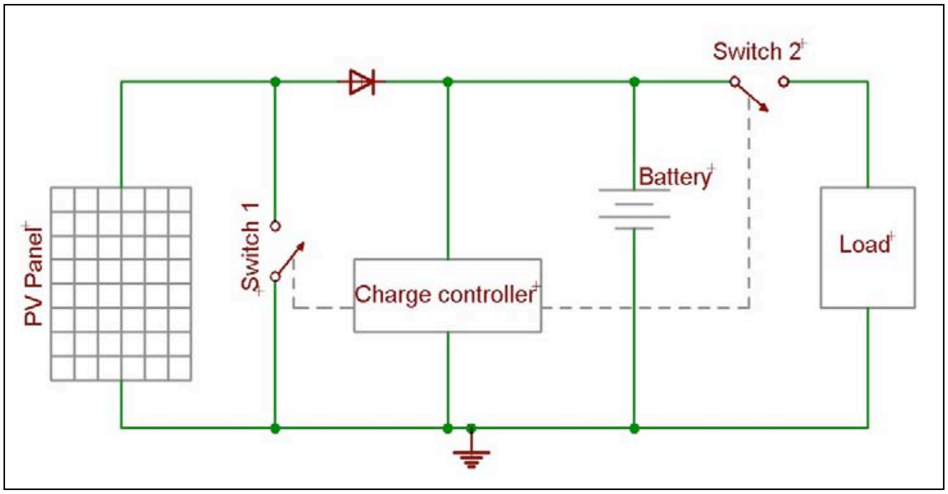

Figure 4.2 Shunt charge regulator.

In systems using multiple solar panels, there is a possible modification to the series and shunt regulators. An alternative to using the *on* and *off* switching to completely connect and disconnect the whole solar array would be to switch individual sub-panels in and out of the charging system. As charging currents would increase towards mid-day, individual panels or sub-arrays would be disconnected. These would then be reconnected as the illumination level fell and more charging current was required [6].

The series and shunt charge controllers both dissipate a lot of power and are limited to use in relatively small solar systems. The more refined system uses a DC/DC converter placed between the solar panels and battery to supply the battery with a completely adjustable amount of charging current. The DC/DC converter will be controlled with a system that monitors the output voltage and temperature of the battery in order to determine its state of charge. This data will then be used to control the PWM feedback loop within the DC/DC converter. As the duty ratio of the DC/DC converter is adjusted, the current supplied to the battery will also be adjusted [1]. Before describing the DC/DC converter charger any further, I will describe common methods that are used to determine the charging current needed by the battery.

The more elaborate variety of charge regulators employ digital systems to measure the quantities needed to determine the state of charge of the battery. These systems will account for temperature variations, voltage inconsistencies cause by internal battery resistance, and other factors that may effect the system. The charge regulator will also be equipped with hysteresis, which will be elaborated on later, to prevent oscillations during charging [3]. A block diagram of a charge controller chip is shown in Figure 4.3.

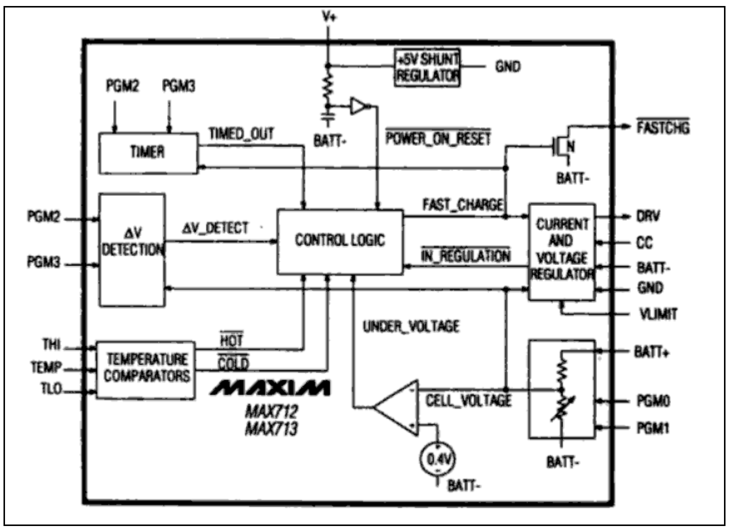

Figure 4.3 Block diagram of charge controller from

Maxim MAX712/713 datasheet. [2]

Each of the charge regulators discussed here uses a variety of battery threshold voltages to manage the charge currents. The primary parameter used in determining a battery’s state of charge is the terminal voltage of the battery. Within the charge controller, which acts to control the charging current supplied by the solar array, there are usually four threshold voltages. The uppermost one is set at the maximum allowable voltage of the battery. The lowermost threshold specifies the voltage where the load is disconnected to prevent excessive discharge. There are also two intermediate threshold voltages. The upper intermediate threshold establishes where normal charging current is re-established and the lower intermediate threshold specifies where the load is reconnected [6].

The need for the multiple thresholds stems from the internal properties of the battery. A battery can be modeled by a constant voltage source in series with an internal battery resistance. The key concept is that during charging, the battery terminal voltage is equal to the sum of the voltage source V_{cell} and the voltage drop across the internal resistance. In this case $V_{terminal} > V_{cell}$. On the other hand, during discharge the battery terminal voltage is equal to the voltage source minus the voltage drop on the battery internal resistance. During discharge, case $V_{terminal} < V_{cell}$ [3]. Figure 4.4 illustrates these concepts.

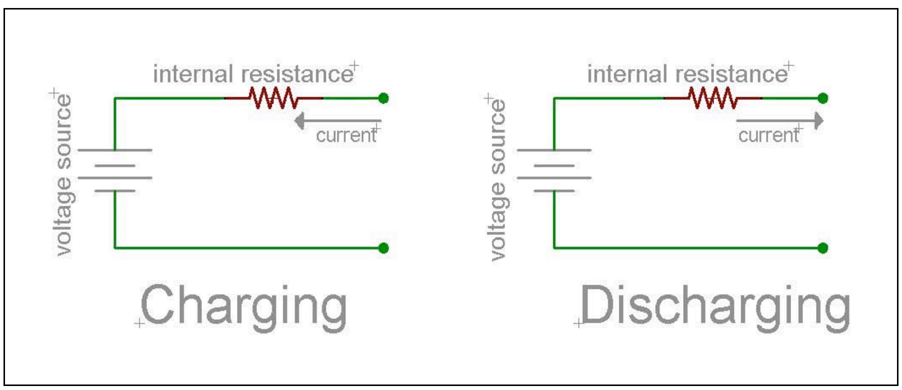

Figure 4.4 Equivalent circuits of battery.

To elaborate on the voltage thresholds, the regulation set point represents the maximum allowable voltage of the battery. Once this threshold is reached the charging current stops or is regulated to a small trickle current. Once the charging current is reduced or eliminated, the battery's voltage will fall by a certain amount. This immediate drop in battery voltage results from the voltage drop on the battery's internal resistance being reduced when charging current is reduced or eliminated. This leads to a problematic oscillatory action where the solar panels will continuously disconnect and reconnect to the battery. This problem can be solved by introducing hysteresis into the system [3].

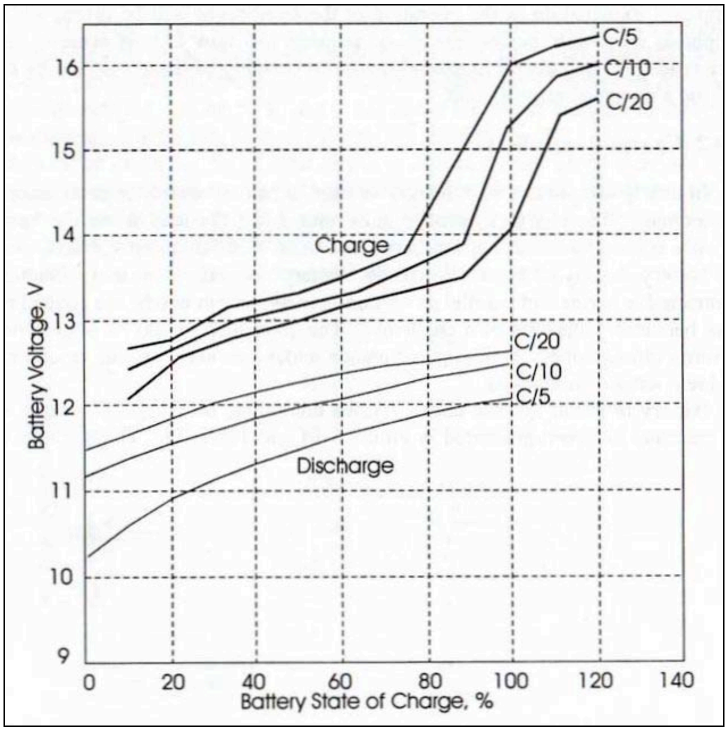

Figure 4.5 This illustration shows how battery voltage depends on current flow [3]. Note* Figure 4.5 shows the relationship between charging current and battery voltage. The value C referred to in the illustration is constant for each battery and denotes the current that is *numerically* equal to the battery's rated capacity. Capacity is essentially the number of electrons that can be supplied by a battery's current and is the integration of current supplied by the cell over time. Capacity is usually specified in units of Ampere-hours. [11]

To introduce hysteresis, the regenerative comparator is especially useful. This type of comparator is an op-amp circuit that uses positive feedback to introduce hysteresis in the comparator’s threshold voltages. For example, once the regulation set point (maximum battery voltage threshold) is surpassed, a *lower* threshold will be introduced. This lower voltage threshold will allow the battery to discharge some before normal charging current is reintroduced. The voltage difference between the regulation set point and the reconnect voltage is often called regulation hysteresis. If the regulation hysteresis is set too small, the system may become damaged and will be noisy due to frequent oscillations [6]. The charging hysteresis curve can be seen on the left hand portion of figure 4.6.

During battery discharge, the lowermost threshold called the low voltage disconnect describes where the load is disconnected to prevent the battery from becoming overly discharged. When the load is disconnected, the battery terminal voltage will increase in the absence of load current and the load will be reconnected. Once again, in the absence of hysteresis at this lower threshold, oscillation will occur as the load is connected and disconnected. With hysteresis, once the low voltage disconnect threshold is passed, a *higher* threshold will be established as the charging current begins. The higher threshold will benefit the system by allowing the battery to receive some charge before the load is reconnected [3].

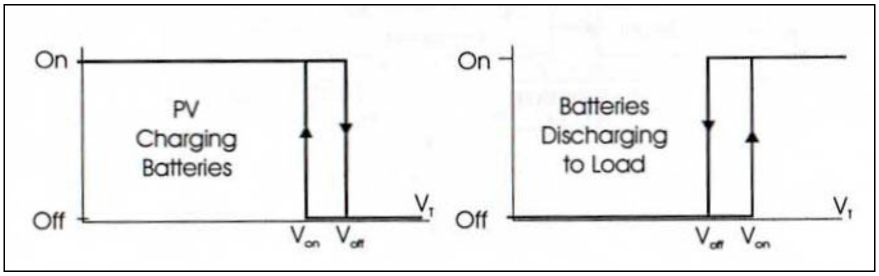

Figure 4.6 Hysteresis curves of battery charging and discharging. [3]

Hysteresis is used in all types of chargers including the shunt, series, and DC/DC converter charge regulators. For the series and shunt chargers, the solar array is most often disconnected and connected depending on which threshold has just been surpassed. The sub-array switching and DC/DC converter chargers have more flexibility in that they can provide a unique charging current depending on which charging threshold has just been passed.

In DC/DC converter chargers, the charging current is generally increased as the battery becomes further discharged and the battery cell voltage falls. Once the cell voltage and temperature reach a certain upper limit, the charging current is reduced to a trickle charge rate [11]. Figure 4.7 shows how a charger adjusts the current into the cell in response to the conditions of the battery. This illustration also outlines how the temperature of a battery increases as is becomes more fully charged. This temperature is also influenced in large part by the ambient temperature. Figure 4.7 shows the behavior of a DC/DC converter charger that supplies current at distinct levels instead of supplying a continuously variable current.

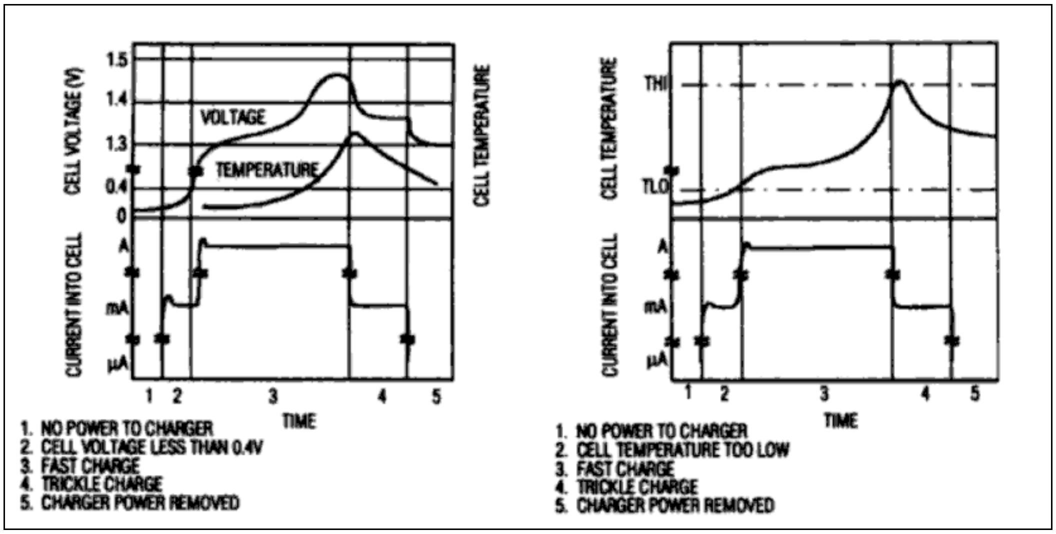

Figure 4.7 Diagram of how charging current is controlled in response to battery cell voltage and temperature. [12]

A complete and more elaborate charge regulator can be represented schematically as in figure 4.8. This particular example contains a charge controller that is equipped with battery voltage and temperature sensors. The shunt shown provides a path for unneeded current to ground. For example, if the battery is fully charged and charging current is eliminated, the current generated by the solar array can be shunted to ground. As battery charge decreases, the priority load selector that can disconnect loads with respect to the importance of the load.

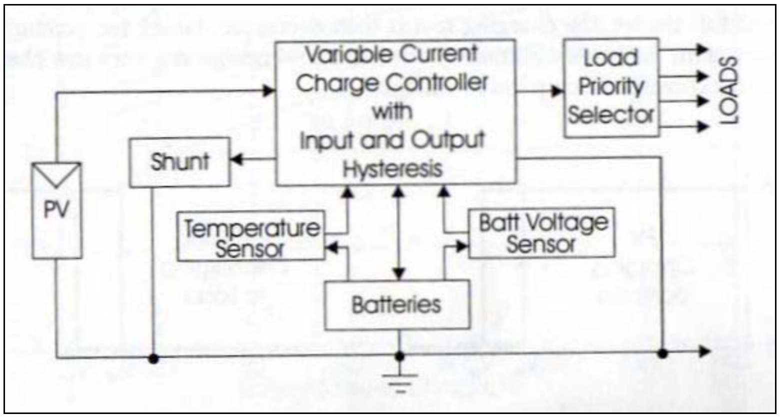

Figure 4.8 A sophisticated type of charge regulator. [3]

Comprehensively, the purpose of the battery charger is to intelligently charge the battery or collection of batteries so that the life of each cell is maximized. Without the charge regulator, the lifetimes of the batteries may become so degraded due to repeated deep discharging and/or overcharging that the costs of the system may become uneconomical. In stand alone systems, the cost analysis should include the materials used to construct a photovoltaic system versus the cost of extending grid services to the proposed location. If the location is remote and far from any grid, the PV system may prove to be more economical as long as resources aren't wasted on destroyed batteries or overly elaborate PV systems. For non-critical applications, it may be more cost effective to consider a simple shunt or series charge regulator instead of the more elaborate DC/DC converter charger.

CHAPTER V

INVERTERS

Since a solar panel is only capable of outputting a DC voltage, a static power converter is usually required to create an AC voltage output. In the case of PV systems, an inverter will be used to make this conversion from a DC voltage to a sinusoidal AC output that is capable of powering conventional home electronics and appliances. Like the DC/DC converter, the inverter uses power switches and a control scheme that utilizes PWM [1].

Currently, inverters are often the primary source of instability in large scale PV systems. If someone were to shop for a PV system capable of supplying power to their home, they may find inverters with 6-10 year warranties while the solar panels are often sold with 20 year guarantees. The difference in guaranteed operation illustrates the awareness that manufactures have concerning the limited lifetimes of inverters.

In addition to stability issues, inverters provide limited power efficiency. On average, inverter efficiency is about 90% and as the load decreases the efficiency can fall below 80%. Like DC/DC converters, most of the energy loss is dissipated as heat in the switching elements within the inverter [1].

The inverter generally works by switching the output state between a positive and negative DC voltage value. The switches will be operated periodically so that the *average* value of the output is equal to that of a true sinusoidal AC waveform. Although, the output of the inverter will not be a true sine wave, filtering components can be used to filter out extraneous frequency content so that a clean 60 Hz signal appears at the filtering output. This filtering system will be made of a capacitor, transformer, and inductors [1].

To describe the operation of a typical inverter, I will begin with the simple single-phase half-bridge inverter. Since the half-bridge inverter only has a two terminal output and is only capable for use in low power circuits, practical applications of it are relatively limited [1]. The half-bridge inverter is shown in figure 14.2.

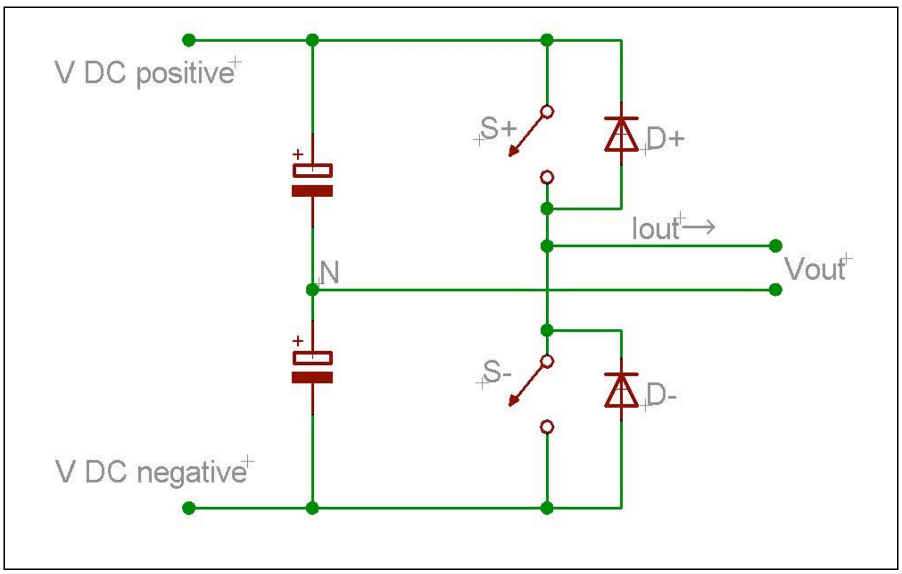

Figure 5.1 Half-bridge inverter circuit.

Like earlier diagrams, the switches are actually transistors that are controlled by PWM. The two capacitors are required to provide a neutral point (labeled *N*) that is halfway between the positive and negative DC inputs. Once connected, the capacitors will each charge up to half of the DC input voltage. From there, the switches *S+* and *S-* will be controlled by a PWM signal to provide a periodically varying output. To prevent the DC supply from being shorted and consequently damaged, it is of utmost importance that both switches are not closed at the same time. For this system there are 3 possible states and one of them is considered undefined. The undefined state should be avoided to prevent ambiguity in the output voltage [1]. The states are outlined in table 5.1.

Table 5.1 Possible states of half-bridge inverter. [1]

State #	State	Vout	Conducting Components
1	*S+* is on and *S-* is off	*(Vin/2)*	*S+* if *Iout*>0
			D+ if *Iout*<0
2	*S-* is on and *S+* is off	*(-Vin/2)*	*D-* if *Iout*>0
			S- if *Iout*<0
3	*S+* and *S-* are both off	undefined	*D-* if *Iout*>0
			D+ if *Iout*<0

The inverter essentially works by utilizing states 1 or 2 which will provide an output that will either be $+V_{in}/2$ or $-V_{in}/2$. The output then simulates a sinusoidal output by switching between states 1 and 2 periodically. The dynamic operation of the switches can be seen in Figure 5.2b and 5.2c.The output, seen in Figure 5.2d, will have an average value and fundamental frequency equal to the dotted sine wave in the illustration. The present output will contain many harmonics and will be composed of discrete values which will vary with large *dv/dt.* To provide a smooth waveform, the load should contain a filtering system, which will be elaborated on later, that eliminates unwanted frequency content [1]. Aside from using filtering components, there exists a variety of methods to minimize harmonic content through the PWM switching scheme.

More specifically, the PWM used in an inverter is referred to as Sinusoidal Pulse-Width Modulation (SPWM). Similar to the DC/DC converter control scheme, a comparator is used to drive the transistor switches either *on* or *off*. For SPWM, there is a sinusoidal control waveform and a sawtooth control waveform at the comparator input.

The sinusoidal and sawtooth control signals will be generated by oscillators and the frequency of the sinusoidal wave will be equal to fundamental frequency of the output [1]. The sinusoidal and sawtooth control waveforms can be seen in figure 5.2a.

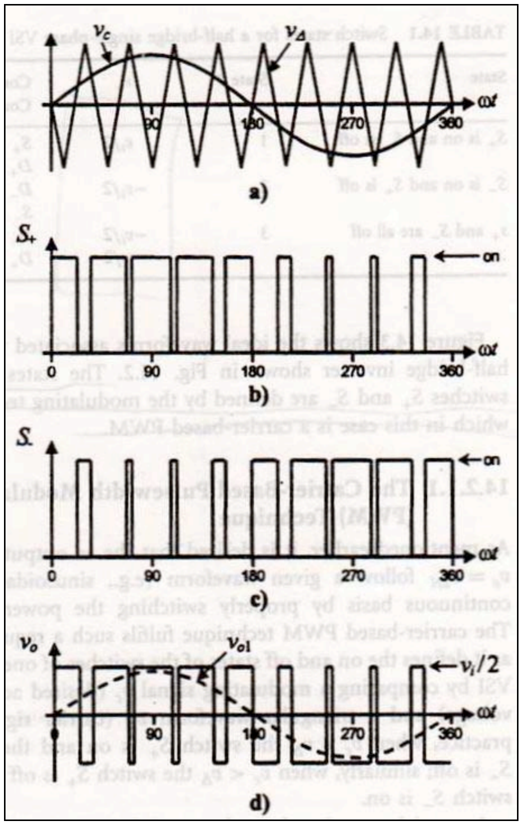

Figure 5.2 Ideal waveforms of half-bridge inverter. [1]

For nearly all inverter applications and especially ones where the inverter is grid connected, the output voltage amplitude and frequency are the centrally important parameters. To ensure proper operation, the SPWM system must monitor the phase of the grid voltage to synchronize the inverter and grid. For possible use in a single-phase grid connected application, the full-bridge inverter is capable of powering higher power circuits than the half-bridge inverter and can be seen in figure 5.3 [1].

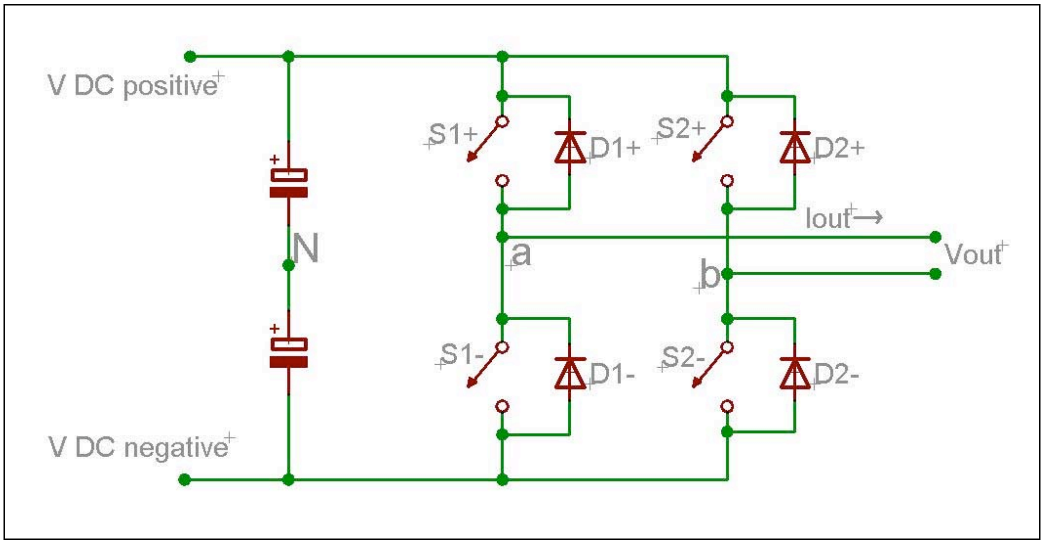

Figure 5.3 Full-bridge inverter.

For the full-bridge inverter, there are four defined states and one undefined as shown in table 5.2. The output can be taken relative to the neutral conductor and output *a* or *b*. Conversely, the output can be exploited by bypassing the neutral connection and taking the voltage across conductors *a* and *b* [1].

Table 5.2 Possible states of full-bridge inverter. [1]

State #	State	VaN	VbN	Vout	Conducting Components
1	*S1+* and *S2-* are on and *S1-* and *S2+* are off	*(Vin/2)*	*(-Vin/2)*	(*Vin*)	*S1+* and *S2-* if *Iout*>0
					D1+ and *D2-* if Iout<0
2	*S1-* and *S2+* are on and *S1+* and *S2-* are off	*(-Vin/2)*	*(Vin/2)*	(-*Vin*)	*D1-* and *D2+* if Iout>0
					S1- and *S2+* if Iout<0
3	*S1+* and *S2+* are on and *S1-* and *S2-* are off	*(Vin/2)*	*(Vin/2)*	0	*S1+* and *D2+* if Iout >0
					D1+ and *S2+* if Iout<0
4	*S1-* and *S2-* are on and *S1+* and *S2+* are off	*(-Vin/2)*	*(-Vin/2)*	0	*D1-* and *S2-* if Iout>0
					S1- and *D2-* if Iout<0
5	*S1-*, *S2-*, *S1+*, *S2+* are all off	*(-Vin/2)*or *(Vin/2)*	*(Vin/2) or (-Vin/2)*	(-*Vin*) or *(Vin)*	*D1-* and *D2+* if Iout>0
					D1+ and *D2-* if Iout<0

The modulating technique should ensure that undefined state 5 is avoided and that the top or bottom of each switch leg is closed at any instant. The full-bridge inverter allows for an output that is equal to the DC input voltage V_{in} which is twice as large as the output supplied by the half-bridge inverter. In addition, the full-bridge inverter can supply an output voltage of zero which will enable it to provide a closer to ideal output waveform. There exists a variety of methods for controlling the full-bridge inverter, but my example will focus on the unipolar PWM technique which employs two sinusoidal control signals that are 180^{o} out of phase. For this technique, one sinusoidal signal will control V_{bN} through switches in the rightmost leg and the other will control V_{aN} through switches in the left leg [1]. The resulting waveforms can be seen in figure 5.4.

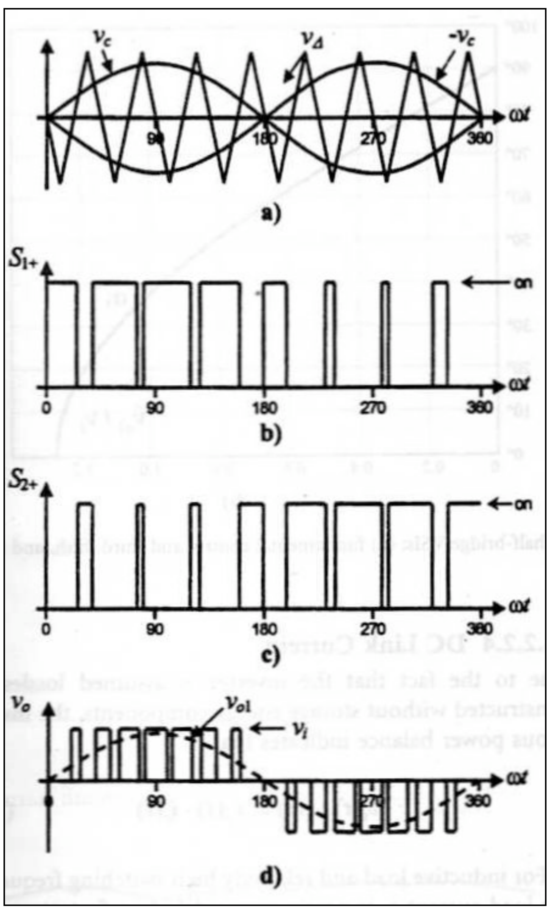

Figure 5.4 Ideal waveforms of full-bridge inverter. [1]

Depending on the load, it may be possible to use a simpler switching technique that doesn't provide a high quality AC signal. For power tools, incandescent lighting, and resistive heaters, the inverter can be operated with a square wave output with little to no adverse effects on reliability and efficiency [1]. However, since most appliances and household electronics require a low-distortion AC input, the inverter with the square wave output may only be utilized for specific scenarios. One likely scenario exists on the Las Vegas strip, where solar panels and a battery system are used to provide lighting for bus stops at night.

In the previous inverter examples, the amplitude of the output depends on the DC input voltage. In most cases, the DC input voltage will not have the necessary voltage amplitude that will be needed for the system output. To remedy this problem, a transformer can be used at the output of the inverter to provide the needed voltage at the system output. Figure 5.5 shows a grid connected inverter system that includes a transformer as well as a filtering capacitor and inductors. The control system in figure 5.5 monitors the phase of the grid and will ensure that the inverter is synchronized with the grid.

The capacitor and inductors in figure 5.5 will form what is known as an L-C filter that will serve to filter out the unwanted frequency components from the output. This is somewhat critical because the filtering will ensure that the output voltage is utility grade AC that can be utilized by home electronics [1]. The L-C filter acts as a band-pass filter by allowing a narrow bandwidth of frequencies to pass through to the output. The bandwidth of passing frequencies are centered around the L-C resonant frequency and can be expressed by equation (5.1). If all frequencies other than the fundamental can be filtered out of the inverter output, it is possible to produce a low distortion sinusoidal waveform at the filtering output. This frequency *f* should ideally be 60 Hz for any grid connected system.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5.1}$$

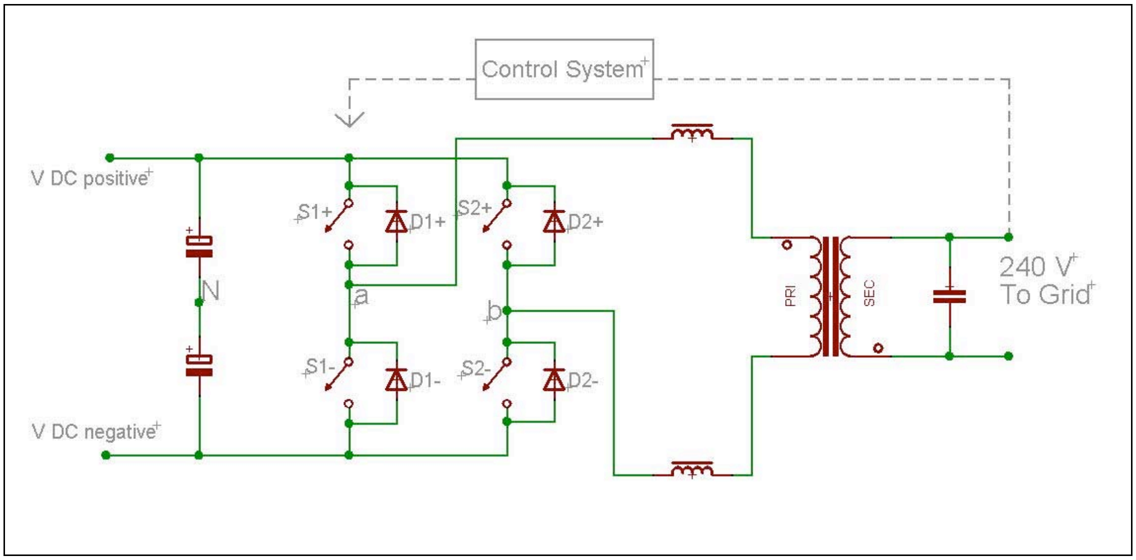

Figure 5.5 Grid-connected inverter system with transformer and filtering components.

Grid connected PV systems can provide many benefits. For example, if the PV system is unable to provide the necessary power to completely power the residence or business it is connected to, the residence will draw additionally needed power from the grid. On the other hand, if the residence has a power demand that is less than the power provided by the PV system, the excess power will be injected back into the grid system and can be bought by the power company. This ability is due to the bi-directional power flow capabilities within an inverter. Power flow from the inverter is controlled by adjusting the phase relationship between the grid and the inverter voltage [1]. Using the previously described characteristics of an inverter, it is possible for the PV system owner to sell electrical power back to the power company.

Since the power provided by PV systems is illumination dependent, care must be taken during power outages where islanding can occur. Islanding occurs when a location still has available power even though power from the electric utility isn't present. Danger to utility workers can occur if the PV system continues to energize the grid without the knowledge of electric company [1].

Now that the fundamental principles that describe inverter operation have been described, an overview of how inverters interface with MPPTs, battery chargers and other types solar systems can now be presented.

CHAPTER VI

EXAMPLES OF INVERTERS IN PHOTOVOLTAIC SYSTEMS

To enhance energy efficiency, it may be prudent to use an MPPT between the inverter and the solar panels. In this case, the MPPT will vary the inverter input voltage until the maximum power point of the *I-V* curve is found [1]. In this type of system, the closed loop PWM in the MPPT will monitor the voltage and current that is at the input of the inverter at all times.

The DC/DC converter can also be utilized by boosting the voltage supplied by the solar panels to a stable input DC voltage at the inverter input. In the case where the inverter outputs to a transformer with a fixed ratio winding, the amplitude of the voltage that reaches the grid is determined by the inverter input voltage. Since the voltage needs to have a proper amplitude before being injected into the grid, the DC/DC converter will provide the inverter input with a fixed DC input despite variations in the voltage supplied by the solar panels or MPPT. Since the maximum solar panel DC voltage is limited by the illumination provided, the best type of DC/DC converter for this application is the boost-converter that was described in chapter 2. An example schematic is shown in figure 6.1 [1].

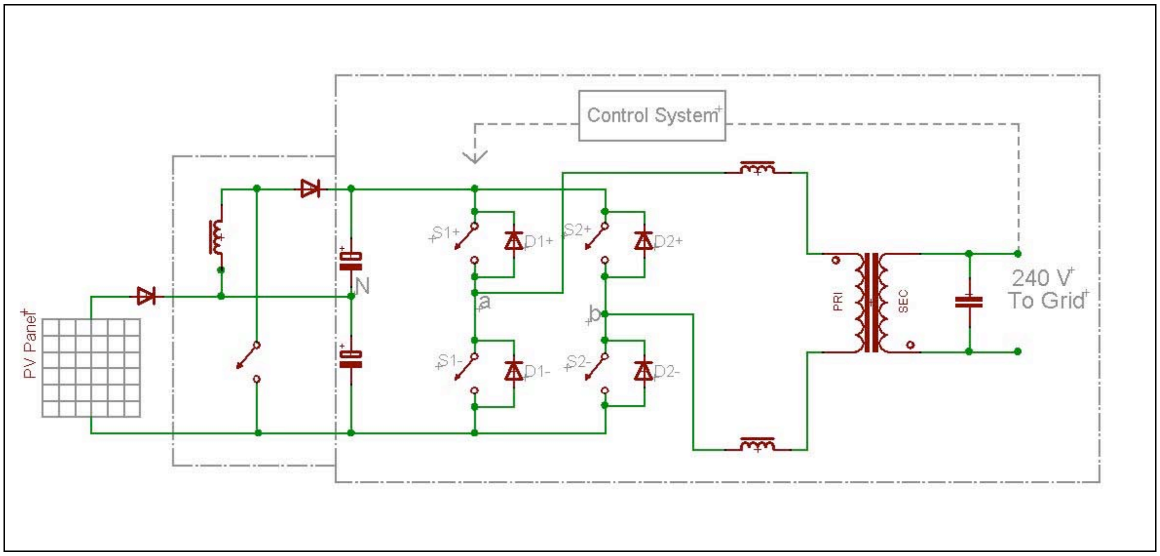

Figure 6.1 Boost converter connected to full-bridge grid connected inverter.

Despite the frequent use of inverters in grid connected systems, they can also be utilized in stand-alone solar systems that require AC capabilities. For this type of system, there will be a battery charging system, battery, and an inverter that are all interconnected. This can be seen in Figure 6.2.

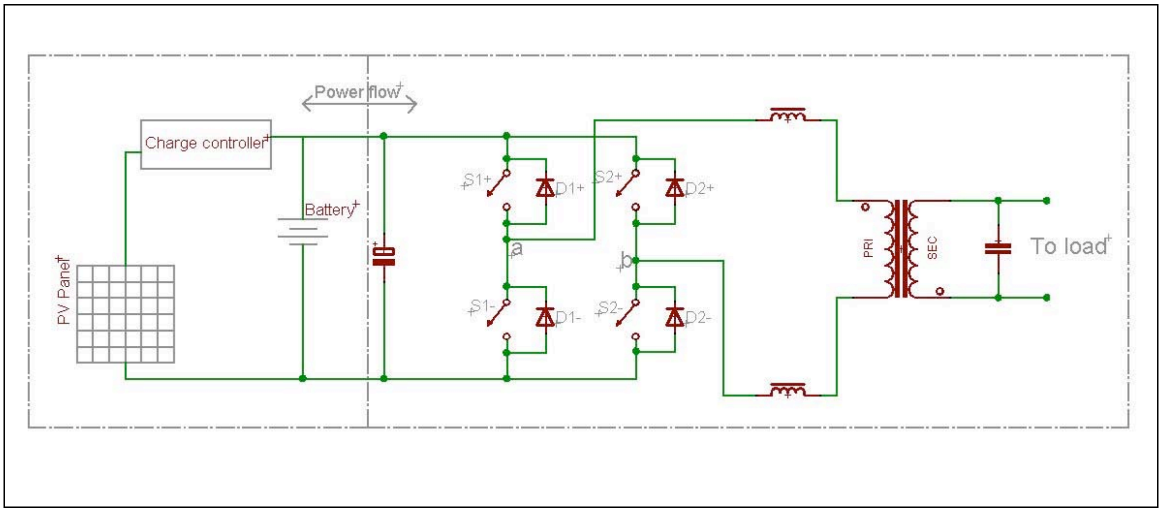

Figure 6.2 Inverter used in stand-alone PV system.

CHAPTER VII

CONCLUSION AND CURRENT DEVELOPMENTS

In comparison to other energy sources such as coal, natural gas, nuclear, wind, and hydro-electric, solar energy is one of the least cost effective. For the most part, the exorbitant cost of solar energy is due to the high cost of manufacturing high quality solar panel material that has a high energy conversion efficiency. Today, most cheaply made solar cells have an energy efficiency of about 14% while the higher quality materials achieve efficiencies of about 20% to 25% [6].

To analyze the effectiveness of clean energy sources, one must account for a variety of factors. Some of these factors include; CO_2 emissions accrued during manufacturing process, manufacturing costs, costs to consumer, power in Watts provided, and CO_2 emissions prevented by use of non-polluting energy source. Although, the analysis can become quite complicated, the two most useful figures are the net amount of CO_2 emissions prevented per dollar spent and the net cost of the energy source. These figures can illustrate the buying incentive that an energy source will provide to any prospective business or consumer.

Despite tax incentives, solar energy is still relatively expensive to a consumer. Therefore, most fundamental challenge facing solar energy researchers is to find a way to enhance solar cell efficiency at a low manufacturing cost. Although the materials used in solar energy are in need of improvement, the effective use of power electronics ensures that the energy generated by solar cells is used as efficiently as possible. If a PV system were constructed with little to no power conditioning electronics, it is highly likely that the preponderance of generated power would be needlessly dissipated in the system components. However, even with a sophisticated system of power conditioning, it is possible during certain conditions that up to 25% or more of the power may be dissipated as heat.

With these shortcomings, current research within the field of power electronics is being carried out with the aim of enhancing energy efficiency of PV systems and their respective power conditioning systems. Furthermore, since inverters exhibit problems in terms of reliability, attempts are being made to enhance the lifetime of inverters for PV systems. Inverters are also one the least energy efficient components in state of the art PV systems with an energy efficiency in the 75-90% range.

With contemporary solar materials that are somewhat costly and typically exhibit efficiencies less than 20%, it is in the interest of the consumer to maximize the power efficiency of the entire PV system. This goal should be motivated by both economical and environmental concerns. Economically speaking, since PV systems are relatively expensive, power efficiency should be maximized so that the investor can get the largest energy return on his investment. Correspondingly and possibly more important, energy efficiency should be increased so that the net CO_2 emissions prevented by the system is as large as possible. As the efficiency and costs of alternative energy sources is optimized, consumers and the business community may choose to use clean energy not only because it is the right thing to do for the environment, but because it will make financial sense.

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