A NOVEL TECHNIQUE FOR MAXIMUM POWER OPERATION OF PHOTOVOLTAIC ARRAYS USING REAL TIME IDENTIFICATION

A Thesis
Presented
to the Faculty of
California State University, Chico

In Partial Fulfillment
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Master of Science
in
Electrical and Computer Engineering
Electronic Engineering Option

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by
Bret Bosma
Spring 2008

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TABLE OF CONTENTS

PAGE

Appendix

LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

ABSTRACT

A NOVEL TECHNIQUE FOR MAXIMUM POWER OPERATION OF PHOTOVOLTAIC ARRAYS USING REAL TIME IDENTIFICATION

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This thesis presents a novel real time technique for maximizing the power output of a photovoltaic (PV) system for commercial applications. The technique uses a parameter identification technique to identify solar irradiation and temperature in real time, and then develops an on line solution to the Maximum Power Point MPP conditions based on an effective solar panel model. Generating the maximum power is important in a photovoltaic system but equally important is what the system does with the power once it is generated. A new power management technique applied to a grid tied system with battery storage is also presented. The power management system is based on a cost optimization taking into consideration a tiered utility rate and storage capabilities of the system. Modes of operation are established based on many factors including the status of the battery and local load demand as well as the time of day related to the utility rate. Based on these inputs the direction and magnitude of power flow in the system is established and controlled.

Results of the proposed techniques were presented on a simulated commercial system and under realistic solar energy availability conditions. The proposed technique effectively identified the operating solar conditions and yielded an optimized panel power tracking. Comparison of the theoretical maximum power point to the identified showed close correlation. Simulation of the proposed power management system also showed successful system operation under a wide range of operating modes and a variety of input data.

CHAPTER I

INTRODUCTION

Social and environmental responsibility, rising energy prices, and depleted reserves of easily attainable fossil fuels have spurred a need for developing alternative sources of energy. This has been successfully accomplished using wind, hydro, geothermal, and solar power. These sources of energy have the potential of offsetting a significant portion of the worlds energy needs. In the United States plans have been proposed for solar power to end the U.S. dependence on foreign oil by 2050[1]. From enormous corporate rooftops [2] to small off the grid residential systems, solar is guaranteed to be part of the energy solution. Inexpensive and efficient production and management of this power is crucial to making photovoltaic systems a viable solution.

In this research a model of a photovoltaic generation and distribution system including a solar panel, boost converter, battery, and inverter will be presented. A method of parameter identification used to locate the maximum power point (MPP) of a solar panel will be used to improve efficiency. A power management scheme for the photovoltaic grid integrated battery system will address reducing net costs. The overall goal of this research is to explore techniques in achieving an efficient, cost effective, photovoltaic system.

Current Photovoltaic Technology

A photovoltaic (PV) cell is a pn junction or Schottky barrier device specifically designed for power generation. When photons strike the cell they knock electrons in a specially doped silicon n-type layer loose. These electrons then try and fill holes created in a specially doped p-type silicon layer. If a conductive path is provided, electrons will flow. A diagram illustrating this phenomenon is shown in Fig. 1.

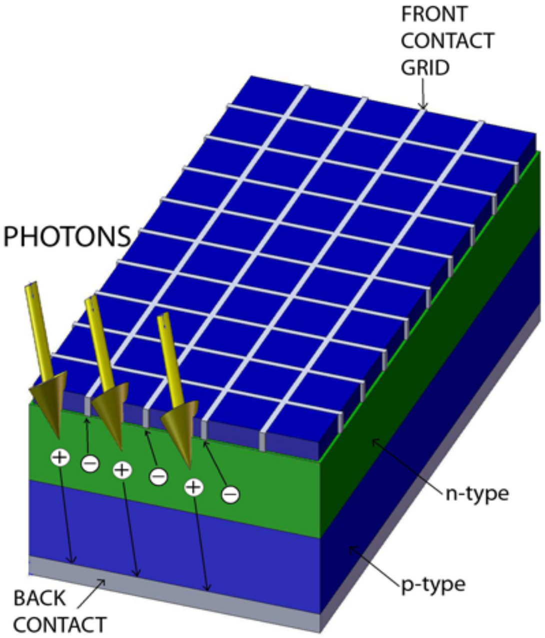


Fig. 1: PV Panel Diagram

In [3] the types and adaptations of photovoltaics are reviewed. There are three major types of silicon type cells, single crystal, polycrystalline, and amorphous type cells. There are four major variations in junction types, homojunctions, heterojunctions, direct and indirect band gap, and Schottky barrier. Current research includes the possibilities of a liquid interface, organic materials, and intermediate transitions. There are many multielement materials that have favorable semiconductor junction properties. These are typically used in thin film applications with copper indium gallium selenide, cadmium telluride, and gallium arsenide being popular combinations. Variations in cell construction also have been explored including thin film cells, stacked cells, vertical multi-junction cells, reflecting or textured surfaces, passivated emitter rear locally diffused, and sliver cells as options. Leading organic thin film research is currently being performed at Stanford University [4] with the focus on low cost light weight easy to process abundant organic materials.

Regardless of the methods of creating a solar cell, a mathematical model can be produced. Techniques in acquiring a model include generating equations based on experimental data, and generating equations based on known constants and general properties. Whichever model is chosen, the model for a solar cell can easily be expanded to achieve a model for a solar panel consisting of many cells arranged in series and parallel. Solar panels can then be expanded in series and parallel combinations to create a model for an array of panels.

The Maximum Power Point Challenge

The maximum power point challenge involves automatically forcing the cell, panel, or array, to operate at the combination of current and voltage that produces maximum power output at all times. Typically this is achieved by tracking the MPP using a power converter to adjust either the voltage or current of the panel. Given a specific irradiation and temperature, a solar cell, panel, or array has the possibility of operating anywhere along a current-voltage (I-V) curve producing varying power output.

For each case of temperature and irradiation there is one maximum power point at which the cell will operate. A typical I-V curve set is shown in Fig. 2.

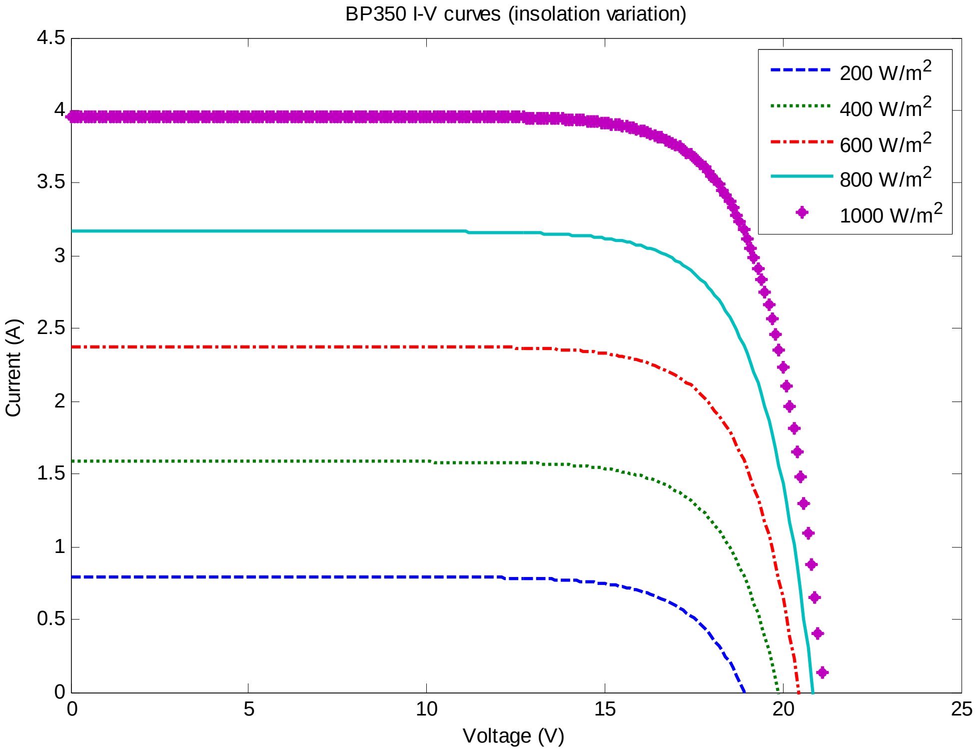


Fig. 2: Typical set of I-V Curves

Most techniques constantly push toward the maximum power point either not responding quickly enough or overshooting the MPP causing the operating point to oscillate about the MPP but never attaining it. Fig. 3 shows a typical P-V curve. Notice how the maximum power point is obvious on the P-V set of curves. As is shown in the next section most current techniques push toward the peak on one of these curves.

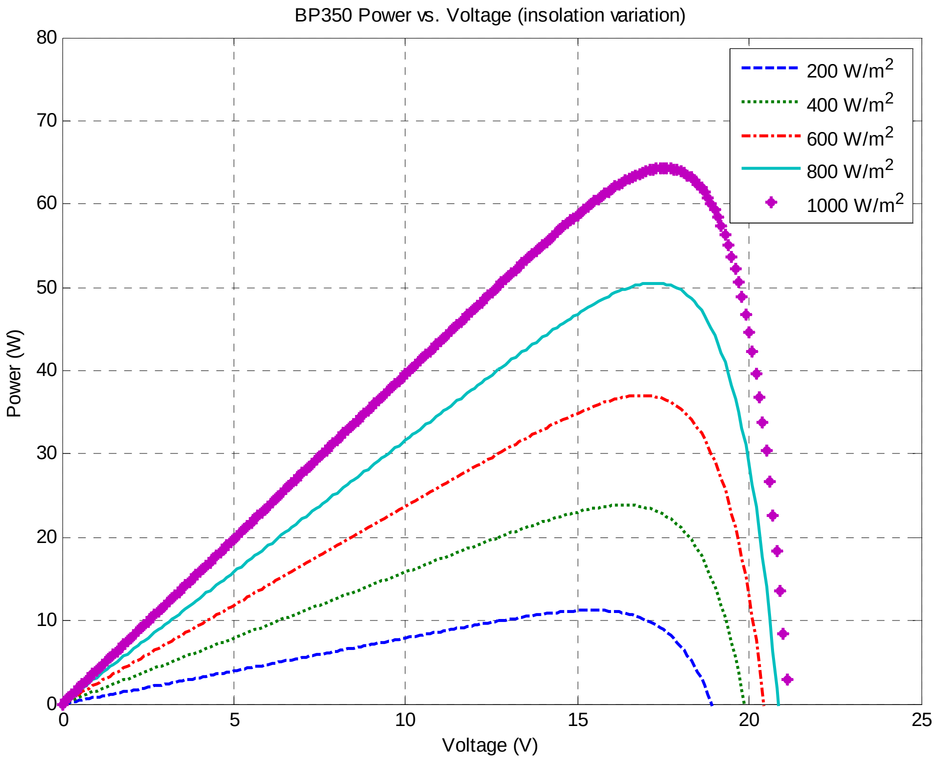


Fig. 3: Typical set of P-V Curves

An Overview of Maximum Power Control Techniques

There are many developed methods of tracking the maximum power point of a photovoltaic array [5]. These include the popular techniques of Perturb and Observe, Incremental Conductance, and Fuzzy Logic Control techniques. One of the major challenges is keeping the system cost down. Although it would be useful to know the panel temperature and irradiation, the apparatus necessary to do this adds to the initial and operating costs of the system. Most techniques measure only current and voltage out of the panel and control a dc-dc power converter.

In the Perturb and Observe technique the voltage of the panel is either increased or decreased and the resulting power is measured. If there was an increase in power from the last control period, the voltage is again perturbed in the same direction. If there was a decrease in power in the last control period, the direction of the perturbation is reversed. When repeated under relatively uniform conditions it creates a situation where the system oscillates about the MPP. This oscillation can be minimized by decreasing the step size; however, this slows down the process of tracking the MPP. Under rapidly changing irradiance and temperature this method can fail causing the system to diverge. There are many techniques that have attempted to overcome these obstacles with varying degrees of success [6], [7], [8].

The Incremental Conductance method requires the slope of the power-voltage curve to be measured. If the slope is positive, the voltage needs to be increased. If the slope is zero the MPP is achieved. If the slope is negative the voltage needs to be decreased. This is accomplished by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$). Based on the results of this comparison the voltage is increased or decreased accordingly. Again, there are possibilities for oscillations around the MPP and again there have been methods that attempt to address this issue.

Fuzzy Logic Control techniques have become a popular MPP solution. Fuzzy techniques work well with addressing the nonlinear nature of the PV system. Inputs usually include the error ($\Delta P/\Delta V$) and the change in error (ΔE). Fig. 4 shows a typical Three dimensional contour plot showing the output boost value versus the error and change in error.

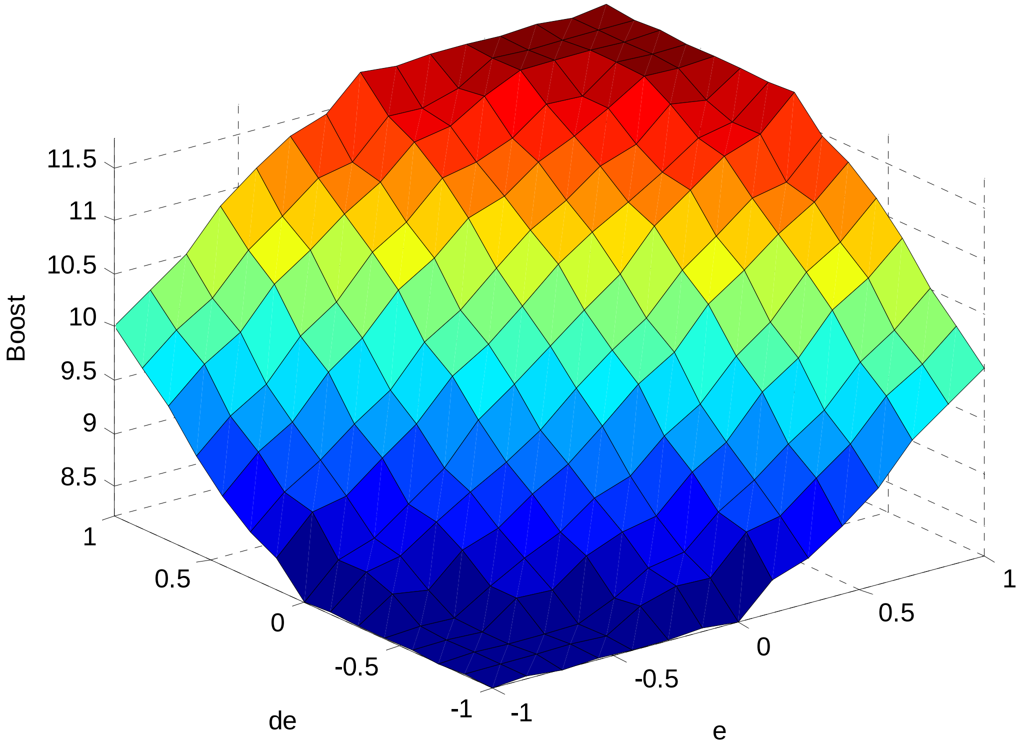


Fig. 4: Fuzzy Contour Plot

The output of the system is typically a change in the duty cycle of the power converter. Fuzzy systems respond well to rapidly changing irradiation and temperature. However, the system requires the use of a microprocessor that needs to be tuned to optimize its effectiveness. This often needs to be done by a user or engineer. There have been adaptive techniques proposed [9] that automatically tune the system providing rapid convergence and small fluctuations around the MPP. Recent developments have been made in photovoltaic fuzzy applications related to power management in a stand alone system [10].

New Approach Using Identification

Maximum Power Point Tracking techniques are effective at staying near the optimal operating point for certain conditions, but each technique either has some error while searching for the MPP or fails all together. The approach presented in this research uses a parameter identification technique to identify, real time, the existing irradiation and temperature values then solve a model of the solar panel for the MPP voltage. A least squares approximation algorithm solves a set of algebraic equations to find the current operating irradiation and temperature. These values are then used to determine the voltage of the MPP of the panel. With this technique, instead of pushing toward the MPP, the MPP is identified and directly implemented eliminating delay and overshoot in the system.

Power Management Approach

Generating the maximum power is important in a photovoltaic system but equally important is what the system does with the power once it is generated. According to Gevorkian [11] there are four major types of solar power systems: directly connected dc solar power system, stand-alone dc solar power system with battery backup, stand-alone hybrid solar power system with generator and battery backup, and grid-connected solar power systems. The system configuration proposed in this research combines a grid-connected and battery based system. A typical system block diagram for power flow is shown in Fig. 5.

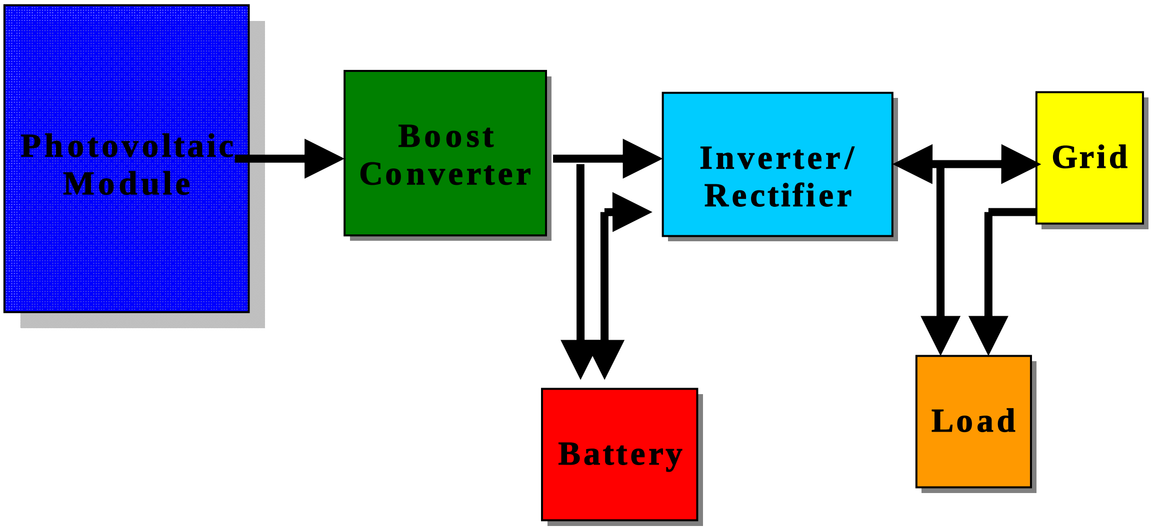


Fig. 5: Power Management Block Diagram

This system is based on a concept of storing energy in the batteries when the utility rate is low and using this power locally when the rate is high.

A management process built on the concept of modes of operation is developed in [12]. The authors define four modes of operation strictly based on the time of day. The new approach used in this paper has time of day as an input to the management system but mode decisions are based on several system parameters. It also takes advantage of a multi-mode system where a number of environmental and economic variables decide what the current mode of operation is. This provides both efficiency and economic benefits to the system. Recent research in this area includes fuzzy algorithms designed for domestic photovoltaic use [13].

Organization of Thesis

In this chapter a survey of photovoltaic properties, systems, management schemes and maximum power point algorithms was presented. In chapter II the components utilized in this research were introduced and models developed. Also, photovoltaic power utilization methods in general and the proposed method in this paper were introduced. Chapter III details the method of identification as implemented on the maximum power point challenge. Chapter IV develops and details the management scheme for this research. Chapter V gives the complete system results, integrating all modeled system components into the final simulation. Finally, Chapter VI gives a summary and conclusions for the paper.

CHAPTER II

PHOTOVOLTAIC POWER GENERATION AND UTILIZATION

An overview of the current photovoltaic technology and power management systems has been presented in the previous chapter. In this chapter, more detailed insight into the system structure and components used in this research is described. Component models and analysis of these models are presented to establish a platform on which control systems and management schemes can be made. The PV panel will be modeled and analyzed. Typical power utilization schemes will be introduced with their component models developed and analyzed.

Modeling the Photovoltaic Panel

The model for a photovoltaic panel array starts with the solar cell, which is essentially a semiconductor p-n junction that can be represented by the equivalent circuit shown in Fig. 6. This circuit includes a photodiode wired across an ideal current source with an intrinsic shunt and series resistance. From this circuit a set of mathematical equations are developed to represent the current-voltage (I-V) relationship of a solar panel array as shown in [14] and equations (1),(2),(3),

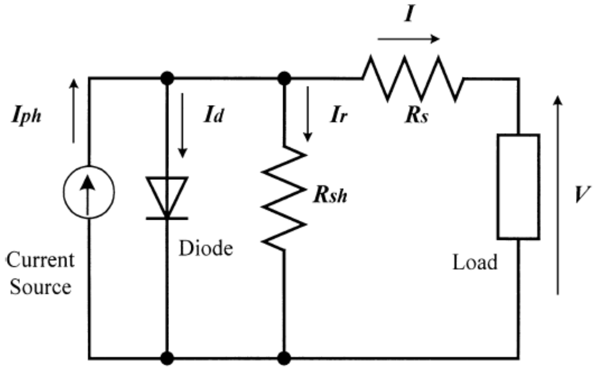


Fig. 6: PV Cell Equivalent Circuit

$$I = n_p I_{Ph} - n_p I_{rs} \left(e^{\left(\frac{qV}{kTAn_S}\right)} - 1 \right) \tag{1}$$

$$I_{rs} = I_{rr} \left(\frac{T}{T_r}\right)^3 e^{\left(\frac{qE_G}{kA}\left[\frac{1}{T_r} - \frac{1}{T}\right]\right)} \tag{2}$$

$$I_{Ph} = \left[I_{scr} + k_i \left(T - T_r\right)\right] \frac{S}{100} \tag{3}$$

where I is the PV array output current in amps; V is the PV array output voltage in volts; n_s is the number of series cells; n_p is the number of parallel groups of series cells; *q* is the charge of an electron; *k* is Boltzmann's constant; A is the p-n junction ideality factor; T is the cell temperature in °K; T_r is the cell reference temperature; I_{rr} is the reverse saturation current at T_r ; E_G is the band-gap energy of the semiconductor used in the cell; I_{scr} is the cell short-circuit current at reference temperature and radiation; k_i is the short circuit current temperature coefficient; S is the solar radiation in mW/ cm^2. The cell reverse saturation current I_{rs} varies with the temperature as shown in (2). The photo-current I_{Ph} varies with the solar irradiation and the temperature as shown in (3).

Typically the manufacturer will provide values of the short-circuit current, I_{scr}, the number of series and parallel cells, n_s, n_p, and a set of I-V curves for different temperatures. Boltzmann's constant k and the charge of an electron q are known constants. The rest of the constants can be found by matching a set of simulated I-V curves, as shown in the following section, to the manufacturers. For this research project a BP-350 50 Watt photovoltaic module was modeled. The photovoltaic panel data sheet gives the short circuit current and number of series and parallel cells as well as a set if I-V curves for varying temperature [15]. Other ways of generating a photovoltaic model include using experimental methods as well as other theoretical methods [16].

Photovoltaic Panel Performance

Using the model outlined in the previous section, a MATLAB^{TM} simulation program (I_V_Variation.m) has been developed to generate I-V and Power-Voltage (P-V) curves for the BP-350 panel as shown in Appendix A. The output from this program shows the array's sensitivity to the atmospheric conditions of temperature and irradiation. Fig. 7 shows the I-V and P-V curves for five different irradiation levels at a fixed temperature of 25 deg C. The biggest rectangle that can be drawn under an operating point I-V curve would give the MPP as the upper right corner of this rectangle. Notice that each curve has a different MPP and that the array current and power depend on the array terminal operating voltage. Fig. 8 shows the I-V and P-V curves for five different

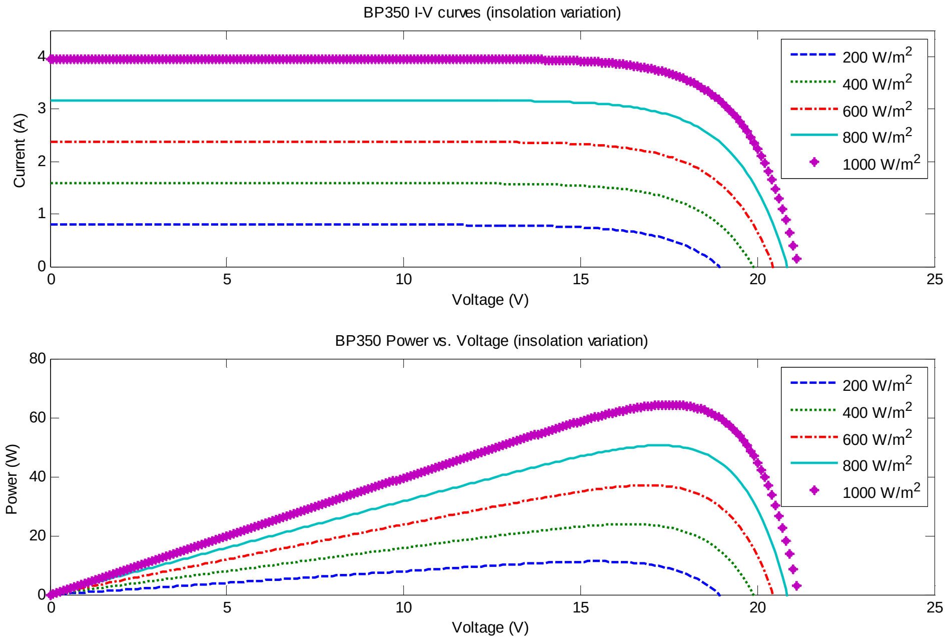


Fig.7: I-V and P-V Curves (Irradiation Variation)

temperatures at a constant irradiation of 80mW/cm^2. The benefits of operating at the MPP are apparent as any change in temperature or irradiation will move the MPP.

In the next section, given the irradiation and temperature for an operating point, an algebraic expression will be developed that will provide a solution to the Voltage at the MPP (V_{max}).

Maximum Power Operation

As is shown in the P-V curves, the MPP is at its maximum when the slope of the power curve is zero or $\frac{\partial P}{\partial V} = 0$. Having established a mathematical model for the photovoltaic panel that give us the I-V relationship, the next step is to find a mathematical relationship for the output power of the panel. Using eqn. 1 and

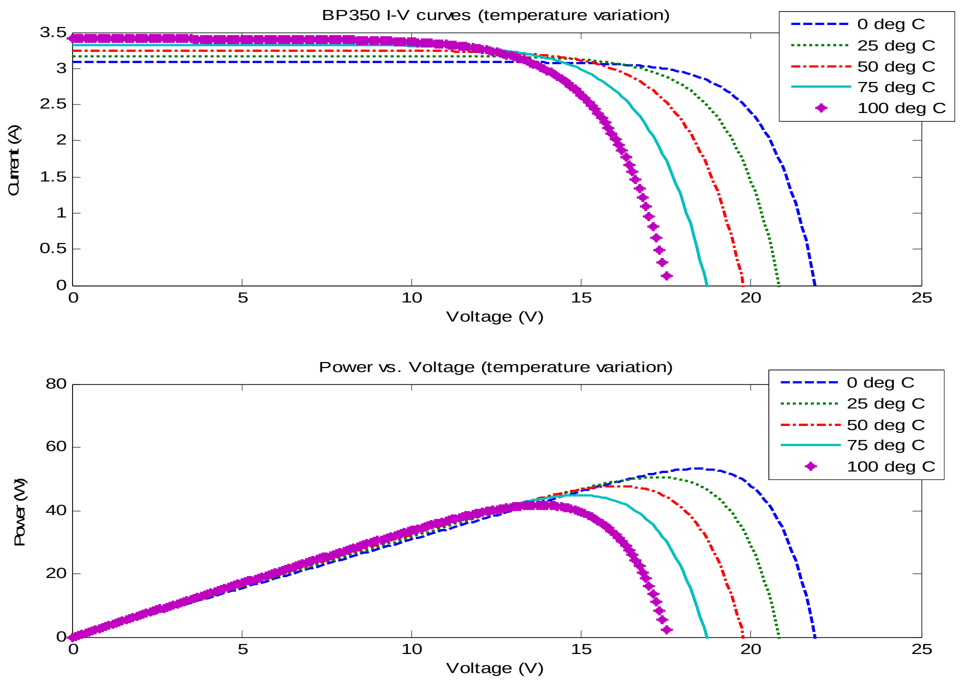


Fig. 8: I-V and P-V Curves (Temperature Variation)

multiplying both sides by V, the power output of the panel can be represented as shown in eqn. 4.

$$P = IV = n_p I_{Ph} V - n_p I_{rs} V \left(e^{\frac{qV}{kTAn_s}} - 1 \right) \tag{4}$$

A mathematical relationship for the maximum power operating voltage, V_{max}, can be calculated by taking the partial derivative of P with respect to V, setting $\frac{\partial P}{\partial V} = 0$ as shown in eqn. 5,

$$\frac{\partial P}{\partial V} = n_p I_{Ph} - n_p I_{rs} \left(e^{\frac{qV}{kTAn_s}} \left(1 + \frac{Vq}{kTAn_s} \right) - 1 \right) = 0 \tag{5}$$

this results in eqn. 6,

$$e^{\frac{qV_{\max}}{kTAn_s}} \left(\frac{qV_{\max}}{kTAn_s} + 1 \right) = \frac{I_{Ph} + I_{rs}}{I_{rs}} \tag{6}$$

so for a given irradiation and temperature the maximum power voltage V_{max} can be calculated using this algebraic equation. This would be useful if we knew the temperature and irradiation at any given time. The problem is that we do not readily have that information as outlined in the next section.

Practical Limitations to Maximum Power Operation

As discussed in the previous section, in order to determine mathematically the MPP, the atmospheric conditions of temperature and irradiation must be known. In most situations it is not cost effective to accurately measure the temperature and irradiation levels surrounding an array in order to determine the MPP. As outlined in Chapter I, a method of tracking the MPP is usually taken. Since it is relatively inexpensive to measure the current and voltage of the photovoltaic array, tracking techniques are usually accomplished using these measurements. Now that the model of the PV panel and MPP has been explained, the discussion will turn to the utilization of the generated power from the PV panels.

General Photovoltaic Power Utilization Schemes

Two of the major schemes for utilization of photovoltaic power are outlined in this section followed by the method proposed by this research. Although there are other schemes, methods related to residential and commercial systems are discussed. The implementation of a MPP controller is done with a dc-dc converter. The following section shows the details of the boost converter model used in this research.

Off Grid Photovoltaic Systems

Off Grid or Stand-Alone PV systems are generally practical when there is no utility within reasonable reach of the system. As the cost of PV systems decrease, the distance from grid connected power that makes economic sense for a stand alone PV system decreases as well. Design criteria such as load determination, battery sizing, and PV sizing are critical in an off grid installation. Generator backup and hybrid systems are frequently part of these systems in the case of prolonged cloudy weather or as a supplement power source. Off grid systems often consist of a battery, charge controller, dc-dc converter, and PV panels.

Once the MPP voltage is identified, or in the case of most trackers a direction and magnitude of change is identified, a boost converter circuit is needed to change the operating voltage of the photovoltaic panel. Fig. 9 shows a boost converter circuit where the output voltage is controlled by the switching of a MOSFET. The transfer function for the ideal circuit model of Fig. 4 is $\frac{V_o}{V_{in}} = \frac{1}{1 - Duty}$ where *Duty* is the duty cycle of the pulse width modulation (PWM) signal used to drive the MOSFET. It was assumed that the boost circuit is ideal and that its response is rapid. In order to simulate the control response of this dc/dc converter a simple Proportional-Plus-Integral (PI) controller is included with above booster circuit as shown in the block diagram of Fig. 10.

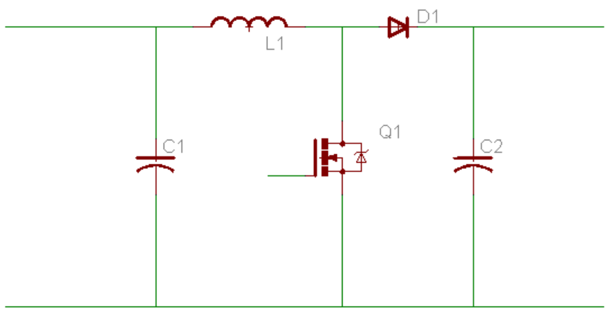


Fig. 9: DC-DC Boost Converter Circuit

In order to simulate the control response of this dc/dc converter a simple Proportional-Plus-Integral (PI) controller is included with above booster circuit as shown in the block diagram of Fig. 10.

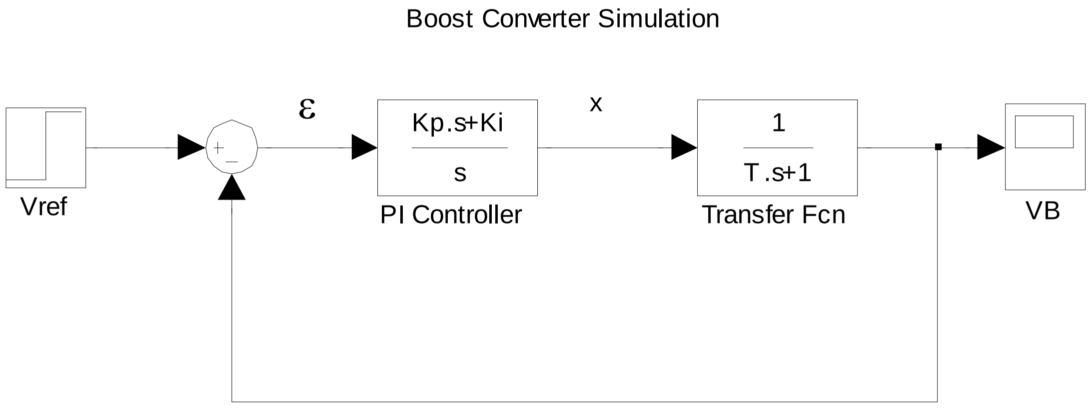


Fig.10: Boost Converter Block Diagram

The input to this system is the desired operating voltage (V_{ref}). There is a PI controller and a response given for the boost circuit. Analysis of this block diagram produced the set of differential equations 7 and 8.

$$\frac{dV_b}{dt} = \frac{x - V_B}{T} \tag{7}$$

$$\frac{dx}{dt} = K_p V_{refxdot} - K_p \left(\frac{x - V_B}{T} \right) + K_i V_{ref} - K_i V_B \tag{8}$$

The analysis of these equations was achieved using the ode23 command in MATLAB^{TM}.

Off grid PV systems provide a great, cost effective solution if the location is far from the electrical utility. For the locations near the electrical utility a grid tied PV system provides an economically sound solution.

Grid Tied Photovoltaic Systems

Grid tied or utility interactive systems currently make the most economic sense if the location is near the electrical grid. These systems typically do not include batteries and have what is commonly referred to as a Power Conditioning Unit (PCU) which houses the inverter and MPP control system fit for interacting with the grid. In order to connect to the grid in the United States a number of codes and standards must be met. The PV system must meet IEEE standard 929-2000, the PCU has to meet UL 1741, and the installation has to fall under the current National Electrical Code [17].

Any PV grid tied system will have an inverter circuit. In this research, a model for the inverter circuit was built based on a PWM based inverter [18]. A PWM signal drives the Insulated Gate Bipolar Transistors (IGBT) which we assume to be ideal. The mathematical model is then the response of the filter network shown in Fig. 11.

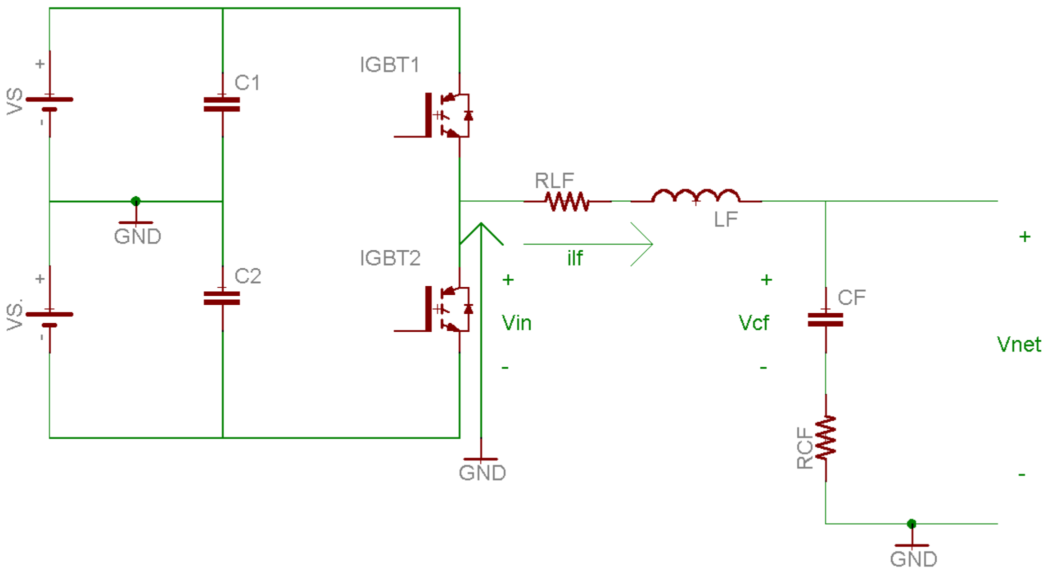


Fig.11: PWM Inverter Circuit

Analysis of this filter circuit provides the set of equations(9),(10),(11).

$$\frac{dV_{cf}}{dt} = \frac{V_{net}}{R_{cf}C_f} - \frac{V_{cf}}{R_{cf}C_f} \tag{9}$$

$$\frac{di_{lf}}{dt} = \frac{V_{in}}{L_f} - \frac{V_{net}}{L_f} - \frac{R_{lf}i_{lf}}{L_f} \tag{10}$$

$$i_o = i_{lf} - \frac{V_{net} - V_{cf}}{R_{cf}} \tag{11}$$

The differential equation solver in MATLAB$^{\text{TM}}$ ode23 was used to solve these equations. Grid tied systems are the most widely implemented systems today because of their cost effectiveness. Most residential and commercial customers rural and urban live near the utility.

When a grid tied system is generating more than the local loads are using the excess power can be returned onto the grid or when the system is not generating enough for the local loads the grid can supply the local system. Now consider the best of both worlds, being able to store energy in a battery bank when advantageous and put power back into the grid when that is desirable.

A Commercial Grid Tied System With Battery Storage

Many commercial customers have a tiered energy rate. For instance, a business may pay a higher rate per kilowatt hour for peak hours, say, 12:00pm-6:00pm, and a lower rate for non peak hours, say, 6:00pm-12:00pm. Suppose a system could store energy during non peak hours and then use the stored energy locally during the peak hours. This is the type of power management system proposed in this paper. The overall system block diagram is shown in Fig. 12 which includes the possible paths for power to transfer.

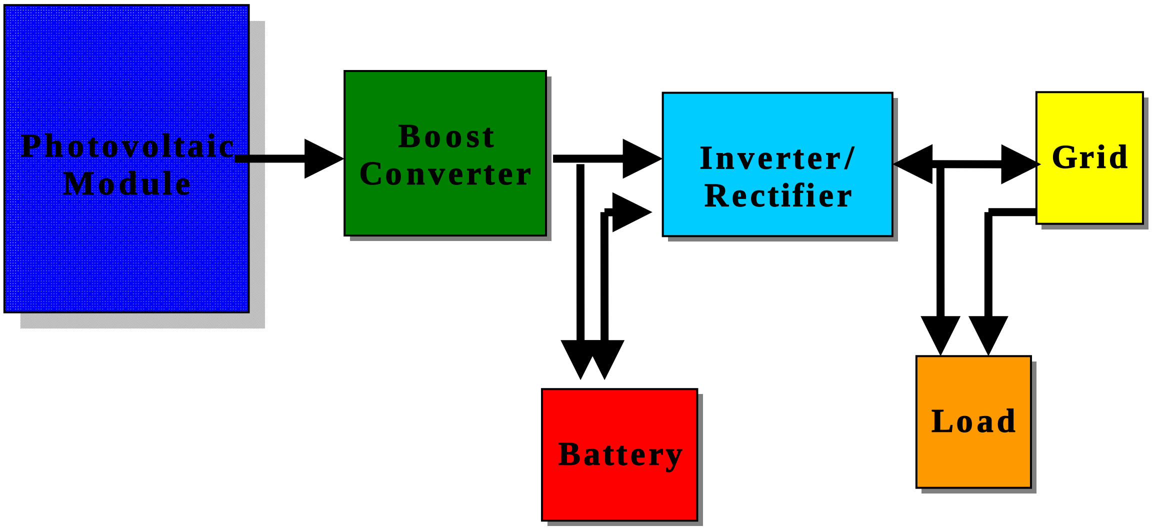


Fig.12: System Block diagram

In order to manage the power flow in the system a control loop is needed on the inverter circuit. This will allow for different charging rates on the battery. Depending on the state of charge (SOC) of the battery only so much of the PV power will be inverted. Fig. 13 shows the control block diagram.

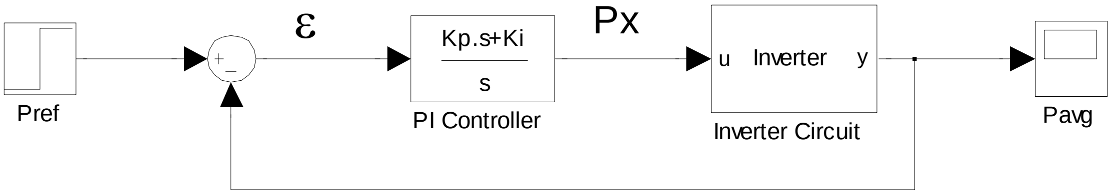


Fig.13: Inverter Control Loop

The control consists of a simple PI controller and inverter circuit model in a unity feedback loop. Analysis of this block diagram gives (12).

$$\frac{dP_x}{dt} = -K_p \frac{dP_{avg}}{dt} + K_i P_{ref} - K_i P_{avg} \tag{12}$$

A MATLAB^{TM} simulation program (Inverter.m) has been developed to generate the signal P_{avg}, which is the output of the inverter for an input of P_{ref}, as shown in Appendix A. Fig. 14 shows the output of this simulation. The alternating current (AC) out of the inverter, output voltage (24V AC), and the output power are plotted vs. time. It is assumed that the system would have a step up transformer that would bring the AC signal up to grid voltage levels.

In summary, this chapter described the model for the photovoltaic system and established the need for MPP operation. An outline of system control schemes has been also discussed. The novel grid tied battery storage system presented in this project will include a control scheme to manage the power between the different components in the system. This will be presented in Chapter IV.

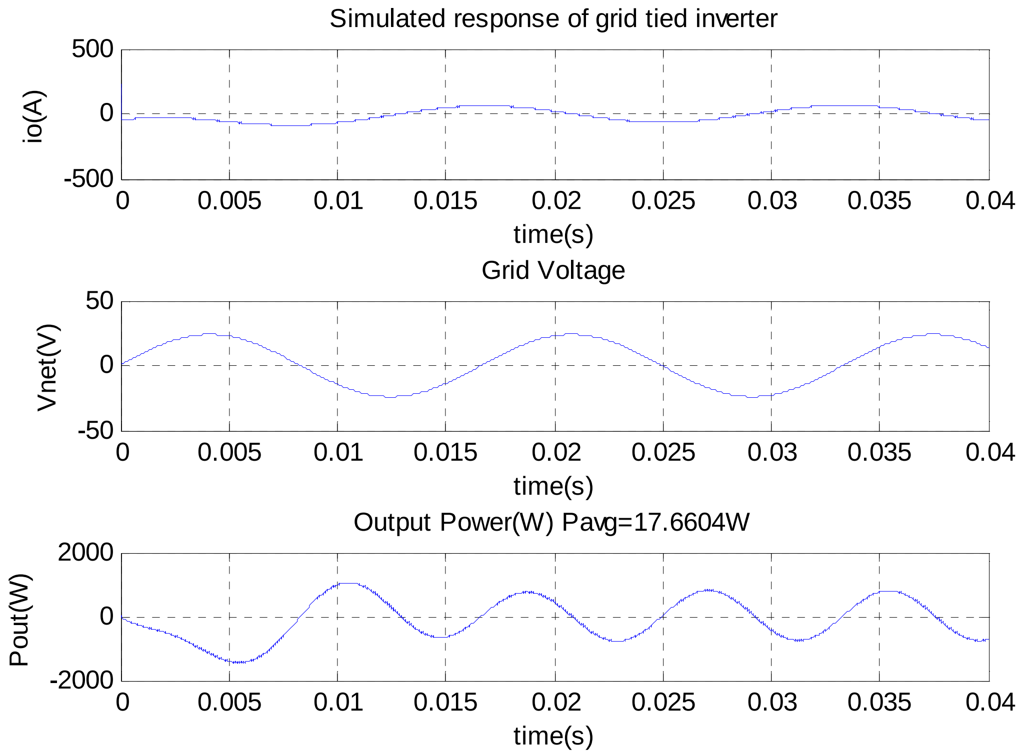


Fig.14: Inverter Simulation Results

CHAPTER III

MAXIMUM POWER OPERATION USING REAL TIME IDENTIFICATION TECHNIQUES

This chapter establishes the process of identifying the existing system parameters of irradiation and temperature real time. Based on the photovoltaic model and measured data, the estimated temperature and irradiation values are calculated by solving a set of algebraic equations based on a least squares approximation.

An Overview of System Identification

System identification is a method that is used in digital control in which plant parameters are estimated based on experimental data [19]. The least-squares method of system identification can be used to identify parameters in a dynamic system. It is assumed that a sequence of inputs has been applied to the systems and a sequence of outputs has been observed. Based on these inputs and outputs parameters are estimated by taking the square of the error between the measured value and the equation model value. The concepts of this approach were used to develop a least squares approximation identification method used to identify temperature and irradiation real time.

Real Time Identification of the Irradiation and Temperature

Using the model described in chapter 2 (1), an algebraic equation for current out of the PV panel is given as I_x. Assuming that the measured value of current out of thePV panel is I_{mx}, the error between these values can be defined as the difference

$$\begin{aligned} \in_1 &= I_1 - I_{m1} \\ \in_2 &= I_2 - I_{m2} \\ &. \\ &. \\ &. \end{aligned} \tag{13}$$

The squared error can then be defined as

$$\begin{aligned} \in_1^2 &= I_1^2 - 2I_1 I_{m1} + I_{m1}^2 \\ \in_2^2 &= I_2^2 - 2I_2 I_{m2} + I_{m2}^2 \\ &. \\ &. \\ &. \end{aligned} \tag{14}$$

Take several of these squared errors and calculate the sum

$$Sum = \in_1^2 + \in_2^2 + \cdots \tag{15}$$

Now take the partial derivative of this sum with respect to the irradiation S

$$\frac{\partial Sum}{\partial S} = \frac{\partial \in_1^2}{\partial S} + \frac{\partial \in_2^2}{\partial S} + \cdots \tag{16}$$

and temperature T

$$\frac{\partial Sum}{\partial T} = \frac{\partial \in_1^2}{\partial T} + \frac{\partial \in_2^2}{\partial T} + \cdots \tag{17}$$

then take the first term of each partial and perform the differentiation

$$\frac{\partial \in_1^2}{\partial S} = 2\left(I_1 - I_{m1}\right)\frac{\partial I_1}{\partial S} \tag{18}$$

$$\frac{\partial \in_1^2}{\partial T} = 2\left(I_1 - I_{m1}\right)\frac{\partial I_1}{\partial T} \tag{19}$$

If the sum of several measurements and equations are differentiated and set equal to zero

$$\frac{\partial Sum}{\partial S} = \sum_{i=1}^{10} 2\left(I_i - I_{mi}\right)\frac{\partial I_i}{\partial S} = 0 \tag{20}$$

$$\frac{\partial Sum}{\partial T} = \sum_{i=1}^{10} 2\left(I_i - I_{mi}\right)\frac{\partial I_i}{\partial T} = 0 \tag{21}$$

The result is a set of 2 * *i* algebraic equations with unknowns of S and T. If these are then solved simultaneously, an estimation of the values of S and T will result. For this research ten measurements were simulated per control period. These twenty equations were then solved simultaneously using the fsolve function in MATLAB^{TM}.

Assessment of the Real Time Identification Algorithm

Irradiation and temperature data for four different days was downloaded from the Solar Radiation Research Laboratory (SRRL) [20]. The dates chosen were 11-11-07, 10-19-06, 04-15-07, and 12-03-07. These raw data files provide the temperature in degrees Kelvin ($^\circ K$), and the irradiation in watts per meter squared ($\frac{W}{m^2}$). The data includes one sample per minute so for a full twenty-four hour set of data there are 1440 points of both S and T.

Using the model outlined in the previous section, a MATLAB^{TM} simulation program (modelch3.m) has been developed to generate plots of the four days of actual S and T data compared with the identified system data as shown in Appendix A. The result of this simulation is shown in Figs. 15-18. Notice that the identification of the irradiation follows very close for the entire day on each of the sample days. The temperature however did not follow as close as the figures show. That is to say that the sensitivity of fsolve to solving for irradiation is higher that that for temperature. This is acceptable however; as you will see in the next section the maximum power output is not as dependant on temperature as it is on irradiation.

Using the Identification Algorithm for Maximum Power Operation

Once the values for the temperature and irradiation are identified they are used to solve for the maximum power point voltage using the equation developed in Chapter II. A MATLAB^{TM} simulation program (modelch3.m) has been developed to generate the maximum power based on the identified values as shown in Appendix A. This provides what is called the identified MPP. The same equation was used with the raw data to obtain what is called the theoretical MPP. These are then plotted together with all 1440 data points for each of the four days selected as shown in Figs.s 19-22. Notice that for all four days of data that the identified MPP matches the theoretical MPP, thus validating the method. Even under rapidly changing conditions as shown on 10-19-06 and 12-03-07 the MPP was successfully identified.

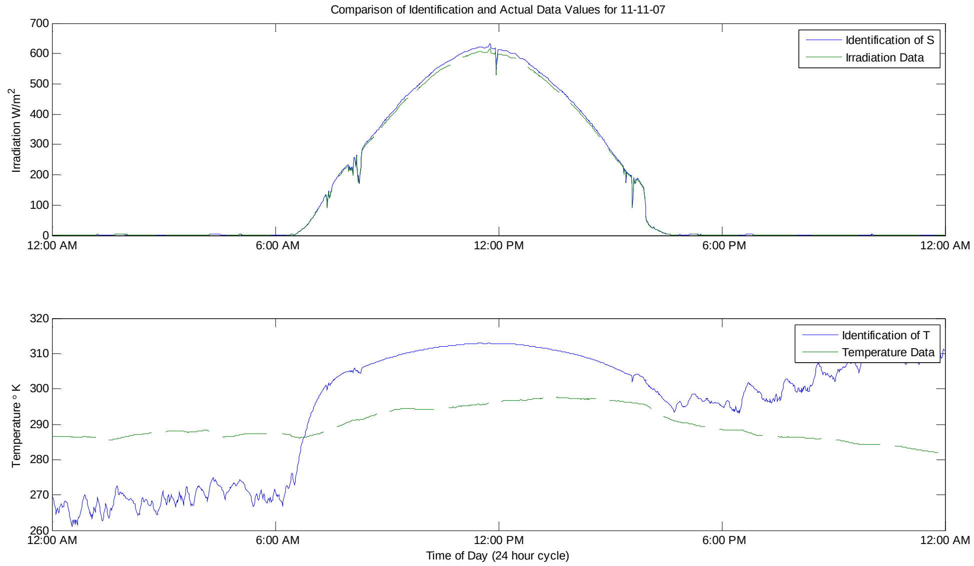


Fig.15: Identification Results for 11-11-07

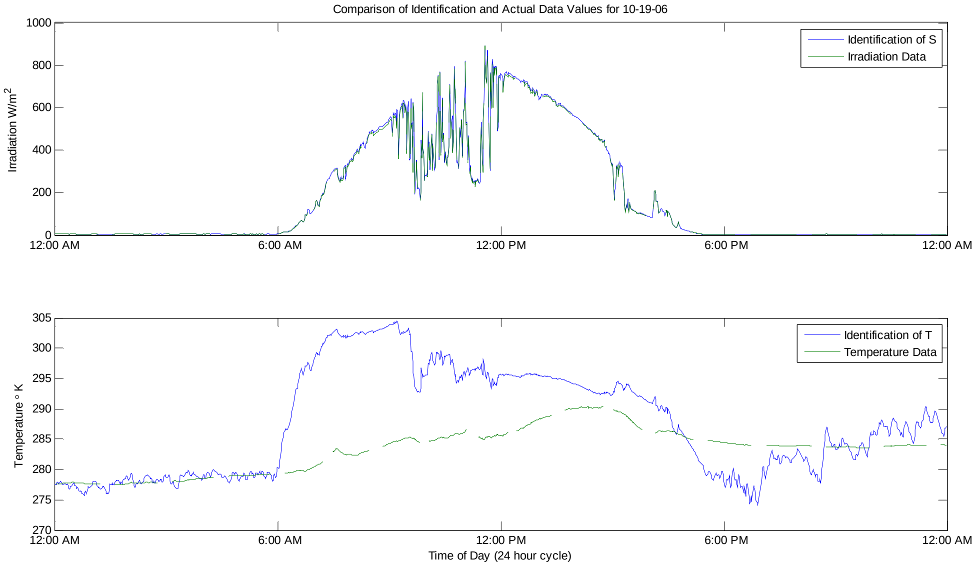


Fig. 16: Identification Results for 10-19-06

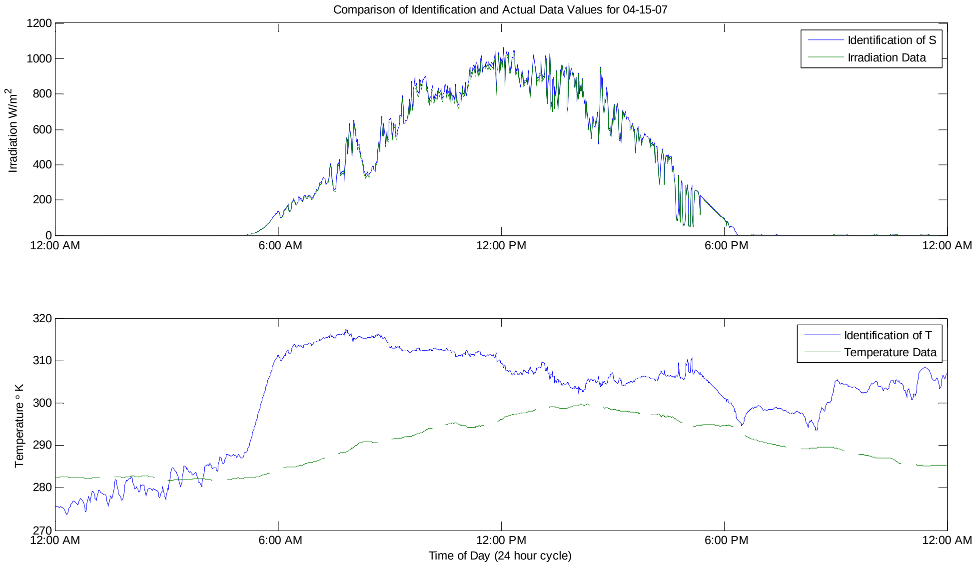


Fig. 17: Identification Results for 04-15-07

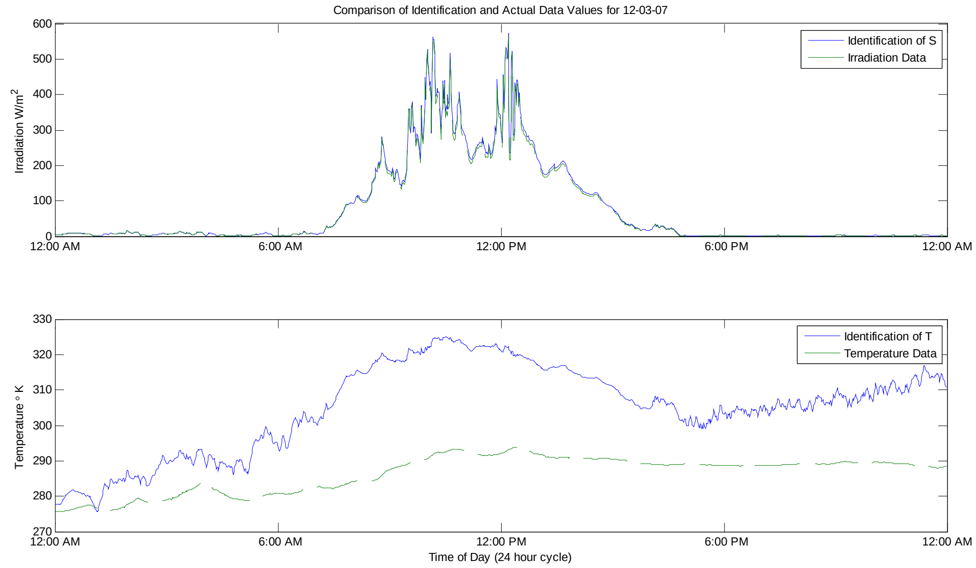


Fig.18: Identification Results for 12-03-07

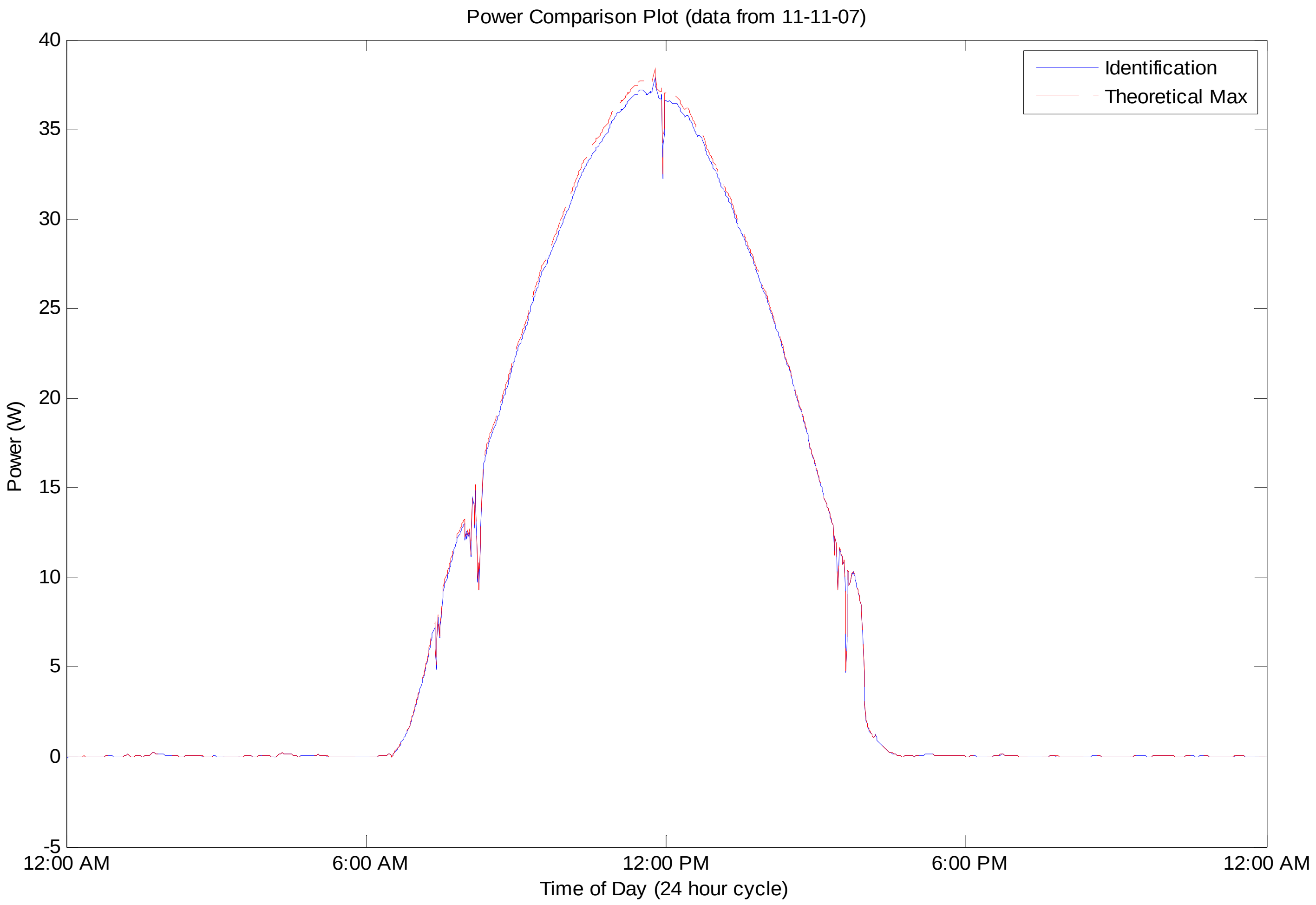


Fig. 19: MPP Comparison 11-11-07

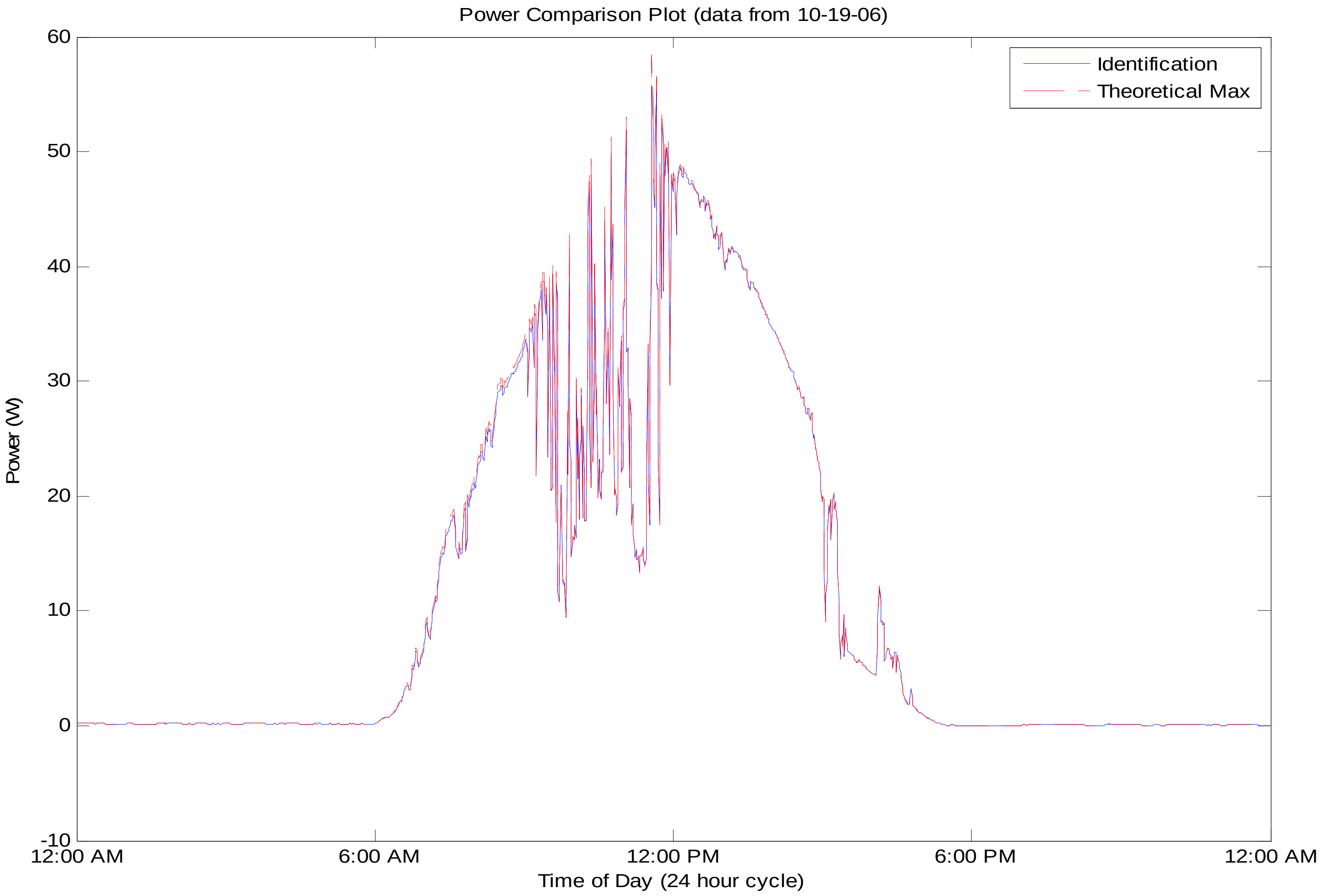


Fig.20: MPP Comparison 10-19-06

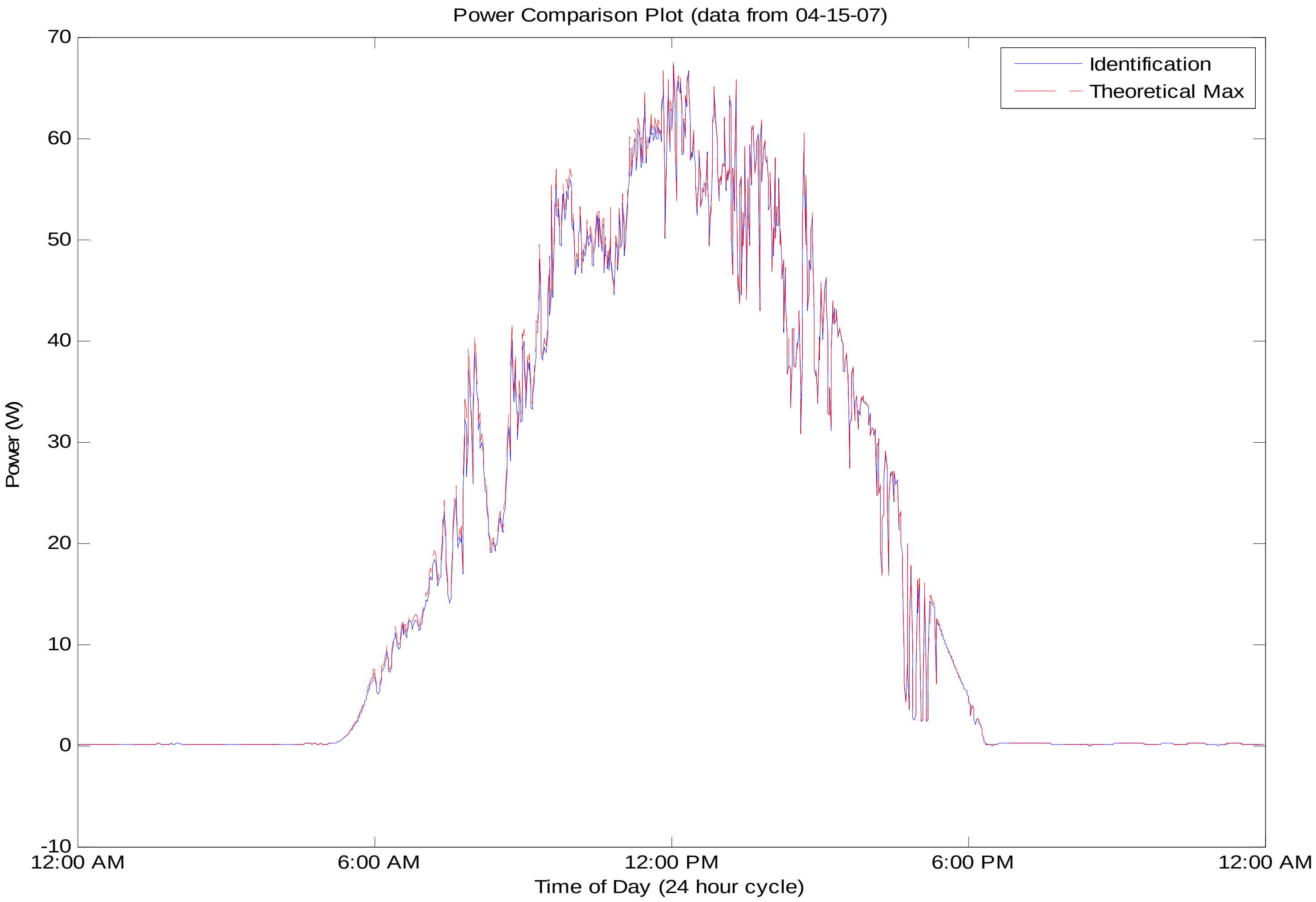


Fig.21: MPP Comparison 04-15-07

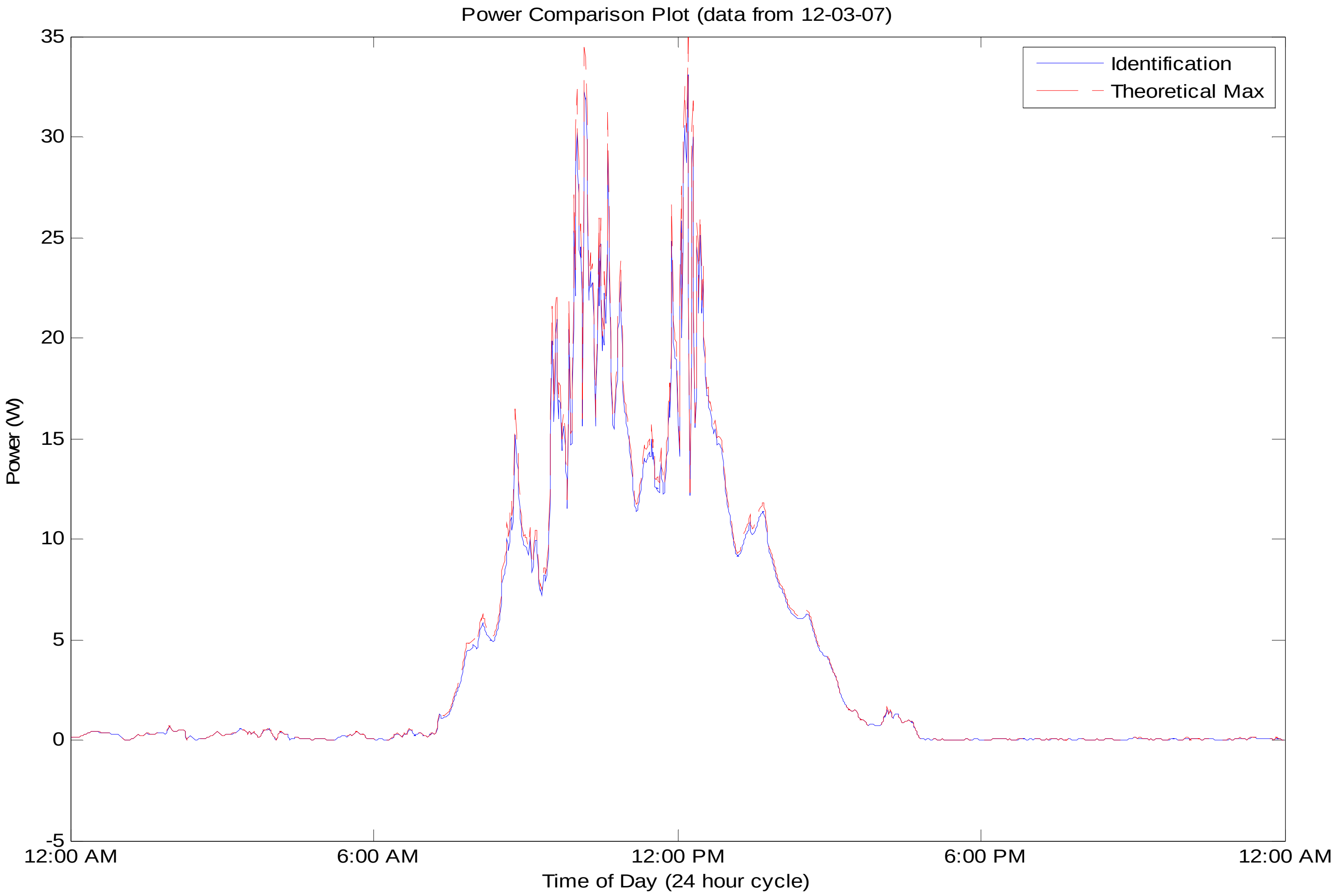


Fig.22: MPP Comparison 12-03-07

In summary, this chapter introduced a new technique of MPP operation. The concept of identifying unknown system parameters based on measured values was explored with favorable results. Instead of tracking the MPP by pushing toward the MPP, this technique allows the system to identify the unknown parameters and solve for the MPP without having to search. In the next chapter this maximum power output will be applied to a practical system where management techniques will be discussed.

CHAPTER IV

POWER FLOW MANAGEMENT OF PHOTOVOLTAIC BASED SYSTEMS

Any sophisticated PV system needs to have control over the use of the power generated by the system. This could include distribution to several different components. In this chapter, a control scheme is developed and simulated, with contrived and real data results of the simulation shown.

Need for Power Flow Management for Photovoltaic Systems

When the utility rates paid by a residential or commercial customer vary with time of day, and the system includes generation and storage capabilities, power management of the system becomes important. The basic idea is when the utility rates are high the system should use the local stored energy as much as possible taking the least amount from the grid. When utility rates are low, the system should utilize the grid to maximize the storage capacity, preparing for the case when rates are high. Local storage can also provide backup when grid power is lost all together. With utility rates increasing all of the time the economic viability of local storage is becoming more attractive. Interaction between various system components including a PV panel, battery, inverter/rectifier, local load, and the utility grid needs to be managed to maximize the cost benefit of the system.

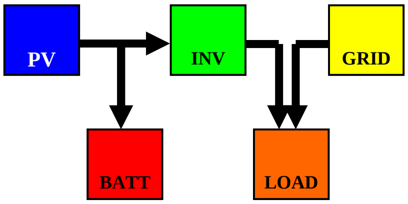
Development of a Management Scheme for a Commercial System

As discussed in the previous section, power management can involve economic considerations. This becomes a motivating factor in the design and decision making process of the management system. The system block diagram shown in Chapter II outlined the possible power direction of flow between system components. Assuming that the system is on a tiered electrical rate schedule, timing of when to charge the battery, and when to invert the PV power, needs to be addressed. Also the determination of how much power to take or give the utility grid is also important.

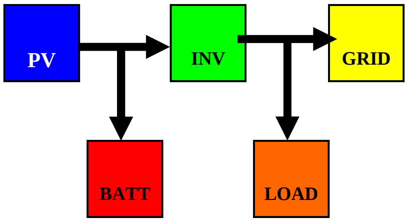
The system operation was divided into ten different modes as shown in Fig. 23. The current mode of operation is dependant on the status of several system parameters. First the time of day (TOD) was split into peak time and non peak time. This separates the time when the utility rate is high from when it is low. Next the state of charge (SOC) of the battery is taken into consideration. Based on the SOC and the TOD, a rate of battery charge or discharge is established. If the battery needs charging, the battery power control is $P_{Batt} > 0$ and if the battery power is to be discharged, $P_{Batt} < 0$. For this research there was ten SOC levels used. In an implementation of this system a device that would provide much greater resolution of SOC would be used. Based on the SOC and TOD the inverter/rectifier level is established. This determines whether the inverter/rectifier block will be functioning as an inverter or rectifier and how much power is to be inverted or rectified. $P_{inv\_rect} > 0$ if power is to be inverted, and $P_{inv\_rect} < 0$ if power is to be rectified.

Power Management Flow Diagrams

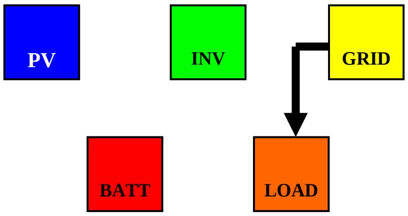
Non Peak Time Modes



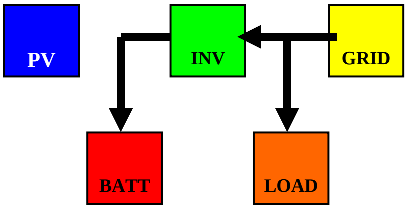
Mode 1: $SOC<95\%$; $P_{Inv\_rect}<P_{load}$; $P_{batt}>0$



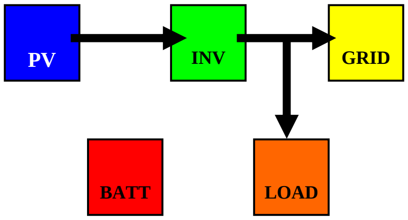
Mode2: $SOC<95\%$; $P_{Inv\_rect}>P_{load}$; $P_{batt}>0$



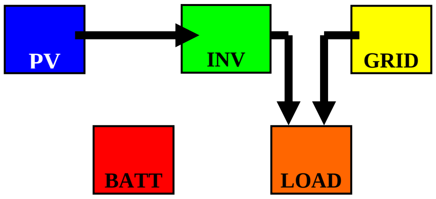
Mode 3: $SOC>95\%$;$P_{inv\_rect}=0$



Mode 4: $SOC<95\%$;$P_{inv\_rect}<0$;

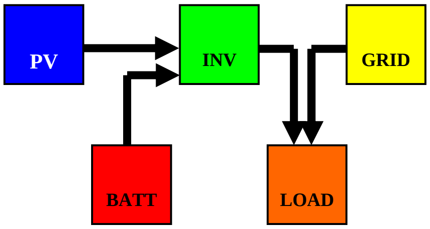


Mode 5: $SOC>95\%$;$P_{inv\_rect}>P_{load}$

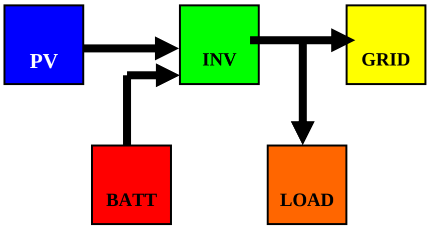


Mode 6: $SOC>95\%$;$P_{inv\_rect}<P_{load}$

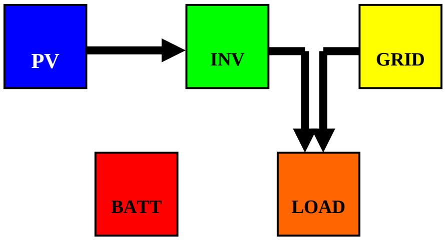
Peak Time Modes



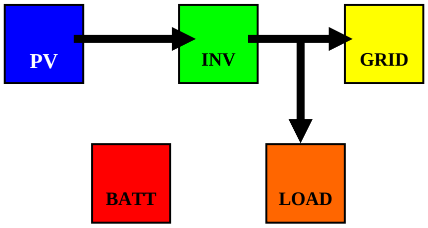
Mode 7: $SOC>50\%$;$P_{inv\_rect}<P_{load}$;



Mode 8: $SOC>50\%$;$P_{inv\_rect}>P_{load}$;



Mode 9: $SOC<50\%$;$P_{inv\_rect}<P_{load}$;



Mode 10: $SOC<50\%$;$P_{inv\_rect}>P_{load}$

Fig.23: Modes of Operation

Based on the local load demand (LLD), SOC, and TOD, the amount of power taken from or delivered to the grid is established. If $P_{grid} > 0$ then local power is being supplied to the grid. If $P_{grid} < 0$ then the utility is supplying the system with power. Now that the basic operation of the management scheme has been discussed, the results of implementing such a scheme will be presented.

Management Scheme Assessment Under Select Operation Modes

Using the management scheme outlined in the previous section, a MATLAB^{TM} simulation program (manage_modes_no_data.m) has been developed to test the ten different modes as shown in Appendix A. The input data to the system was contrived in order to enter into each mode of operation sequentially. The results of this simulation are shown in Fig. 24.

Notice that the time is broken into peak and non-peak time of day. The inputs are the battery power control, PV power produced, and the local load demand. The outputs are the quantity of power inverted or rectified and the amount of power bought from or sold to the grid.

Management Scheme Assessment Under Realistic Demand Cycles

The next step in testing the management scheme was to feed some real data to the system. Actual irradiation and temperature data from the Solar Radiation Research Laboratory (SRRL) was input for the date of 10-19-06. The theoretical MPP was calculated and input to the management system. A load profile for the same day for

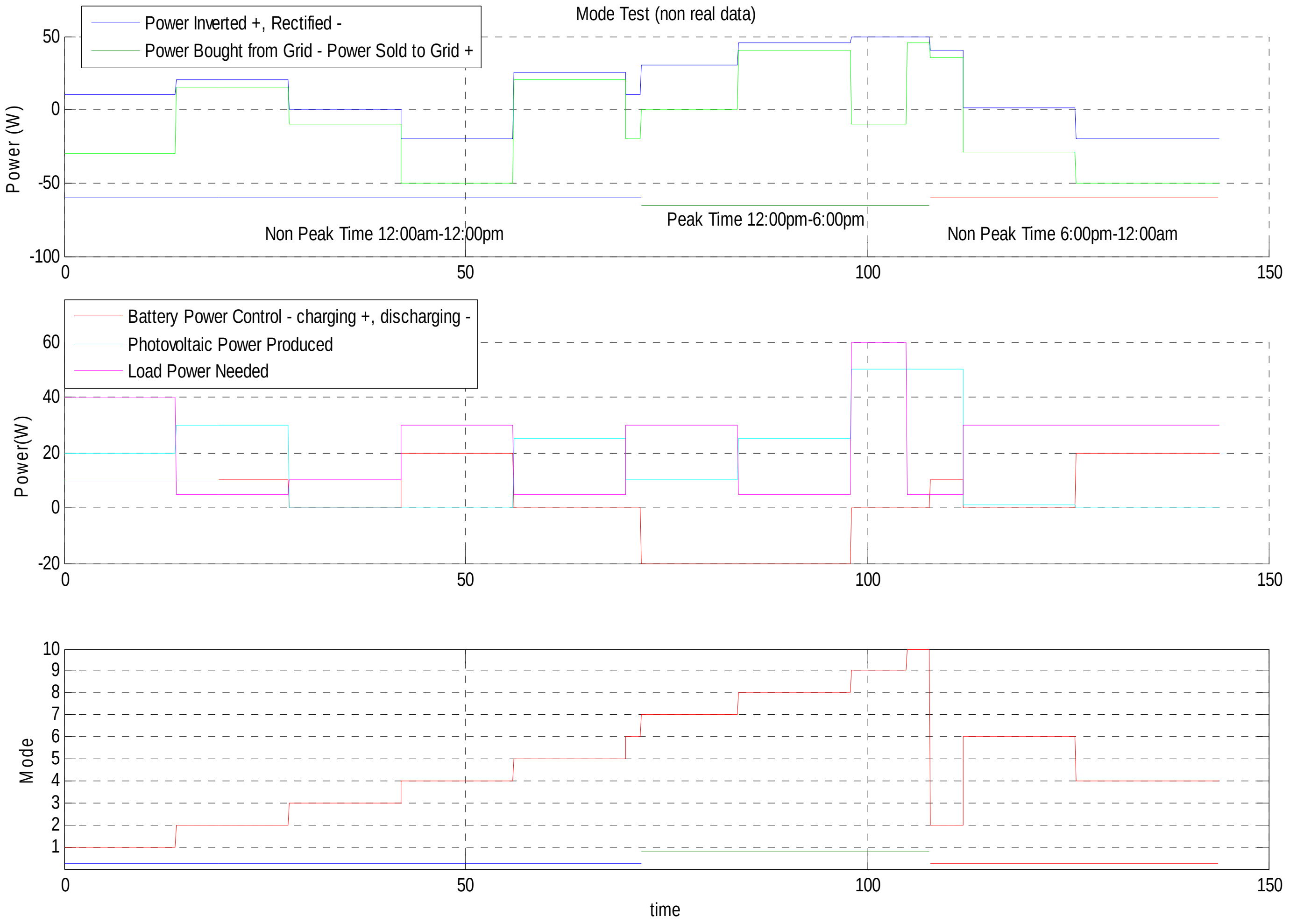


Fig.24: Mode Test

O'Connell Technology Center at California State University Chico was obtained and scaled to the appropriate input level. This was also input to the management system. The battery system was not modeled for this research and the SOC of the battery was taken to be typical values for this simulation.

Using the management scheme outlined in the previous section, a MATLAB^{TM} simulation program (manage_modes_with_data.m) has been developed to test real data in the management scheme as shown in Appendix A. Notice that the system entered eight of the ten modes as shown in Fig. 25 for this particular set of data.

In summary, this chapter outlined, and showed the results of a power management scheme for a combined PV grid integrated, and battery storage system. The implementation of this control scheme would contain either a microcontroller or computer with analog or digital inputs and outputs. The computer or microcontroller would make the decisions based on basic if then logic, as outlined, and control the power flow within the system. With the management system in place a complete system model including parameter identification and power management will be put forth in the next chapter.

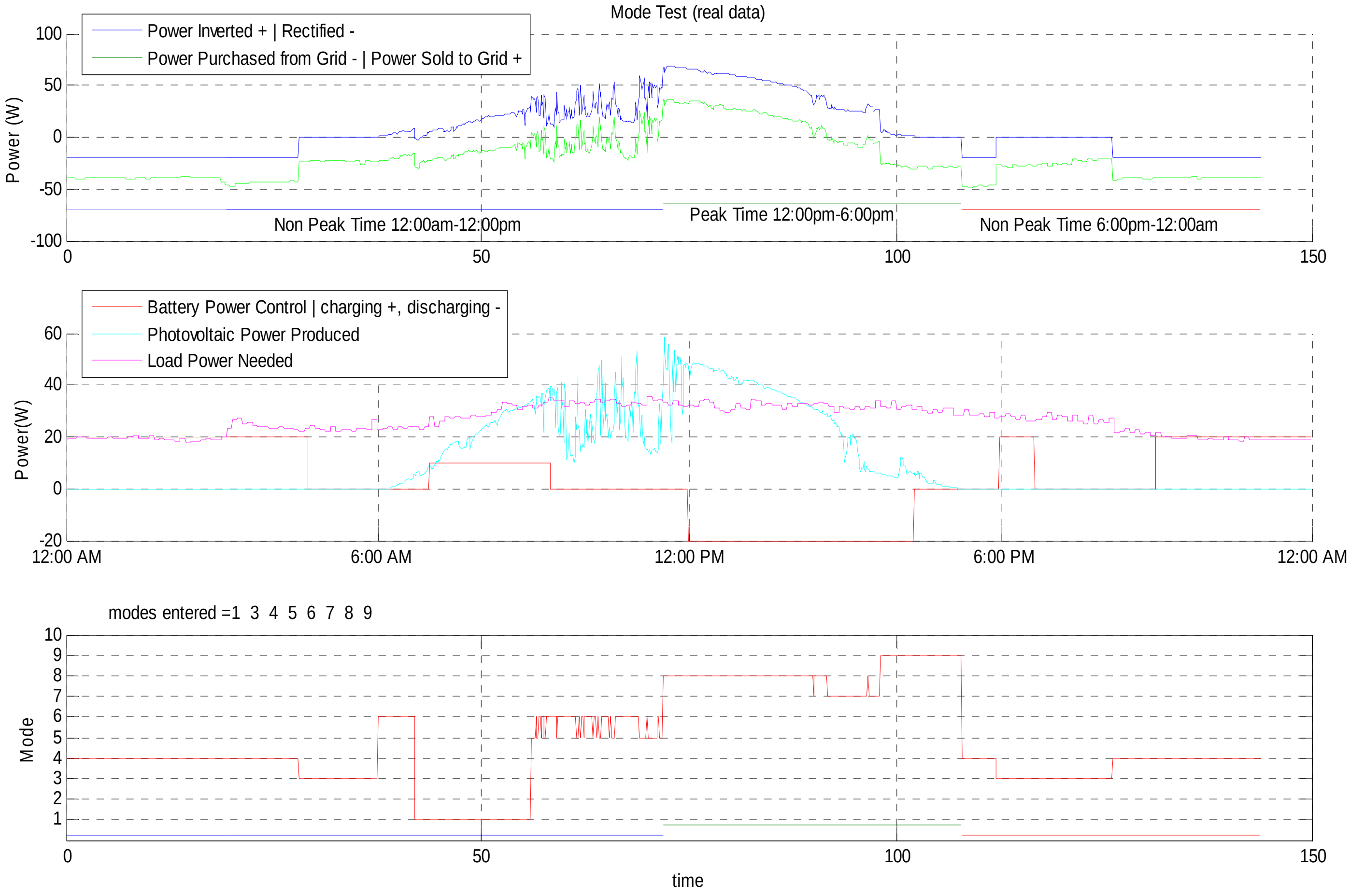


Fig.25: Mode Test (Real Data)

CHAPTER V

APPLICATION TO THE COMMERCIAL GRID TIED SYSTEM WITH BATTERY STORAGE

In the previous chapters several of the main components of a PV system were developed. A unique MPP identification technique was established and a power management scheme devised. In this chapter all of the components earlier introduced will be combined into one simulation of the overall system.

Overall System Model

The first step in testing the complete system was to obtain the input data. Temperature and irradiation data from the Solar Radiation Research Laboratory was gathered for the dates 4-15-07, 10-19-06, 11-11-07, and 12-3-07 [21]. Local load data was taken to be scaled logged data from the O'Connell Technology Center at California State University Chico. The battery state of charge data was generated to be typical values under the circumstances. The next step was to combine the power management code and the identification code. This was achieved by creating a separate file in MATLAB^{TM} that performs the power management routine. This was done for organizational purposes as the routine could have been inserted within the main program code. Within the identification code a function call to the management routine is executed. The inputs to this management routine are the power out of the PV panel, local load demand, and state of charge of the battery. The current operating mode is returned.

As discussed in Chapter IV, the management program establishes the amount of power inverted/rectified and the amount of power taken/given to the grid.

The inverter simulation creates a 60 hertz sinusoidal signal. In order to obtain satisfactory resolution for this signal the sample time needs to be small. As discussed in Chapter II the ode23 function was used to simulate the inverter. For each overall system sample period the inverter circuit needs to run for ample time to generate a steady state waveform. With 1440 overall sample points for a twenty-four hour period this takes a long time to simulate with simulation times taking several hours.

If the inverter circuit was active according to the power management program the inverter simulation was run. A reference power level was fed to the simulation with an average power output for that sample period as the result.

System Simulation Study - Maximum Power Operation Technique

The MATLAB^{TM} simulation program (model.m) has been developed to generate complete system operation plots as shown in Appendix A. The output from this program includes plots of the system inputs, identification validation, and output from the power management scheme. The results are shown in Figs. 26-29.

The results of the simulation were successful with the methods proposed verified. The management scheme successfully supervised the transfer of power throughout the system, while maximizing for cost of system operation. The MPP identification algorithm satisfactorily identified the system parameters of irradiation and temperature and set the operating point at the maximum. The plots clearly show that the theoretical maximum power output matched the actual values based on experimental data. These results were achieved for four different days of data with notably different characteristics.

In summary, this chapter provided the complete system results from the research. A complete grid tied battery storage photovoltaic system was simulated. The results showed the system operation responded to a wide variety of input conditions and the new techniques developed were effective in efficiently delivering power to the respective system components.

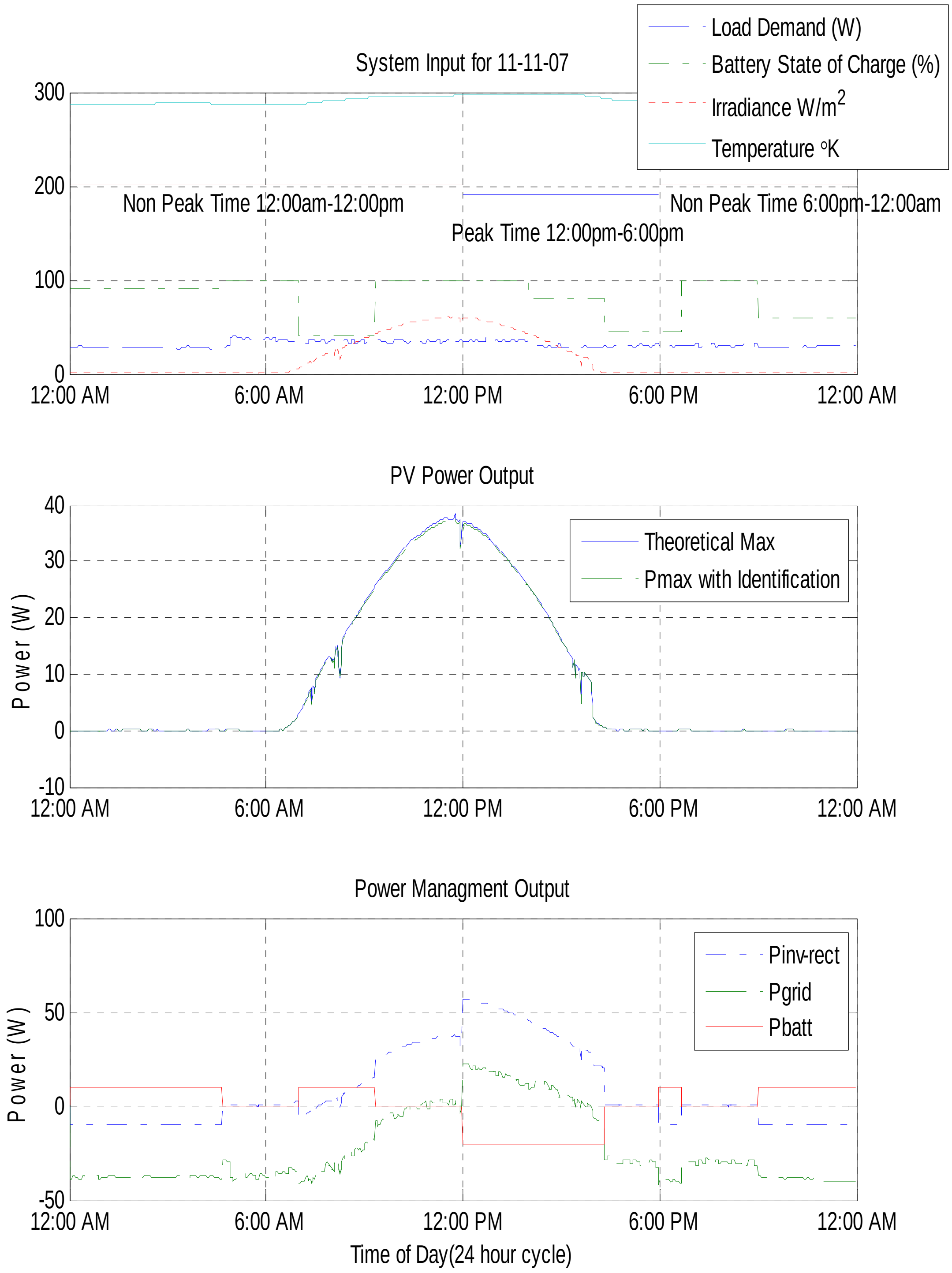


Fig. 26: Complete Simulation 11-11-07

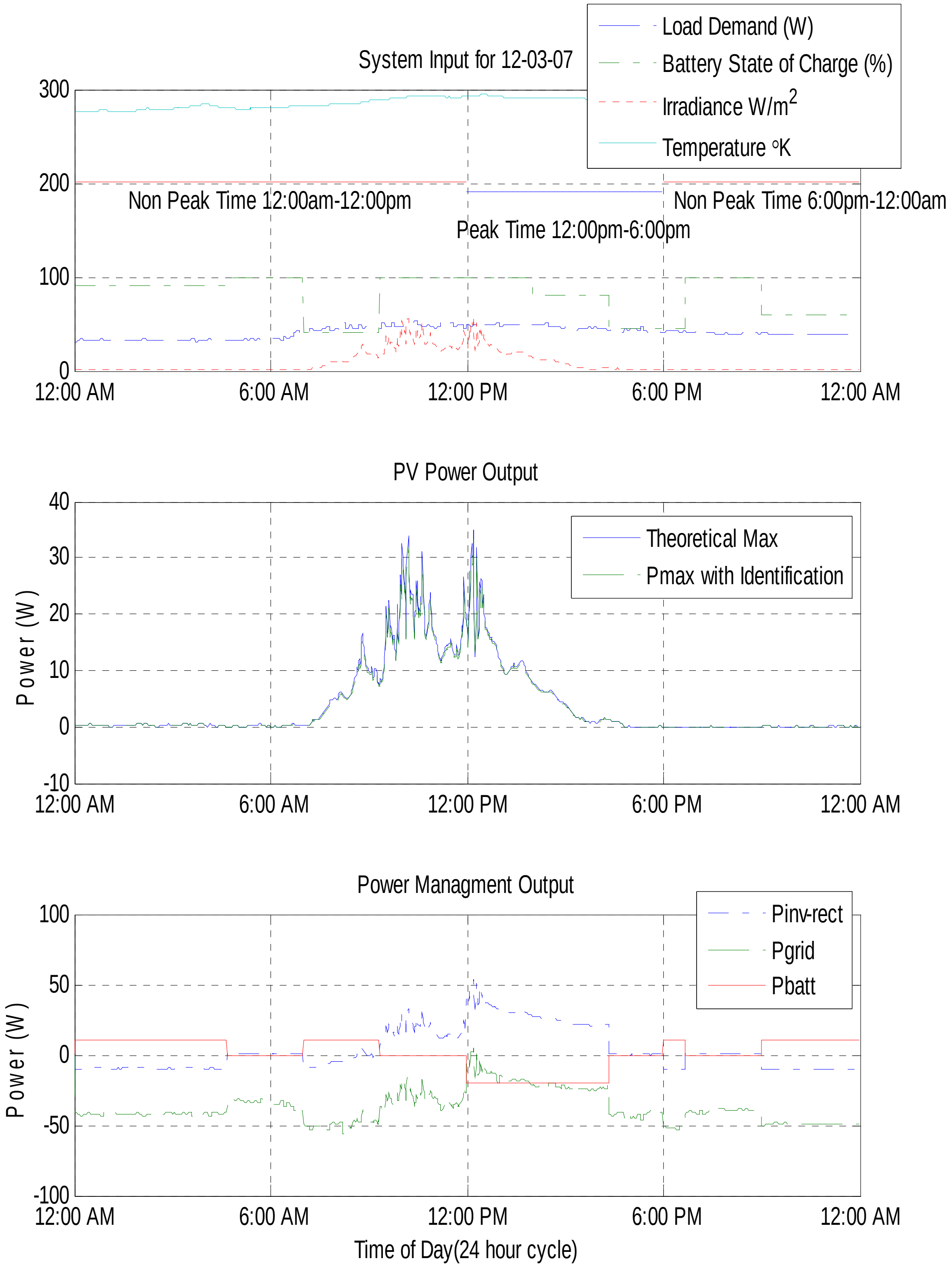


Fig. 27: Complete Simulation 12-03-07

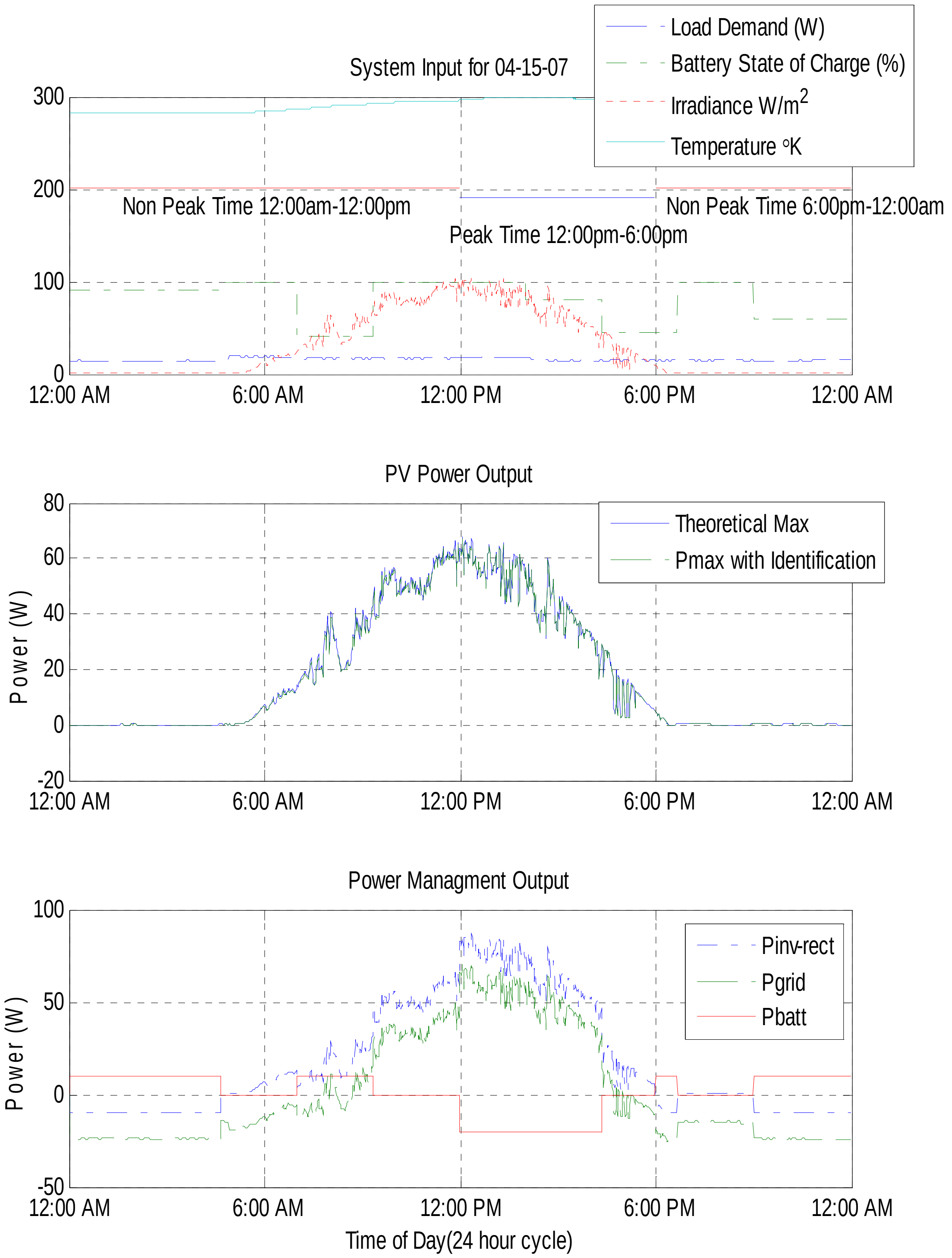


Fig. 28: Complete Simulation 04-15-07

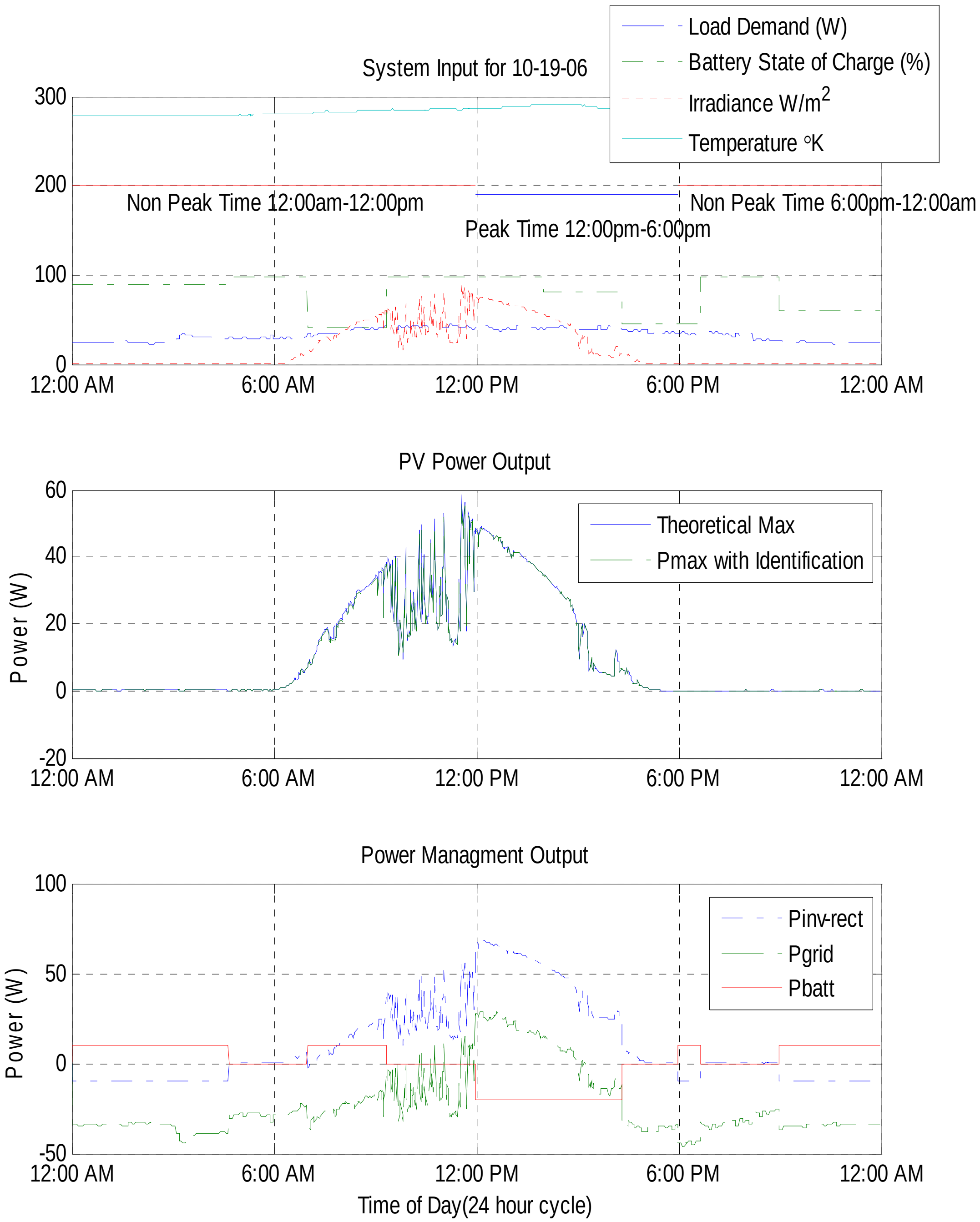


Fig. 29: Complete Simulation 10-19-06

CHAPTER VI

CONCLUSIONS

In this research a photovoltaic generation and distribution system was proposed. A method of parameter identification was used to ascertain the maximum power operating point of a photovoltaic panel. A power management scheme based on efficiency and cost considerations was also presented.

The research starts with a review of the literature. Included are the current photovoltaic technology, an introduction to the maximum power point challenge, and an overview of different tracking techniques. These topics serve as the background for introducing the novel techniques described in this research. An introduction to the identification and power management approach taken in this research is then described. These topics were then wrapped up with an organization of the document as a whole.

Next, all of the major system components including the photovoltaic array were modeled. The performance of a photovoltaic panel was analyzed showing the characteristics of the panel used in this research. The simulation of the photovoltaic panel characteristics successfully matched up with the manufacturer’s data sheet. The theoretical maximum power point equation was established and practical constraints on obtaining this maximum were shown. Main schemes for power generation and utilization were presented focusing on grid tied, off grid, and the proposed method for this research. A hybrid approach of grid tied and battery based system was decided to be the approach taken in this research

The identification algorithm established in this research was the next topic presented in this paper. First, an introduction to identification techniques is presented to illustrate the general principals. Next, the method of use of identification in this research is shown. This section details the process of identifying system parameters based on known values. Then, the results of the identification process and the application of the identified parameters are shown. The results proved favorable as the identified values sufficiently matched the simulated actual values.

The next topic of this research describes the power management scheme developed. The need for power management in a photovoltaic system is discussed as well as the approach taken in this research. The results from contrived data and actual data are also presented. The contrived data was used to test the system under non-real conditions in order to verify functionality. Then, real data was inserted and the results were shown for different sets of input data. Next, the complete system results are presented. This includes putting all of the individual modeled pieces together into one large simulation package. Combining the power management and identification simulations is discussed as well as adding the inverter circuit to the model. Complete system results are then displayed showing the output of the entire system simulation. These simulations showed favorable results with the resulting MPP following the theoretical MPP. The management system was able to effectively provide power to the appropriate system in the simulation.

The results of simulation based on the previous topics were successful, showing that these methods have the potential to be a valid solution to the challenges stated. The next step for continuing this research is to implement prototypes of the respective developments. For the identification technique a data acquisition board could be used to read the output from a solar panel into the MATLAB^{TM} software. The algorithm developed in this research could then be run in MATLAB^{TM} and the output used to control a dc-dc converter used to change the maximum power operating point of the panel. Two similar panels, one running the identification algorithm and the other a different algorithm could be used and the results compared. Also, measurements of temperature and irradiation could be compared to identification algorithm estimated values.

With the necessary system components the power management scheme could also be tested. Again values could be read into a computer using a data acquisition board and the outputs used to control the various system components. Verification of proper operation could be obtained by logging the transfer of power between the system components. Also data from a similar system without the battery and power management systems could be compared to the data from the system with these components.

Developments in alternative energy sources generation and distribution will be a key in solving the world energy needs for the generations to come. Innovation in new technologies combined with optimization of existing technologies is crucial in addressing an energy solution.

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APPENDIX A

LIST OF SIMULATION PROGRAMS

All simulations were conducted in the simulation environment of MATLAB^{TM}. A complete listing of program code can be obtained in the Department of Electrical and Computer Engineering at California State University Chico. These listing reflect the organization of the compact disk located in the department office containing the programs.

<u>Chapter II</u>
I_V_Variation.m
Inverter.m

<u>Chapter III</u>
modelch3.m

<u>Chapter IV</u>
manage_modes_no_data.m
manage_modes_with_data.m

<u>Chapter V</u>
model.m