Dynamic Modelling of Single Phase Grid Connected Photovoltaic System

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DYNAMIC MODELING OF SINGLE PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

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ABSTRACT

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Grid-connected photovoltaic (PV) power systems have been sustaining an exponential growth rate during the past decade. This steep growth is driven by a growing concern about climate change, the adoption of an aggressive regional renewable portfolio standard, rebates and tax incentives, and reduction in PV system cost. One of the main technical barriers that can ultimately limit further PV penetration is the fast variations in the PV system’s output power induced by cloud transients. Such events are known to cause voltage fluctuations which may lead to excessive operations of voltage regulation equipment and light flickering.

Solar irradiance variability, which can be easily recorded using a pyranometer and a data logger, is used in numerous studies to assess the AC power injected into the electrical network by PV systems. But in reality, the two variables are not perfectly proportional with one another, nor synchronized in time due to delays within the inverter circuit elements and controls.
As a consequence, computer models that accurately simulate the dynamic behavior of PV systems under moving clouds would thus be of high value. In this thesis, a dynamic MATLAB/Simulink model of a single phase single stage grid-connected PV system that can be used to predict the deviations in AC power output under variable solar irradiance is presented. The commonly used perturb-and-observe technique for Maximum Power Point Tracking (MPPT) is used in the model. It is found that the deviation between solar radiation and output power variability that may be caused by the MPPT and buffer capacitor is minimal and can often be neglected. As a consequence, variations in solar irradiance can be considered as a good indication of power fluctuations.
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CHAPTER 1
INTRODUCTION

The importance of Renewable Energy sources has been growing at a fast pace for the two primary reasons, one being the ever unavoidable quest for inexhaustible sources of energy and the other being the reduction of the environmental effects. When compared to the traditional non-renewable resources like gasoline, natural gas and coal which have many restrictions like geographical abundance, business transactions, import regulations and price fluctuations, the renewable energy sources are independent of the above factors mentioned. Also, the main drawback of the non-renewable sources is being exhaustive in nature. Hence extensive emphasis is placed on the energy utilization through renewable energy sources, the recent examples being the new brand of hybrid cars launched into the market [1] and the increased percentage of energy generation through renewable energy sources such as solar, wind etc [2]. Consequently, the current researchers are faced with the evolving challenges regarding issues of efficient renewable energy conversion and intermittency in availability of renewable energy resources.

Currently, solar energy and wind energy are economically viable and abundantly available forms of renewable energy. Especially, solar energy owing to its abundance is growing rapidly in the form of heating and electrical energy generation applications [2]. Although, the initial installation cost of a solar power plant may be high, but a simple lifecycle cost analysis will demonstrate competitive levelized cost of electrical energy compared to conventional power plants, when including the state and federal incentives.
Recent research proves the potential of solar energy to meet utility peak load demands [3]. Moreover, solar energy can also be used as a supplementary power unit where there is a demand fluctuation for energy usage in different seasons.

As a result of world’s fast growing energy demand on solar energy and advanced solar technology like concentrated solar power (CSP) coming into the market, there might be a chance of large scale solar power plant connected to the electric grid [3]. Concentrated solar power (CSP) systems use mirrors or lenses to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat, which drives a heat engine (usually a steam turbine) connected to an electrical power generator [3]. When large systems in the order of megawatts are installed into the grid, it might lead to operational problems in the network. These kind of negative impacts include power and voltage fluctuation problems, harmonic distortion, malfunctioning of protective devices and so on.

Therefore, in recent years both academic institutions and electric utilities have focused their research attention on studying the possible impacts of distributed power systems - PV systems on the electrical grid network. Most of this research focuses on dynamic responses and PV system performance when interfaced with a power grid; viz. sudden grid voltage changes, system faults - both on AC and DC sides, power fluctuations due to solar irradiation changes etc. In order to detect faults and protect devices/systems, various control schemes have been developed.
The output power of a solar PV system fluctuates with time-varying parameters such as solar irradiance. Therefore, considerable PV research focuses on the effect of these transient variables on the PV system. Now-a-days, computer models are employed to estimate the effects of these transient parameters on a PV system. The accuracy of these models is usually dependent on the location where accurate meteorological data is available.

1.1. Intermittency Problem

PV power output mainly depends on the time of day and the weather conditions such as clouds. Since the variations of solar irradiance occur in the minute-to-minute time frame, PV power systems are called intermittent energy sources. The passage of clouds will cause considerable fluctuations in PV power output both in “stand alone” as well as “grid connected” systems [4]. Instantaneous output changes have considerable impact on system voltage and also operating reserve requirements. At the time of power output fluctuations or due to failure of generation due to bad weather conditions, the backup generators should act instantaneously to compensate for the loss of energy.

Figure 1.1 shows a typical cloud transient that was recorded locally over a 100 minute period. Note that changes can occur slowly at times and rapidly at other times. This thesis to explore the problems associated with MPPT algorithms and determines how the MPPT interacts with intermittency.
1.2. Report Organization

The work carried out in this thesis is organized in five chapters. The present chapter introduces the necessity for renewable energy sources and prominence of photovoltaic energy. The problem of intermittency on power system due to cloud transients and its impact and need for further analysis.

Chapter 2 presents the detailed mathematical modeling of ideal PV cell and Practical cell models. The characteristics of the PV module are simulated in MATLAB/Simulink by solving the non-linear equations involved in the modeling.

Chapter 3 addresses the impact of PV power variability (under high penetration) on voltage regulation in distribution systems. The possibility of excessive operation of transformer load-tap changers, and voltage flicker are illustrated through an example.
Chapter 4 reviews the various types of DC-AC inverter topologies that are found in the commercial world. The necessity for maximum peak power tracking (MPPT) and common techniques for implementing this are summarized.

Chapter 5 discusses the PV system design procedure using Matlab/Simulink Power system block set library. Each subsystem (PV array, Inverter and associated controls, and utility supply) is addressed separately.

Chapter 6 discusses the simulation results for a grid-connected 2,050 W PV array with “Perturb & Observe algorithm” under different variations in solar irradiance.
CHAPTER 2

IMPACT OF PV POWER FLUCTUATIONS ON VOLTAGE REGULATION

2.1. Background

Currently, Photovoltaic (PV) power systems represent only a small fraction of the local electrical power generation capacity, but this renewable resource has been sustaining an exponential growth rate during the past decade. This steep growth has been driven by a growing concern about climate change, the adoption of an aggressive state-level renewable portfolio standard, rebates and tax incentives, and reduction in PV system cost. Many energy experts predict that solar energy will likely become a serious contender for meeting the state’s energy needs in the coming decades.

As the PV industry continues to grow, there are numerous challenges which will need to be addressed in order to determine the best policies and methodologies under high penetration scenarios. Many of these challenges have been described in the Renewable Systems Interconnection Study [5] that was prepared by the US DOE Office of Energy Efficiency and Renewable Energy in conjunction with Sandia National Laboratories, the National Renewable Energy Laboratory and the Electric Power Research Institute.

High PV penetration could lead to technical barriers that would ultimately limit further penetration: Variations in the PV system’s output power induced by cloud transients may result in the following:
- At the transmission system level - transients that require significant back-and-forth throttling of the gas-fired units in order to maintain the balance between generation and load (i.e., frequency regulation).

- At the distribution system level - undesirable voltage fluctuations which may lead to excessive operations of the Load Tap Changers (LTC) and flicker.

As a consequence, electric utilities, national laboratories, and power conversion industries are preparing for these grid-integration challenges of increasing renewable sources, such as the effects of sudden or significant fluctuations in PV system output power [6].

Both slow voltage regulations (for managing distribution system voltage profiles) and fast voltage regulation (for addressing flicker due cloud-induced fluctuations) in high-penetration scenarios have been addressed in the literature in the 1980’s [7]-[10]. One of these studies examined cloud transient effects if the PV were deployed as a central-station plant and found that the maximum tolerable system-level penetration level of PV was approximately 5%. Another study dealt with voltage regulation issues when clouds passed over an area with high PV penetration levels, if the PV were distributed over a wide area. At penetration levels of 15%, cloud transients are found to cause significant but solvable power swing issues at the system level, and thus this level was deemed to be the maximum level of penetration allowed. The interactions between PV systems and automatic load-tap-changing (LTC) transformers was studied by means of a computer model, and found that cloud-induced PV output fluctuations could cause excessive operation of LTCs, but no maximum penetration level was suggested.
The problem of voltage fluctuations resulting from the passage of clouds is also addressed more recently in References [11] and [12]. In particular, variations of node voltages in small or weak electrical grids (e.g., micro-grids) are reported to even cause system instability. Studies have also been conducted to explore the extent to which the geographical diversity of distributed PV mitigates the short-term output variability caused by rapidly changing weather conditions. Spatially distributing PV systems is found to significantly reduce the system impacts of slow transients caused by clouds.

One method that was suggested to mitigate the effects of PV output variability is to use onsite battery energy storage that is integrated into the PV inverter control system [13]-[15]. In here, the storage system will generate and absorb energy as the PV array power fluctuates according to the available solar resource. This mode of operation obviously requires the energy storage system to operate at a partial state of charge.

This chapter is intended to contribute to the accumulated knowledge regarding the impact of PV power variability on voltage regulation in distribution systems. A simple system that consists of an actual substation transformer that feeds a couple of residential distribution feeders is analyzed in case where 20% PV penetration takes place in the future. Analysis is conducted on 3 days of summer using actual load and weather data with 1-minute sampling rate. These days consist of both clear and cloudy skies. Based on a number of assumptions made due to lack of detailed information, the study indicates that such a high level of PV penetration more than doubles the number of transformer tap changes, but no visible light flickering is expected.
2.2. System Description

The system under study is conducted on a portion of a local distribution substation which consists of a 20 MVA, 69 kV / 12.47 kV Δ-Y connected transformer that serves two primarily residential feeders. The impedance of the transformer is equal to 8% with and X/R ratio equal to 20. Note that such impedance is purposely made relatively high in order to limit the short-circuit current below 12 kA on the distribution side of the transformer. The feeders are relatively short (less than 3 miles) due to high load density, and use a relatively large conductor size. Hence voltage drop along the feeder is expected to be not significant relative to that caused by the transformer impedance.

The substation voltage is automatically controlled by a load-tap changer (LTC) that is built in the transformer secondary winding and is managed by a voltage regulating relay. The LTC effectively varies the transformer turns ratio to maintain the transformer secondary voltage at the substation as the load and/or the primary side voltage vary. The LTC regulates and maintains the voltage value within ANSI C84.1 limits [A12]. The transformer taps provide a range of ±10% of the nominal voltage with 32 steps, and each step corresponds to 0.625% of the rated voltage. The taps are adjusted by a motorized mechanism that is slow and prone to failure if used excessively.

2.2.1. Load Data

A time window of 3 days in mid-summer (July 11-13) of 2010 was selected to perform the study. Among these days, there is one day during which there is very significant variability, one day of partial variability, and one day of minimal variability.
from the normal solar irradiance. The system is analyzed for 72 hours in order to provide insight into the performance during hours of both cloudy and clear days.

Figure 2.1 shows the actual transformer loading (MW) during the 3-day window under study using a sampling rate of 1 minute. Note that the diversity of the many loads served by the transformer results in an aggregate load with slow changes in demand. Therefore, the LTC in such conventional usage (i.e., without PV systems) are expected to respond slowly to daily trends in circuit loading.

![Figure 2.1. Substation Transformer Real Power Load.](image)

### 2.2.2. Solar Irradiance and PV System Data

It is estimated that less than 1% of PV penetration currently exists in the system under study; hence, its impact of voltage regulation is negligible, even under the most extreme fluctuations in PV power. In this study, it is assumed that significant residential PV
penetration (up to 20%) will take place in the not too distant future, the impact this will have on voltage regulation under the presence of cloud-induced transients is analyzed.

To simulate PV power variability, actual solar irradiance data (based on 1-minute sampling rate) during the above time window at a location within the vicinity of the substation is obtained from Ref. [17]. The global horizontal irradiance (in W/m$^2$) is shown in Figure 2.2. While the 1-min sampling rate is more than sufficient for characterizing the feeder load, it is reported to under estimate solar irradiance, hence, PV power variability during extreme events [6]. On the other hand, it is realized that the cumulative variability of irradiance at multiple locations within the area served by the transformer is expected to be lower than the single-point irradiance measurements at 1 minute intervals [6].

![Figure 2.2. Global Solar Irradiance.](image_url)
2.3. System Modeling

In order to simulate the movement of the transformer tap changer under the current situation (with negligible PV penetration) and with 20% PV penetration, the following assumptions are made due to lack of detailed information, and in order to simplify the problem at hand:

1. The load power factor during the study period was noted to vary between 88% (lag) and 0.98% (lead). A number of sudden steps changes in load reactive power occurred each day due to some capacitor switching along the feeder. In here, we assume that the load power factor is constant and is equal to 90% (lag).

2. Due to the short length of the feeders and large cable size used, the voltage drop along the feeder is ignored, and the load is assumed to be lumped at the transformer secondary bus. Further, the primary side of the transformer is assumed to be connected to an infinite bus with a fixed voltage of 1 p.u. Hence, the variation in voltage is caused solely by the fluctuations in transformer loading.

3. The transformer secondary bus voltage is regulated at 1.05 p.u. and the bandwidth is set to correspond to one load tap change, i.e., 0.625%. On a 120 V scale, this setting allows the bus voltage to vary between 125.25 V and 126 V, and a tap change takes place every time the voltage drop changes up or down by 0.75 V. An adjustable time delay between the voltage change and tap changer action is made available to avoid unnecessary movements during temporary changes in power flow. Two time delays, 1 minute and 5 minutes, are examined in this study.
4. A 20% PV penetration (based on substation transformer ration), or 4 MW of photovoltaics, is assumed to be installed on the roof tops of the homes served by the two feeders. Although the actual power produced depends on the operating temperature, orientation, tilt, and efficiency of the PV modules, it is fair to assume at first approximation that PV power production is proportional to the available solar irradiance. A de-rating factor of 80% is assumed in order to take into account power losses in the wiring and inverter, module soiling, and any mismatch. This number is multiplied by the array size to achieve the simulated power output under maximum solar irradiance.

5. Finally, it is assumed that the entire PV system experiences the same solar irradiance at the same time. As indicated earlier, the effects of intermittent PV power will be less noticeable when the array is distributed over a sufficiently large area. Nevertheless, utilities often need to address worst-case possibilities.

The resulting simplified system based on the above assumptions is shown in Figure 2.3 below where the substation transformer is represented by its series impedance. The PV array is modeled as a current source that is in phase with the transformer secondary voltage. The inherent delay between a quick change in solar irradiance and the PV’s ability to change its output power (attributed to the DC link capacitance and MPPT algorithm) is in the order of seconds, hence can be ignored when using a 1-minute time interval.
Without the PV array, the voltage drop across the transformer impedance is simply given by:

\[ VD_{\text{w/o PV}} = I_L (R \cos \theta + X \sin \theta) \]

Under the presence of the PV array, the above expression becomes

\[ VD_{\text{with PV}} = (I_L \cos \theta - I_{PV}) R + I_L X \sin \theta \]

Where,

\( I_L \) is the load current, \( \theta \) the load power factor angle, \( I_{PV} \) is the current generated by the PV system, \( R \) and \( X \) are the resistance and reactance of the transformer series impedance.

**Figure 2.3.** Schematic Diagram of System under Study.

### 2.4. Simulation Results and Observations

To evaluate the dynamic voltage regulation associated with the interaction of the varying PV output with the variation of system load, the movement of the transformer tap changer is first simulated for the base case without the PV array. The LTC is set to
regulate the secondary voltage according to the 3\textsuperscript{rd} assumption made in the previous section.

When a 1-minute time delay is used in the LTC controller, the tap is found to change a total of 40 times during the 3-day period (20, 10, and 10 during the 1\textsuperscript{st}, 2\textsuperscript{nd}, and 3\textsuperscript{rd} day, respectively). A larger number occurred in the first day due to the fact that the load fluctuated around an average value for nearly 4 hours (between 16:00h and 20:00h) on that particular day. When extending the time delay to 5 minutes, the total number of tap changes dropped to 28 (14 on day 1, 8 on day 2, and 6 on day 3). The corresponding tap movement as a function of time is shown in Figure 2.4, where the vertical axis represents the tap position. Figure 2.5 shows the corresponding voltage profile on the transformer secondary side. Note that the voltage is maintained between 1.4375 and 1.05 pu, as specified in the above assumptions.

![Figure 2.4. Substation Transformer Tap Changer Position (w/o PV).]
Figure 2.6 shows the power produced by the PV array and the transformer net MW loading. The PV power, which follows the pattern of change in the solar irradiance shown in Figure 2.2, reduces the transformer loading during the daylight hours by subtracting the generated power from the aggregate load. On clear days, the change in the net load is of time duration that is comparable to conventional daily loading cycles (without PV), thus not likely to compromise conventional voltage regulation strategies. On cloudy days, however, the net load curve is more complex because of the spikes induced by cloud movement.

![Figure 2.5. Voltage Profile at Substation (w/o PV)](image-url)
The resulting erratic changes in transformer net loading result in fast voltage fluctuations. Figure 2.7 shows the resulting voltage drop/rise per minute, which exceeds 0.5% occasionally during large changes in solar irradiance. One main concern over such fluctuations is the possibility of voltage flicker which is a voltage quality problem that is annoying to the eyes. According to the flicker curve displayed in Figure 2.8 (extracted from Ref. [18]), the borderline of visibility of flicker at 1 minute interval is 0.7% voltage dip. Since the graph shows that this particular value is exceeded only once during the 3-day period, it is concluded that voltage flicker should not be a concern under these particular conditions. However, it is important to note that faster sampling rates (in the order of seconds) will likely result in voltage dips exceeding the visibility and even the annoying limits on a repetitive basis.
The other voltage regulation concern is the increased wear on the LTC due to frequent tap changes in response to the spikes in the net transformer loading. To determine such impact, the above simulation of the LTC movement is repeated after connecting the 4
MW PV array. For 1-minute time delay, the number of tap changes is found to be equal to 160 which is four times more than the base case without PV. A 5-minute time delay reduced this number down to 78, which is 2.8 times higher than the corresponding base case. Figure 2.9 shows the tap position as a function of time for the latter case, and Table 2.1 summarizes the daily tap changes for all simulated cases. The significant amplification in the tap movement due to cloud movement is a definite concern and some actions are needed to mitigate this problem.

Table 2.1. Daily Number of Tap Changes with and without PV.

<table>
<thead>
<tr>
<th>Date m/d/y</th>
<th>w/o PV &amp; 1 min. delay</th>
<th>w/o PV &amp; 5 min. delay</th>
<th>with PV &amp; 1 min. delay</th>
<th>with PV &amp; 5 min. delay</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/11/10</td>
<td>20</td>
<td>14</td>
<td>92</td>
<td>34</td>
</tr>
<tr>
<td>7/12/10</td>
<td>10</td>
<td>8</td>
<td>42</td>
<td>24</td>
</tr>
<tr>
<td>7/13/10</td>
<td>10</td>
<td>6</td>
<td>26</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>28</td>
<td>160</td>
<td>78</td>
</tr>
</tbody>
</table>

Note that the total number of tap changes discussed here does not take into account any tap changes due to voltage changes on the primary side of the substation transformer (i.e., the actual number of tap changes could be much higher if the transmission voltage were to vary significantly).
2.5. Results Summary

This chapter addressed the impact cloud-induced transients on voltage regulation in distribution systems with high PV penetration levels. More specifically, both voltage flicker and excessive transformer tap changes may result from the induced fluctuations in PV Power. Actual load and solar irradiance data is used to simulate the impact of 20% PV penetration on a simple distribution system during cloudy days. Based on observations on the simulations using 1-minute sampling rate at a single-point, while this level of PV penetration causes no flicker problems, it results in a significant increase in the number of transformer tap changes that will likely reduce the life expectancy of the LTC mechanism, even when implanting a 5-minute time delay. It is important to note, however, that variability observed at a single-point will not correspond to the variability of a cluster of small dispersed PV systems. Furthermore, the voltage flicker can be a
problem if the solar irradiance is sampled at a higher rate (in the order of seconds) since
the 1-minute interval tends is invisible to the faster changes in solar irradiance.
CHAPTER 3
MATHEMATICAL MODELING OF PHOTOVOLTAICS

This chapter reviews the basic operation and mathematical modeling of a photovoltaic cell. Furthermore, electrical performance characteristics of a practical PV module are discussed. The STC specifications of the practical PV module are presented. This information will be used in the MATLAB/Simulink modeling which is described in the following chapter.

3.1. Photovoltaic (PV) cell

A photovoltaic (PV) cell converts light energy into electrical energy. The output power from a PV cell is rather low about 2-3W at 0.5-0.7 V. Therefore a single cell is not of much practical use. Several cells have to be connected in series to produce useable power and voltage. Such strings are connected in series in a sealed, weather proof package [19], which forms a PV module. Based on the power requirement, several such modules are often connected in series and parallel combinations to form a solar or photovoltaic (PV) array. PV systems operate with no moving parts, thus requiring very low maintenance. PV energy finds application ranging from few watts to several megawatts in power capacity.

Some of the factors that restrict the wide usage of PV sources are as follows:

1) Photovoltaic energy is more expensive than any other source of energy.

2) Need for large collection area for installation of the panels to get high power output.
3) PV energy is not available at night and is less available in cloudy weather conditions. This necessitates the use of energy storage systems or alternative power systems during these intervals of non-availability [4].

### 3.2. Photovoltaic Power

Photovoltaic power is one of the important renewable sources as it is a clean, pollution free operation, inexhaustible and can be operated with minimal variable costs. With the rapid growth in semiconductor and power electronic technologies over the past decade, photovoltaic energy has been acquiring significant interest in electrical power applications.

![Electron and Current Flow in Solar Cells](image)

**Figure 3.1. Operation of a PV cell [14].**

The basic building block of a photovoltaic (PV) source is a simple P-N junction diode shaped by semiconductor material termed as solar cell as illustrated in Figure 3.1 above. When light falls on the n-type silicon on the surface, the energy of the incident photon create an electron-hole pair.
These carriers form electric potential across the junction and are separated by an electric field as shown in Figure 3.1 [14]. If a closed electrical path is provided by means of electric load across the solar cell terminals, current will flow through the external circuit. Hence light energy is converted into electrical energy.

3.3. Modeling a PV cell

The use of equivalent electric circuits makes it possible to model the characteristics of a PV cell. The model presented in this chapter is also implemented in a MATLAB/SIMULINK program for the purpose of computer simulations. The same modeling technique can also be applied for modeling a PV module or a PV array.

3.3.1. Ideal PV cell Model

The ideal PV cell circuit model consists of an ideal current source in parallel with an ideal diode as shown in Figure 3.2. In this circuit, $I_{ph}$ is the photon generated current and $I_d$ is the shunt current through the diode [6].
The circuit above can be described by the following equations [20].

The output current \( I \) is given by

\[
I = I_{ph} - I_d
\]  

Where,

\( I_{ph} \) is photon current (A)

\( I_d \) is diode current (A)

From the Shockley’s diode equation, \( I_d \) is given as:

\[
I_d = I_0 \left\{ \exp \left[ \frac{qV}{nkT} \right] - 1 \right\}
\]  

where,

\( I_0 \) is the reverse saturation current of the diode (A),

\( q \) is the electron charge \( (1.602 \times 10^{-19} \text{C}) \),

\( V \) is the forward voltage across the diode (V),

\( k \) is the Boltzmann’s constant \( (1.381 \times 10^{-23} \text{J/K}) \),

\( T \) is the junction temperature (in Kelvin),

\( \alpha \) is the ideality factor and takes the value between one and two.
Replacing equation (3.1) by equation (3.2) gives the current-voltage relationship of a PV cell:

\[ I = I_{ph} - I_0 \left( e^{\frac{qV}{eKT}} - 1 \right) \]  

(3.3)

Where,

\( V \) is the voltage across the PV cell, and \( I \) is the output current.

The reverse saturation current of diode \( (I_o) \) is constant under constant temperature and it is calculated from the open-circuit condition. i.e., \( V=V_{oc} \) and \( I=0 \) as shown in Figure 3.3.

Under zero-terminal voltage, the short-circuit current is equal to photon current i.e., \( I_{ph} = I_{sc} \). In the simplest form, this PV cell model has two parameters, the open-circuit voltage \( (V_{oc}) \) and short-circuits current \( (I_{sc}) \) [6]. Thus from equation (3.3),

\[ 0 = I_{sc} - I_0 \left( e^{\frac{qV_{oc}}{eKT}} - 1 \right) \]  

(3.4)

\[ I_{sc} = I_0 \left( e^{\frac{qV_{oc}}{eKT}} - 1 \right) \]  

(3.5)

\[ I_0 = I_{sc} / \left( e^{\frac{qV_{oc}}{eKT}} - 1 \right) \]  

(3.6)

Figure 3.3. a) Short circuit b) Open circuit conditions
If the value, $I_{sc}$, is known from the datasheet under standard test condition (STC), $G_o=1000 \text{ W/m}^2$, $T=25^\circ\text{C}$, the photon generated current at any other irradiance, $G \text{ (W/m}^2\text{)}$ is given by

$$I_{sc_{att}} = \left(\frac{G}{G_o}\right)I_{sc_{att}o} \quad (3.7)$$

The simplest equivalent circuit model simulated in Matlab yields the plot shown in Figure 3.4 for two insolation values- 1000 and 500 W/m$^2$. This shows that the cell current is directly proportional to the solar irradiance.

![Figure 3.4. I-V plot of ideal PV cell under two different levels of irradiance (25°C).](image)

### 3.3.2. Practical PV Model

There are a few elements which are not yet taken into consideration in the simple PV cell model described above which affects the performance of a PV cell in practice [21]. As shown in Figure 3.5, a practical PV cell includes a series resistance ($R_s$) and a parallel
resistance \( (R_p) \). Including these additional parameters to the basic equation, the current-voltage relationship of PV cell is written as [21]:

\[
I = I_{ph} - I_0 \left[ \exp \left( \frac{q(V+I.R_s)}{kT} \right) - 1 \right] - \frac{(V+I.R_s)}{R_p}
\]  

(3.8)

Where,

\( I_{ph} \) and \( I_0 \) are the photon and saturation currents (A)

\( I \) is the cell current, \( V \) is the cell voltage

\( R_s \) and \( R_p \) are equivalent cell series and parallel resistance

![Practical equivalent circuit of a PV cell](image)

Figure 3.5. Practical equivalent circuit of a PV cell

The above expression can be extended for a PV module or PV array which consists of a number of series and parallel branches: [21]

\[
I = N_p I_{ph} - N_p I_0 \left[ \exp \left( \frac{q(V+I.R_s)}{N_S kT} \right) - \frac{N_p}{N_S} \right] - \frac{(N_p V + I.R_s)}{N_p R_p}
\]  

(2.9)
where,
\( N_s \)- Number of series connected cells, \( N_p \)-number of parallel connected cells

Alpha (\( \alpha \)) is the ideality factor and takes a value between one and two.

A typical value of 1.3 is suggested for normal operation, and higher alpha value softens the knee of the I-V curve [5].

3.4. Photovoltaic Module

In order to produce sufficient voltage for most practical applications, the cells are connected in series. Most of commercially available PV modules have either 36 or 72 cells connected in series. A 36-cell module provides a voltage suitable for charging a 12V battery and a 72-cell module is appropriate for a 24V battery. When the PV cells are wired together in series, the output current is the equal to that of a single cell, but the output voltage is the sum of the voltages across each cell. Based on the power requirement, several such modules are connected in series and parallel combinations to form a solar or photovoltaic (PV) array.

3.4.1. Modeling a PV module by MATLAB/Simulink

In this present work, the Kyocera KD205GX-LPU PV module is chosen for a MATLAB/Simulink simulation model. The module is made of 54 Poly-crystalline silicon solar cells in series and provides 205 W of nominal maximum power [22]. Table 3.1 enumerates its electrical specifications. Both the strategy of modeling a PV module is no different from modeling a PV cell. It uses the same PV cell model. The parameters are the all same, but only a voltage parameter is different and must be divided by the number
of cells. The model consists of a current source ($I_{sc}$), a diode (D), series resistance ($R_s$) and parallel resistance ($R_p$).

Table 3.1. Electrical Characteristics of Kyocera KD205GX-LPU PV module [22].

<table>
<thead>
<tr>
<th>Electrical Performance under Standard Test Conditions (*STC)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power ($P_{max}$)</td>
<td>205 (+5 W/-0 W)</td>
</tr>
<tr>
<td>Maximum Power Voltage ($V_{mpp}$)</td>
<td>26.6 V</td>
</tr>
<tr>
<td>Maximum Power Current ($I_{mpp}$)</td>
<td>7.71 A</td>
</tr>
<tr>
<td>Open Circuit Voltage ($V_{OC}$)</td>
<td>33.2 V</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{SC}$)</td>
<td>8.36 A</td>
</tr>
<tr>
<td>Max System Voltage</td>
<td>600 V</td>
</tr>
<tr>
<td>Temperature Coefficient of $V_{OC}$</td>
<td>$-1.20 \times 10^{-1}$ V/ºC</td>
</tr>
<tr>
<td>Temperature Coefficient of $I_{SC}$</td>
<td>$5.02 \times 10^{-2}$ A/ ºC</td>
</tr>
<tr>
<td>*STC: Irradiance 1000 W/m², AM 1.5 spectrum, cell temperature 25 ºC</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrical Performance at 800W/m², *NOCT, AM 1.5</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power ($P_{max}$)</td>
<td>145 W</td>
</tr>
<tr>
<td>Maximum Power Voltage ($V_{mpp}$)</td>
<td>23.6 V</td>
</tr>
<tr>
<td>Maximum Power Current ($I_{mpp}$)</td>
<td>6.17 A</td>
</tr>
<tr>
<td>Open Circuit Voltage ($V_{OC}$)</td>
<td>30.0 V</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{SC}$)</td>
<td>6.78 A</td>
</tr>
<tr>
<td>*NOCT (Nominal Operating Cell Temperature) : 47.9 ºC</td>
<td></td>
</tr>
</tbody>
</table>

In practice, there is need to develop a practical model from the module data sheet [23]. This model obtains the parameters of the I-V equation by using the following nominal
information from the module data sheet: open-circuit voltage, short-circuit current, maximum output power, voltage and current at the maximum power point, current/temperature and voltage/temperature coefficients. A detailed MATLAB/Simulink model is explained in a later Chapter.

For example the following Figure 3.6 and Figure 3.7 explain that the PV module characteristics obtained by solving the nonlinear equation (3.8) in circuit based PV model by specifying the necessary values in the MATLAB/Simulink command window. It is observed from Figure 3.7 that the short-circuit current $I_{sc}$ increases with an increase in insolation. This is due to the fact that an increase in insolation, the generation of electron-hole pairs increases, and thus the current generation. However, an increase in insolation has very little effect on open circuit voltage $V_{oc}$. When temperature increases, the amount of saturation current will increase more than the amount of photocurrent, which results in the open-circuit voltage $V_{oc}$ to decrease. This is verified in Figure 3.6.

From the discussed characteristics, a conclusion can be drawn that larger power output is generated by PV array at high insolation and low temperature conditions. It is clear that PV arrays have a single maximum operating terminal voltage, only at which the array gives maximum power under a particular insolation and temperature condition. It is important to operate the system at that MPP (Maximum Power Point) of a PV module so that the maximum power from the module can be extracted.
Figure 3.6. I-V characteristics of PV module for different temperatures at $S=1000 \text{ W/m}^2$

Figure 3.7. I-V characteristics of PV module for different irradiances at $T=25 \degree \text{C}$
CHAPTER 4
PV SYSTEM CONFIGURATIONS AND MPPT TECHNIQUES

The various power plant topologies and maximum power point tracker (MPPT) techniques are discussed in this chapter.

4.1. Inverter Configurations

PV modules generate direct current (DC) and voltage. However, to feed the electricity to the grid, alternating current (AC) current and voltage are needed. Inverters are the equipment used to convert DC to AC. In addition, they can be in charge of keeping the operating point of the PV array at the MPP. This is usually done with computational MPP tracking algorithms. There are different inverter configurations depending on how the PV modules are connected to the inverter [24]. Some of the main types are described in this sub-section. More information about all the following topologies can be found in [24] and [25].

4.1.1. Central Inverter Configuration

A group of PV modules connected in series comprises a string of PV modules. In central inverter configuration (as shown in Figure 4.1), multiple strings of PV modules are connected in parallel and the DC power output from the all the string put together is fed into a single MPPT inverter. The inverter serves two purposes:

1. To operate the PV modules at the maximum power point
2. To convert the input DC power to AC power and feed it to the grid.
Figure 4.1. Central Inverter Configuration

In this configuration, although the second purpose is served well, there are some issues with the first. Since the maximum power point of each module varies depending on the solar radiation (changing with tracking, shading, cloud cover etc), module material etc. Thus a local maximum power point of a module may not correspond with the global maximum power point of the whole system resulting in under-operation of some PV modules. This configuration suffers from disadvantageous issues, including high voltage DC cable from a big number of strings to the inverter and losses in string diodes. It is also limited by mismatch between strings causing low efficiency and low reliability of individual PVs. With all these issues, this configuration is seldom used in new solar systems installation.

4.1.2. String Inverter Configuration

In string inverter configuration (as shown in Figure 4.2), each string, comprising a group of PV modules connected in series, is connected to a MPPT inverter. Although, there is
an additional investment cost that need to be considered, this configuration eliminates power losses due mismatch of MPP between two different strings. If necessary each string can operate at a different MPP during instances when shading of strings occurs.

Figure 4.2. String Inverter Configuration

4.1.3. Multi-String Inverters

In the multi-string inverter configuration (as shown in Figure 4.3), each string of PV modules is connected to a DC-DC converter whose primary function is to perform MPPT on the string. The output power from all the DC-DC converters is fed into a single inverter for DC to AC conversion. This configuration also boasts the same benefits as string inverter configuration. However, it is comparatively more expensive than central inverter configuration.
4.1.4. Module Inverter Configuration

In case of module inverter configuration (as shown in Figure 4.4), each PV module in the system is connected to a MPPT inverter. This configuration will be comparatively expensive due to the additional cost of inverters. It is not usually preferred unless there is a substantial difference in the MPP of the modules. It is quite obvious that this configuration would ensure the best performance of each module with minimum power losses.
4.2. Maximum power utilization of photovoltaic (PV) power sources

At any given time, to extract the maximum power generated by a solar cell, the solar system has to be equipped with a maximum power point tracker (MPPT). It helps to operate the PV system at the maximum output power point for a given set of conditions, thereby maximizing the array efficiency. The MPPT does this by constantly controlling the PV voltage or current independently regardless of the load connected. The MPPT technology is commonly implemented in the DC-DC converters, but due to technological advancements in recent times, now it can also be implemented in the DC-AC inverters. Although, several MPPT methods are available, the most commonly practiced methods and their drawbacks are discussed below [26-27].
4.2.1. Constant voltage (CV) method

In the constant voltage method, the MPP voltage changes moderately with varying solar irradiance. In this method, the ratio of voltage at MPP ($V_{MPP}$) and open circuit voltage ($V_{OC}$) is assumed to be approximately constant.

$$\frac{V_{MPP}}{V_{OC}} \cong K < 1 \quad (3.2)$$

Initially, the solar array is temporarily disconnected with the MPPT and the value of $V_{OC}$ is recorded. Then the MPPT calculates the operating point based on the pre-set value of ‘K’ using equation (3.2), and adjusts the array voltage till it reaches the $V_{MPP}$. In general the ratio depends on the solar cell parameters, but a value in the range of 73%-80% is commonly used. The only drawback in this method is the loss of energy when the load is disconnected and reconnected with the source.

4.2.2. Perturb-and-observe (P&O) method

The perturb-and-observe (P&O) algorithm is the most commonly used in practice for MPP tracking. It is based on the fact that as the voltage is perturbed and the rate of change of power (dP/dt) is observed. Based on the sign (positive or negative) of the derivative-'dP/dt’, the voltage value is increased or decreased to reach MPP, thereby yielding a zero ‘dP/dt’ derivative. As the nature of this algorithm is absolutely based on perturbation, one can notice some oscillations even after the MPP is reached. A flow chart describing the P&O algorithm is shown in Figure 4.5 [26].
4.2.3. Incremental conductance (INC) method

In the incremental conductance algorithm, the PV power (P) is differentiated with respect to voltage (V) and by rearranging the equations we obtain the following equations shown below.

\[ P = VI \]
\[
\frac{dP}{dV} = I + V \frac{dI}{dV}
\]

At MPP: \( \frac{dP}{dV} = 0 = I + V \frac{dI}{dV} \)

\[
\frac{dI}{dV} = -\frac{I}{V}
\]

The right-hand side of the final equation signifies the negative of PV arrays instantaneous conductance, whereas the left-hand side signifies incremental conductance. Thus, at the MPP, the instantaneous conductance and the incremental conductance are equal in magnitude but opposite in sign. The MPPT adjusts it voltage until the final equation is satisfied. Once the final equation is satisfied, the MPPT continues to operate at this point until a change is noticed. The advantage with this method is that it rectifies the oscillation of \( V_{MPP} \) in the perturb-and-disturb algorithm. The only disadvantage with this method is the increased complexity compared to the other methods. A flow chart describing the INC algorithm is shown in Figure 4.6 [26].
4.2.4. Parasitic Capacitance (PC) method

This method relies on the fact that every solar cell is built with a parasitic capacitance, and this capacitance helps in finding the MPP. As the size of parasitic capacitance is very small in each module, it is only used in systems with several modules in parallel. In this method, the array conductance is calculated by using the average ripple in the array power and voltage. Then the direction of the operating point of the MPPT is determined using previously described incremental conductance algorithm. This method is a type of modified incremental conductance technique, and is equally complex.
4.2.5. Efficiency of the MPPT techniques

Even though the incremental conductance and the parasitic capacitance methods are more complex than others, all the methods presented here are designed to be implemented in low cost systems with low computational capacity. Table 3.1 shows a comparison among the above three methods in term of their efficiency [27].

<table>
<thead>
<tr>
<th></th>
<th>CV Method</th>
<th>P&amp;O Method</th>
<th>INC Method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Array Efficiency</strong></td>
<td>88.1%</td>
<td>96.5%</td>
<td>98.2%</td>
</tr>
<tr>
<td><strong>Simulator Efficiency</strong></td>
<td>92.7%</td>
<td>97.2%</td>
<td>98.5%</td>
</tr>
</tbody>
</table>

Table 4.1. Efficiency of the MPPT methods

These results indicate that CV method has a low efficiency, and the difference between efficiencies of P&O and INC methods is small, while they both have high efficiencies. However, the comparison of the parasitic capacitance method with these methods is unknown. But since it is a refinement of the INC method, one can safely assume an efficiency of the INC method or even a slightly better value.
CHAPTER 5
DESIGN AND SIMULATIONS

This chapter discusses the design and simulation procedures of a PV module, inverter and electrical load using Matlab/Simulink power system block set libraries.

5.1. PV Module mathematical modeling and Simulink circuit design

The Mathematical model used for this simulation is shown in equation (5.1)

\[ I_o = \frac{I_{SC,n} + K_I \Delta T}{\exp \left( \frac{V_{OC,n} + K_v \Delta T}{aV_t} \right) - 1} \] .......................... (5.1)

The various components used in developing the circuit design for a PV module are chosen from the MATLAB/SIMULINK library. The voltage measurement block, current measurement block, go to block, from block, and control current source block are used to model various outputs such as Shockley diode current, the light generated photovoltaic current, cell temperature equation, and energy output.

Figure 5.1 shows the Simulink modeling for the reverse saturation current \( I_o \) at the reference temperature which is given by the equation (5.1).
Figure 5.1. Simulink model for evaluating $I_0$

Figure 5.2 shows the Simulink model for the light generated current of the photovoltaic cell which is a linear function of temperature and solar radiation as shown in the equation (5.2) below

$$I_{PV} = \left( I_{PV,n} + K_i \Delta T \right) \frac{G}{G_n} \quad (5.2)$$
Figure 5.3 shows the Simulink model to evaluate the model current $I_m$ referring to the appropriate model circuit for which is given by the equation (5.3).

$$I = I_{PV} - I_0 \left[ \exp \left( \frac{V + R_S I}{V_{t,a}} \right) - 1 \right]$$ (5.3)

Figure 5.3. Mathematical model implementation for model current $I_m$

5.2. DC-AC inverter

The Matlab/Simulink library offers a universal bridge inverter which is used in the present model. This component can be used as a universal single phase power converter. The desirable power switch and converter configuration can be chosen from the dialog box.
The Universal bridge inverter block allows simulation of converters using both naturally commutated (line-commutated) power electronic devices (diodes or thyristors) and forced-commutated devices (GTO, IGBT, MOSFET).

Figure 5.4. A PWM IGBT inverter and a Full Bridge IGBT inverter topology [30]

The universal bridge inverter has been modeled as a full bridge, two arm IGBT inverter. The pulse width modulator triggers the pulses for switching. The pulse width modulator in turn has an external supply connected to a sinusoidal carrier wave.
5.3. Maximum Peak power tracker Controller

The MPPT Control block generates the reference voltage using the MPPT algorithm under test. The reference voltage generated by the MPPT Control block is converted to a current reference using the control scheme described in [28] and shown in Figure 5.5.

![Diagram of MPPT Controller]

Figure 5.5. MPPT Controller

In this scheme, the error between the reference and the actual DC voltage (the output voltage of the PV array) is fed in a proportional gain, whose value depends on the DC link capacitance and the sampling period. The output of this gain is subtracted from the current of the PV module and the result is the reference current for the controlled current source.

The sampling frequency of the MPPT algorithm was selected according to [29] whereas the sampling frequency of the voltage and current measurements was chosen according to the sampling time of a modern DSP. The sample frequency of the MPPT algorithm should not be very high because the dynamics of the weather conditions is slow compared to the dynamics of systems typically studied in control theory.
Figure 5.5. Simulink Model of grid connected Photovoltaic system.

The utility grid supplies a voltage of 170 V peak. Therefore, it is necessary to tune the 170V to 1 V before it is fed to the pulse width generator. This way, the inverter behaves as a grid-tie inverter. The measurement blocks such as voltage measurement and current measurement will be used to determine the current, voltage to be measured across the photovoltaic terminal, utility terminal and also the load.
5.4. Utility Supply

The utility supply is nothing but an Alternating Current (AC) supply. Matlab/ Simulink allow a direct and simple component of AC voltage supply. The voltage peak specified for the utility grid is 170V amplitude. Therefore, it is necessary to tune the 170V to 1 V before feed it back again to the pulse width generator. This way, the inverter behaves as grid tie inverter.
CHAPTER 6
SIMULATION RESULTS

A 2 kW grid-connected PV array that is made of 10 series-connected modules, identical to the one modeled earlier is simulated in this chapter. The simulations provide the valuable opportunity investigate the intermittency problems associated with MPPT algorithms and effect of input dc link capacitance on intermittency. The only fast changing variable used in simulation is solar insolation, at the same time module temperature value is fixed at 25°C as change in temperature is not directly related to system dynamic response.

6.1. Qualitative Analysis

For the analysis, The Mosfet switching frequency is considered as 50 KHz whereas the MPPT sampling frequency is considered as 1 KHz. The simulations are carried out in discrete time domain for different cases; the below sections will elaborate those cases.
Case 1: This case is designed to compute the performance under constant solar irradiance $G=1000 \text{ W/m}^2$, $T=25^\circ\text{C}$ with MPPT algorithm. Figure 6.1 shows the voltage, current, power plots with MPPT at $G=1000 \text{ W/m}^2$. The PV module is operating at maximum voltage of 266V, maximum current of 7.71 A, thus, has a maximum output power of 2,050W.

Figure 6.1. Simulation result with MPPT sampling rate of 1 Hz at $G=1000 \text{ W/m}^2$
Case 2: This case is designed to compute the performance under variable solar irradiance that starts at $G = 1000$ then drops to 800 in two seconds, then rises back to 1000 W/m$^2$. Figure 6.2 shows the voltage, current, power plots with MPPT at $G=1000$ W/m$^2$. The PV module is operating at maximum voltage of 266V, maximum current of 7.71 A, thus, has a maximum output power of 2,050W.

Figure 6.2. Simulation result with MPPT sampling rate of Hz at $G=1000$ -800 -1000 W/m$^2$
Case 3: This case is designed to compute the performance under data collected in real
time solar irradiance, T=25°C with MPPT algorithm. Figure 6.3 shows the voltage,
current, power plots with MPPT at G=1000 W/m². The PV module is operating at
maximum voltage of 266V, maximum current of 7.71 A, thus, has a maximum output
power of 2,050W.

Figure 6.3. Simulation result with MPPT sampling rate of 1 Hz for real time insolation
6.2. Conclusion and Future work

In this thesis, a dynamic model of grid connected photovoltaic system is simulated using Matlab®/Simulink®. The model proposed here consists of a model of the PV array, the DC-link capacitor and a controlled current source, which replaces the power converter. Detailed models of the PV system with the switching model of the power converter are computationally very heavy and hence, in a normal computer the simulation has to be scaled down to a timeframe of only a few seconds. However, the simulation time required for testing the system with the irradiation profiles proposed in [31] can take up to several minutes. This can be difficult or impossible to achieve on a PC if a complete model of the PV system is used because the computer runs out of memory after some seconds of simulation.

Finally, the model is tested for three cases - one with constant insolation value and the other two with varying insolation values (fluctuating between 800 and 1000 W/m$^2$). The temperature is assumed constant (25 °C) in all the three cases. In all the cases, MPPT behaved as expected and is able track the maximum power point. An initial delay of 0.7 seconds is observed due to the presence of buffer capacitance in the model.

Further work in this area would comprise simulations for longer time periods which demands higher computational capabilities. With the emerging developments in meteorological sciences, future weather phenomena can be predicted fairly accurately. When it is coupled with heavy computational capabilities, the power fluctuation can be predicted accurately. These predictions can be particularly useful for power utility industry where the need to meet the load demand is highly critical.
References


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DYNAMIC MODELING OF SINGLE PHASE GRID CONNECTED PHOTOVOLTAIC SYSTEM

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