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Evaluation of Inverter Reconnection for Large Solar Parks

Master of Science Thesis in the Master Degree Programme, Electric Power Engineering

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Göteborg, Sweden, 2010

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Abstract

The growing demand in energy consumption as a result of both accelerated growth in human population and advancement in technology is exerting tremendous stress on our environment. Majority of electrical production are typically provided from fossil fuels like coal, natural gases and oil which contribute highly to the increasing CO₂ production. To reduce the negative impact of these resources and reduce the societies dependency on them, sustainable, renewable energy resources like biomass, geothermal, solar, wind, ocean thermal, wave action and tidal action have come into focus. This master thesis looks into the improvement of efficiency of large solar parks.

The work investigates the application of inverter reconnection mechanisms of solar inverters applied to large solar park. This is performed by modeling the possible switching mechanisms in Mat lab and analyzing the loss reduction potential of each inverter reconnection. The loss profile of solar inverter is derived from datasheet values available for a 100KW and 500KW Gamesa Inverter. To generate the output from the solar park, two types of commercial available photovoltaic simulation softwares were used namely PVSyst 5.12 and INSEL 8.

To incorporate the effect of shading on the performance of solar park, the work also investigates modeling of large solar parks. Three mathematical models were investigated and the results are presented. The implementation of the model was done in Mat Lab. The modeling for large solar parks is performed in order to investigate the performance of the inverter reconnection with respect to partial shading. Since measurement setups weren't available, none of the models can be verified with measured data. The model results confirm theoretical analysis.

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1 Introduction

This chapter presents a short description of the thesis work. Section one describes the purpose of the work. Section two includes the post condition as well as the limitation and scope of the work. The area investigated, results and short comings of the work are also presented in this section. Section 3 of this chapter presents definition of terms used throughout the report. The last section gives a description of report's structure.

1.1 Purpose

To address the environmental impact of today's power production methods and the increasing energy consumption, a lot of research is carried out to increase the large scale applicability of sustainable power production systems like wind and solar. Today large photovoltaic (PV) generation system with a capacity up to 60 MW exists [23]. With a price of range of 3-5cents/Kwh, the price of energy from PV generator is much more expensive compared to conventional power generation. Despite the cost, due to attractive incentives presented by government, PV generation systems are expanding quiet rapidly. To bring the cost down would require several coordinated initiatives like improvement on efficiency of components building up the system. At the same time the improvement of the system efficiency to bring the cost down is regarded as a solution.

Different stage exists before the power generated by the PV array reaches the medium voltage grid. Figure 1.1 below presents the various stages and their associated losses.

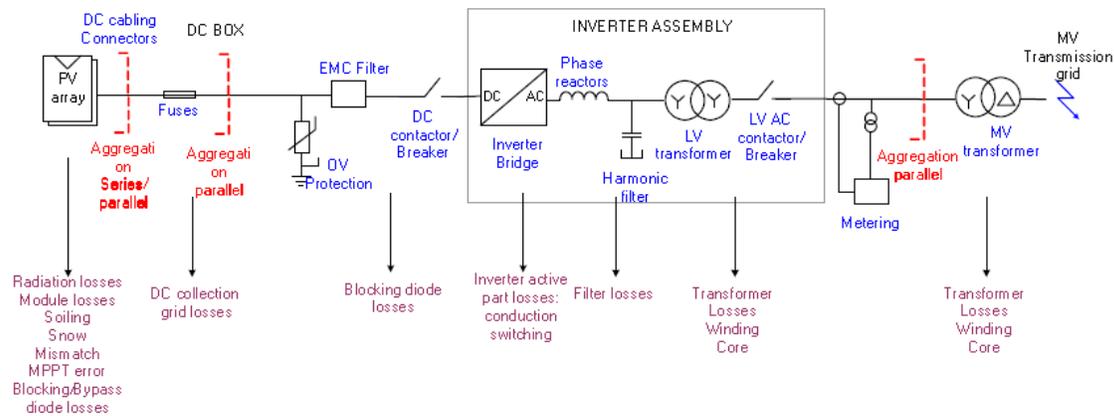


Figure 1.1 Schematic view of a PV generation system

The loss characteristic of PV inverter doesn't present a linear relation to the power. This is associated to constant iron loss that exists in the low voltage transformer. To alleviate the efficiency problem associated with PV inverters, inverter manufacturers employ different inverter reconnection strategies to operate two or more inverters as a single unit. The applicability of these strategies on large PV generator system will be covered in this work.

The output of a PV generator system can be simulated using different commercially available software namely PVSyst, INSEL, PV*SOL, PV design pro. But to this day, how this software treat the effect of partial shading on the output behavior of large solar parks isn't really clear. Plus most function that are available with some software deal with shading caused by stationary objects in the vicinity of PV

generator [7]. To develop a model that can consider the effect of partial shading can be quite a valuable tool.

1.2 Scope

The scope of the report covers four inverter reconnection methods. These methods are analyzed with respect to their loss reduction potential. The whole work is primarily aimed at grid connected PV generator system. When it comes to the modeling, three PV generator modeling approaches were chosen and tried. The reader at this point should be warned that, the results from the modeling are not compared to any experimental data. In addition the models employed do not cover partial shading scenario caused by fast moving cloud. The work can be taught of a starting ground to modeling the effect of shading on large PV generator system.

1.3 Definition

algorithm	Method of solving a problem using a sequence of finite instruction
Equivalent circuit	Simplest form of a circuit that preserves all electrical characteristics of a more complex system
Flow chart	Diagram that represents an algorithm of a process. A schematic representation of how the different stage in a process are interconnected
Galvanic isolation	Principle of separating functional section of electrical system so that no current flows directly between separated sections
Grid	System of electrical distribution serving a large area that is maintained by electrical utility
irradiation	Amount of solar energy received on a surface in a certain amount of time
MPPT	Maximum power point tracker, a power conditioning unit that operated a PV generator at its maximum power point
model	A set of mathematical equation describing the behavior of a system
modeling	All process involved to express mathematical the behavior of a system
nonlinear	A direct relationship doesn't exist between the input and output
Photon	Basic unit of light
Photovoltage	Voltage generated across an unloaded photovoltaic generator at a particular temperature and irradiance as measured with a voltmeter

1.4 Structure

The structure of the report is as follows

Chapter 1: Introduction describes the purpose of the report, the scope of the work and terms and abbreviation used.

Chapter 2: Description of the problem to be solved

Chapter 3: Literature review on PV generator system, reconnection methods to improve efficiency of the system and different possible approach to model a large PV generator system

Chapter 4: Discussion on the approach taken in solving the problem in section 2. It starts by presenting the methods for inverter reconnection. It then covers the implemented method for PV generator modeling

Chapter 5: Result shows all the result in the methods implemented. A small description and discussion for some results are presented along.

Chapter 6: Conclusion and future work

2 Problem Description

2.1 Inverter Reconnection

In large Photovoltaic generator system, several inverters are operated in parallel to convert the DC power generated by the system. The output from this inverter can be connected to a medium voltage transformer that is connected to medium voltage transmission line. Present day PV generators donot have loss characteristics that vary linearly with load. Constant power losses exist due to iron losses in low voltage transformer. Transformer less PV inverters are available that can reduce this problem but due to grid requirement for galvanic isolation between PV generator system and the grid, their universal applicability are limited.

In order to mitigate the problem at hand, several solutions have been proposed where the number of inverters operated is reduced during low load condition. This helps in avoiding operating inverters in their low efficiency region. It would be interesting to evaluate the different solution with respect of loss reduction potential.

2.2 PV Generator System Modeling

Shading upon a PV generation system can bring down the performance of the generation system. To this day several PV Generator system simulation program exist that can be used to simulate the output of PV generator system. Some not all developed program have features to treat shading condition caused by stationary objects. In addition how this software deal with condition of partial shading is not clearly defined. A model that can be used to generate the output of a non uniformly illuminated PV generator system can be a good asset.

3 Literature Review

3.1 PV Generator System

Photovoltaic generation system is becoming quite significant among sustainable energy system since it offers many advantages such as no fuel cost, no pollution, requirement of little maintains and no noise. On the down side PV module until today has relatively low conversion efficiency in the order of 12-15% [24]. In medium and large size PV power system, the efficiency of the system becomes a key design issue. Various conversion stages exist to convert the energy from the sun to a usable energy form. The basic units in the conversion stages will be discussed. A simplified block diagram representing the process is shown below.

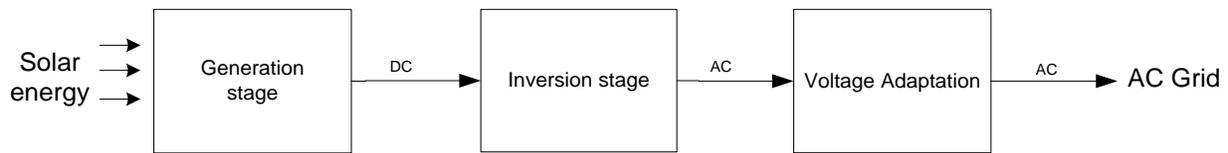


Figure 3.1 Simplified block diagram of a PV generator system

3.1.1 Generation Stage

PV Cell and PV module

PV cells are large area semiconductor devices. In simple words, a PV cell can be explained as a two terminal device that conducts like a diode in the dark and produce photo voltage when illuminated by light. An ideal PV cell can be represented as an ideal current source in parallel with a diode (fig 3.2). The current source represents the current generated by the PV cells as a result of Photons received and is dependent on the amount of irradiation (will be proved shortly) and temperature whereas in the absence of light the PV cell behaves as a diode.

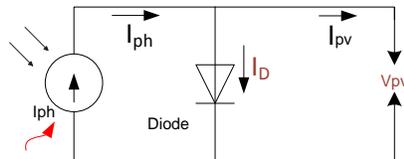


Figure 3.2 Equivalent circuit of an ideal PV cell.

The current from an ideal PV cell (I_{PV}) can be expressed in terms of the photon current (I_{ph}) and the diode current (I_D)

$$I_{PV} = I_{ph} - I_D \tag{3.1}$$

The diode current can be expressed using the Shockley's diode equation as

$$I_D = I_o * (e^{\frac{q*V_{PV}}{k*T}} - 1) \quad 3.2.$$

Where I_o = Reverse saturation current of the diode

V_d = Voltage across diode

K = Boltzman's constant

q = Electron Charge

T = Junction Temperature [K]

The I-V characteristics equation for an ideal PV cell can be obtained by inserting equation 3.2 into 3.1

$$I_{PV} = I_{ph} - I_o * (e^{\frac{q*V_{PV}}{k*T}} - 1) \quad 3.3.$$

Under short circuit condition, i.e. when $V_{PV} = 0$ in equation 3.3, the cell's current is equivalent to the photon generated current. This shows, the cell's current to be directly proportional to the cell's irradiance. On the other hand, the effect of irradiation on the open circuit voltage is solved by setting ($I_{PV} = 0$) in equation 3.3.

$$V_{oc} = \frac{k * T}{q} \ln\left(\frac{I_{ph}}{I_o}\right) \quad 3.4.$$

From equation 3.4, it can be observed that the open circuit voltage is only logarithmically dependent on the cell illumination where as it is directly proportional to the operating temperature.

Since in reality no solar cell is ideal, a shunt resistance (to represent the leakage current through solar cell) and a series resistance (representing resistance in emitter and base region) are added to the model. The equivalent circuit representing a PV cell using the one diode model is shown below. The detailed derivation of the model will be covered in part 3.2.1

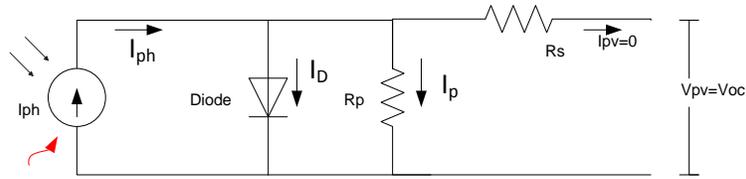
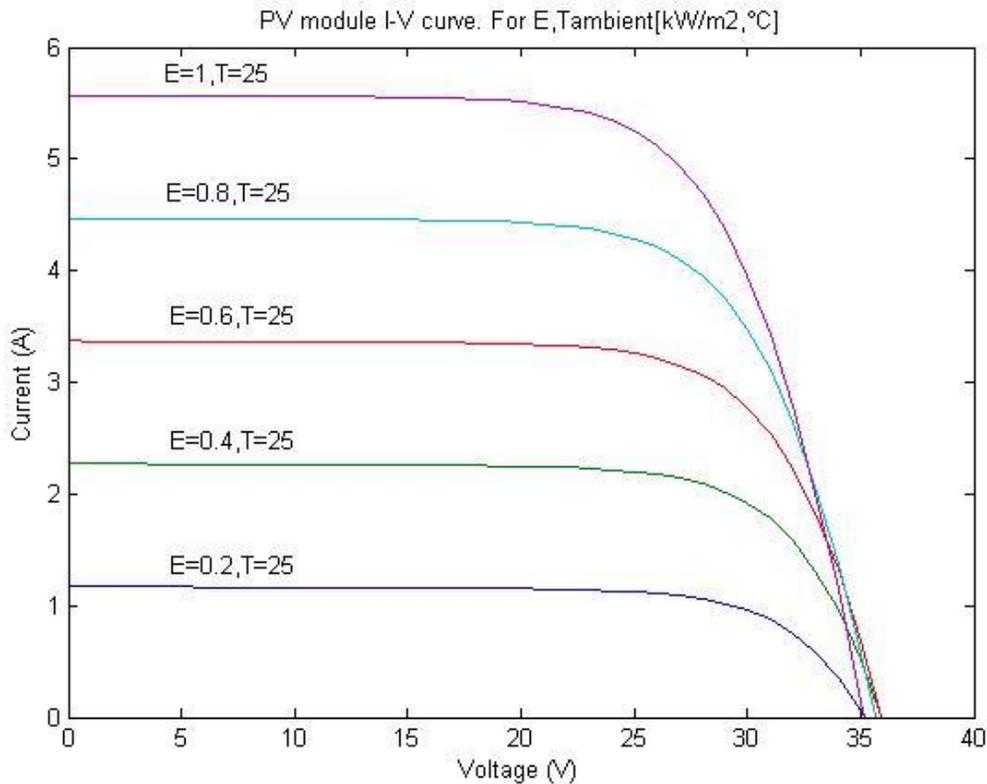


Figure 3.3 Equivalent circuit of a non ideal PV cell

In Equation 3.4, it is shown that the voltage current characteristic of any photovoltaic unit is dependent on the solar radiation and working temperature. When charged by a light source, a PV cell generates a DC voltage of 0.5-1 volts and in short circuit, a photon current density of some ten's of milliamps/cm² [14]. The voltage level from a single PV cell is too small for any application, and as a result several cells are connected in series and encapsulated to form modules. For standalone system 36 cell modules is the normal standard. But recently due increasing grid connected PV generator system, the power requirement of each module has gone up. In most commercial available module it is now usual to have 54 cells or 72 cells in series [24]. The most used parameter for characterizing a PV module is the open circuit voltage and the short circuit current which are generally provided on the manufacturer's data sheet. The use of these parameters will be discussed in later sections.

The characteristic I-V curve of a module is highly nonlinear [2]. During short circuit condition, the maximum current from the PV module is attained. If we attach a load resistance and increase it, the current starts to fall off at a lower rate until a knee point. Beyond the knee point the current falls drastically to zero (where V=Voc). Figure 3.4 illustrates this and the effect of irradiation and temperature on the I-V characteristic of a PV module.



(a)

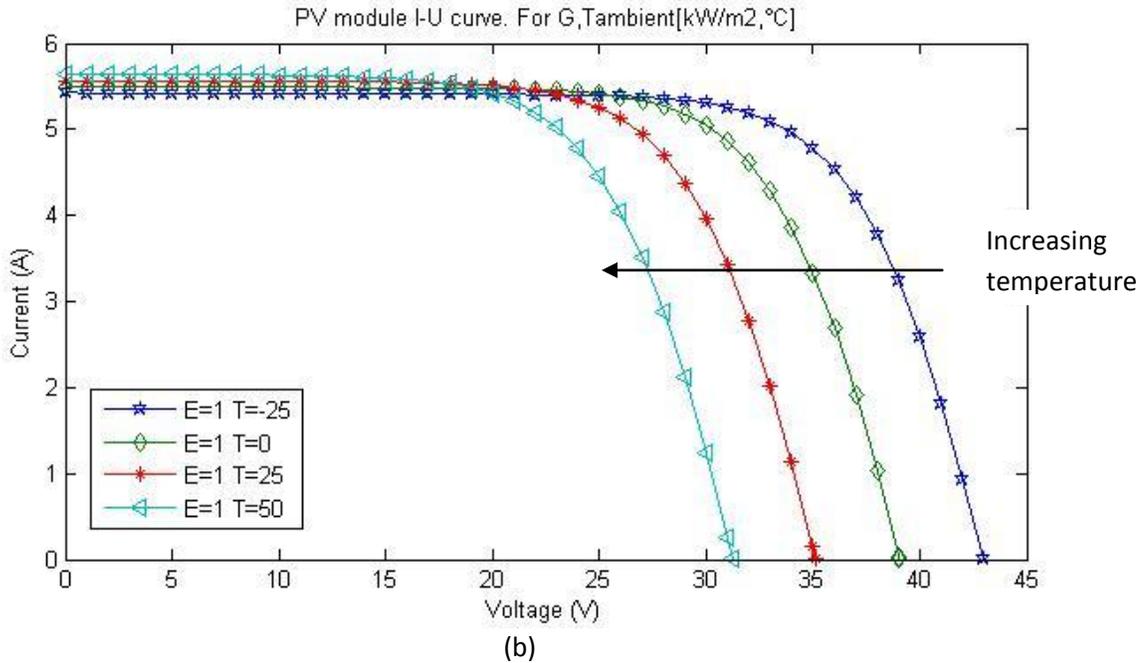
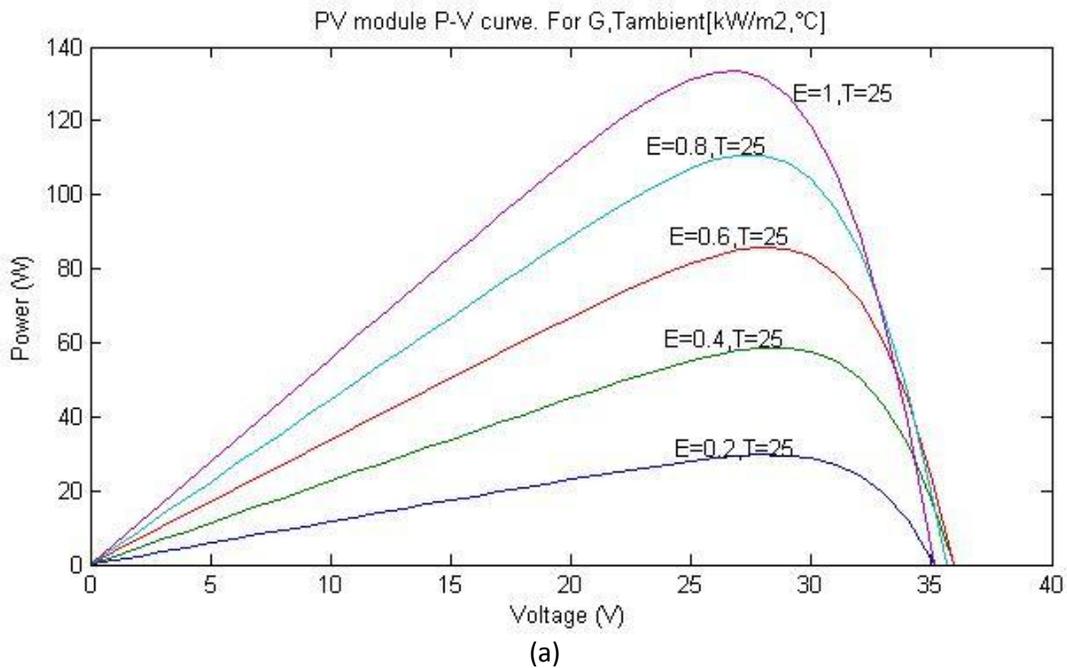


Figure 3.4 I-V characteristics of a Photovoltaic module (a) different irradiation condition (b) different operating temperature.

The power (P) versus voltage (V) can be found by direct multiplication of the current (I) and the voltage (V) for each operating point. The P-V characteristic for increasing irradiation condition (figure 3.5 a) and decreasing temperature (figure 3.5 b) is shown. Important point we need to observe from figure 3.5 is that, there exists a single point where the power output of the PV module is maximum. This point is referred to the maximum power point (MPP).



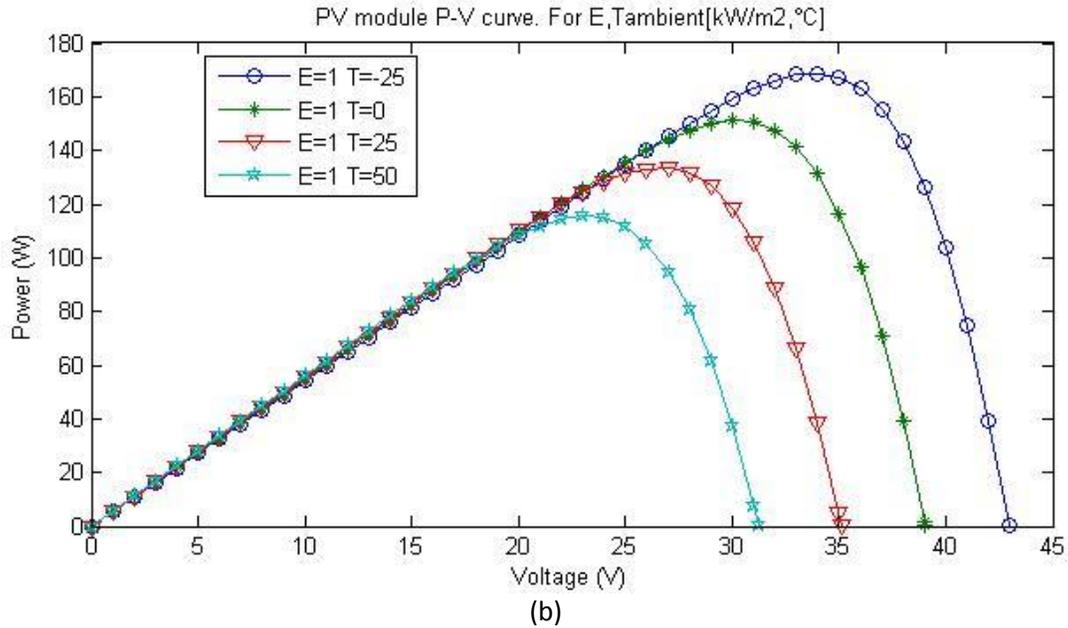


Figure 3.5 P-V characteristics of a Photovoltaic module (a) different irradiation condition (b) different operating temperature.

Since cells are series connected in a module, it is important that the I-V characteristics of the cells match as close as possible. Shading of a single or string of cells in a module would cause the output current of the shaded portion to be lower. The series connection forces all cells to operate at the same current. If the string current goes beyond the short circuit current capacity of the shaded cell, the cells starts to produce negative voltage (instead of a source it starts to act as a sink). The power produced by the unshaded cell is dissipated by the shaded cell. As a result a heating phenomena known as hotspot occurs [12]. If the summation of voltage of the unshaded cell exceeds the diode reverse breakdown voltage, an irreversible damage occurs on the cell.

PV Generator

To achieve a higher level of voltage, modules are connected in series to form strings and to achieve a higher level of current; the strings are connected in parallel. For grid connected system it is nowadays common to have the output voltage value of the PV generator greater than the grid voltage value [4]. These increase the overall efficiency of the system by avoiding a boost process within the conversion stage. On the other hand, the PV generator total efficiency would be compromised due to mismatch loss as the number of module connected in series increases [14]. Therefore during the design process an optimal solution should be reached taking into consideration the customer's choice on Inverter type.

3.1.2 Inversion stage

Since the generated power is in DC, the output from the system is then feed to the grid after passing through an inversion stage. The inversion stage consists of a DC-DC stage using power electronics: for adaptation of load characteristics with that of the PV generator (A maximum power point tracker) and a second stage which is an inverter in order to perform the DC-AC conversion

MPP Point and MPP Tracker

The output power of PV generator is the product of the current delivered and the operating voltage of the generator. In a PV generator, there exists a single point where the value of the current and the voltage results in a maximum power. The mathematical equation describing the current voltage relation has an exponential behavior which shows that there a knee beyond which the product of the current and voltage fall drastically. This can be seen in figure 3.5 of the previous section. Moreover the characteristics curve varies with varying irradiation and temperature condition. Hence where we operate is highly determination for the output from our generator.

If direct coupling between the PV generator and the system load, a problem lies in the mismatch between the operating point of the system load and the PV generator's maximum power point. This can be explained using figure 3.6. Assume that the characteristics I-V curve of the system load line is as shown by the straight line. The I-V curve for the PV generator which varies with the varying irradiation level is shown. When the load is directly connected to the PV generator, the overall system operating point is the intersection point of the two curves, which is further away from the actual MPP point of the PV generator. To operate the PV generation at its most efficient point, maximum power point trackers (MPPT) are employed.

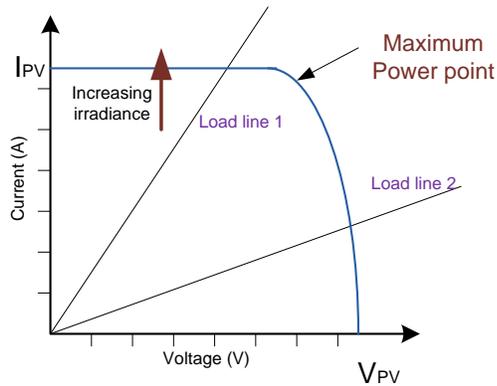


Figure 3.6 I-V curve of PV Generator and load I-V characteristics

According to the definition stated in Wikipedia, a MPPT is a high efficiency DC-DC converter used to present an optimum electrical load to PV generator so that it operates at its MPP point while at the same time produce a suitable voltage for the load. The choice whether the converter should be a buck or a boost or a buck boost depends on the requirement of the load voltage. Many algorithms exist for implementation of MPPT. The algorithms are used to determine the required duty cycle for the DC-DC converter. To get an overview of how they function, two common algorithms are discussed here

The most common algorithm is “perturb and observe” (P&O) algorithm. In this algorithm Voltage is incremented in steps by a fixed amount and the change in power (dP/dv) is observed. The algorithms then only changes direction when it detects a drop in power in between the steps. Figure 3.7 is used to describe the algorithm

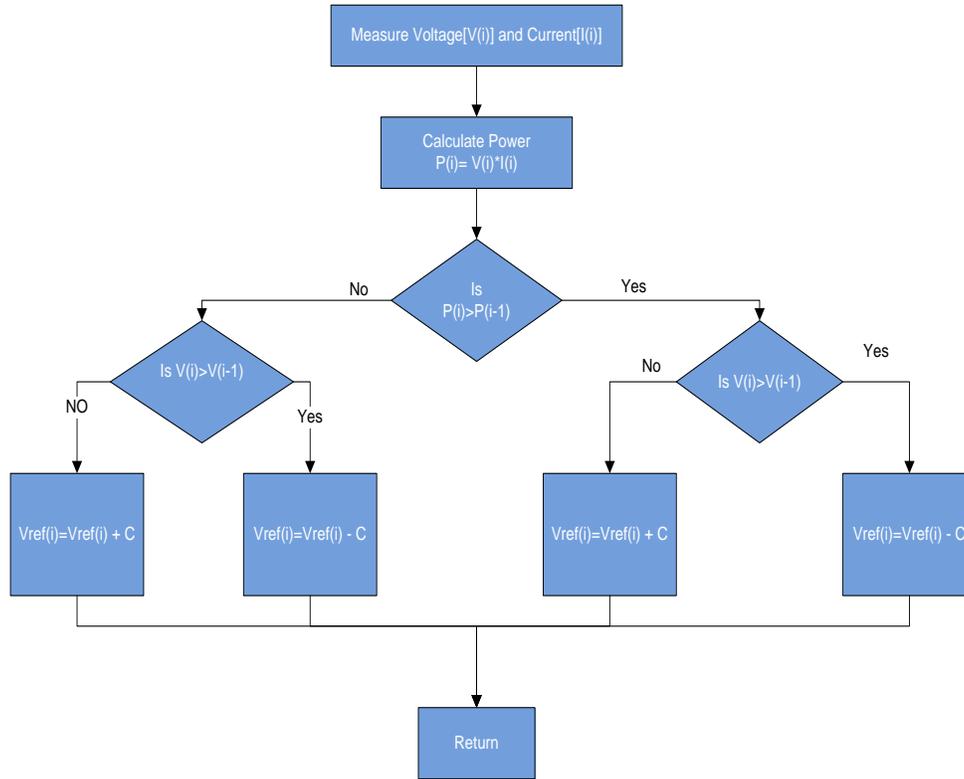


Figure 3.7 Flow chart showing “perturb and observe” algorithm.

The converter by adjusting its duty cycle puts up V_{ref} for the PV generator and measures the change in power and the cycle continues. This algorithm is the most common used because of its simplicity. The downside to this algorithm is that it would have oscillation around the MPP point [2]. Another major fault with P&O algorithm is its faulty performance under fast irradiation changes (caused by a cloud) [10]. The algorithm increments the voltage and measures the change in power (ΔP), if the power increases, in the next cycle the voltage is increased. Here the increase in power can be as a result of increased irradiation level as a result of a cloud moving away from the PV generator. This causes the voltage to be incremented where as the MPP for the present operating condition is at a lower voltage. This causes the search for MPP point to deviate from the actual MPP point.

An algorithm that is proposed to overcome the fault of the P&O algorithm is the Incremental conductance algorithm. At MPP the derivation of the power with respect to voltage equals zero.

$$\frac{dP}{dV} = 0 \quad \text{at MPP}$$

$$\frac{dP}{dV} < 0 \quad \text{right of MPP}$$

$$\frac{dP}{dV} > 0 \quad \text{left of MPP}$$

3.5.

$$\frac{dP}{dV} = \frac{d(I * V)}{dV} = I + V * \frac{dI}{dV} = 0 \quad 3.6.$$

By rearranging equation 3.6 the conductance can be expressed

$$G = \frac{dI}{dV} = -\frac{I}{V} \quad 3.7.$$

The Algorithm using a flowchart is presented below

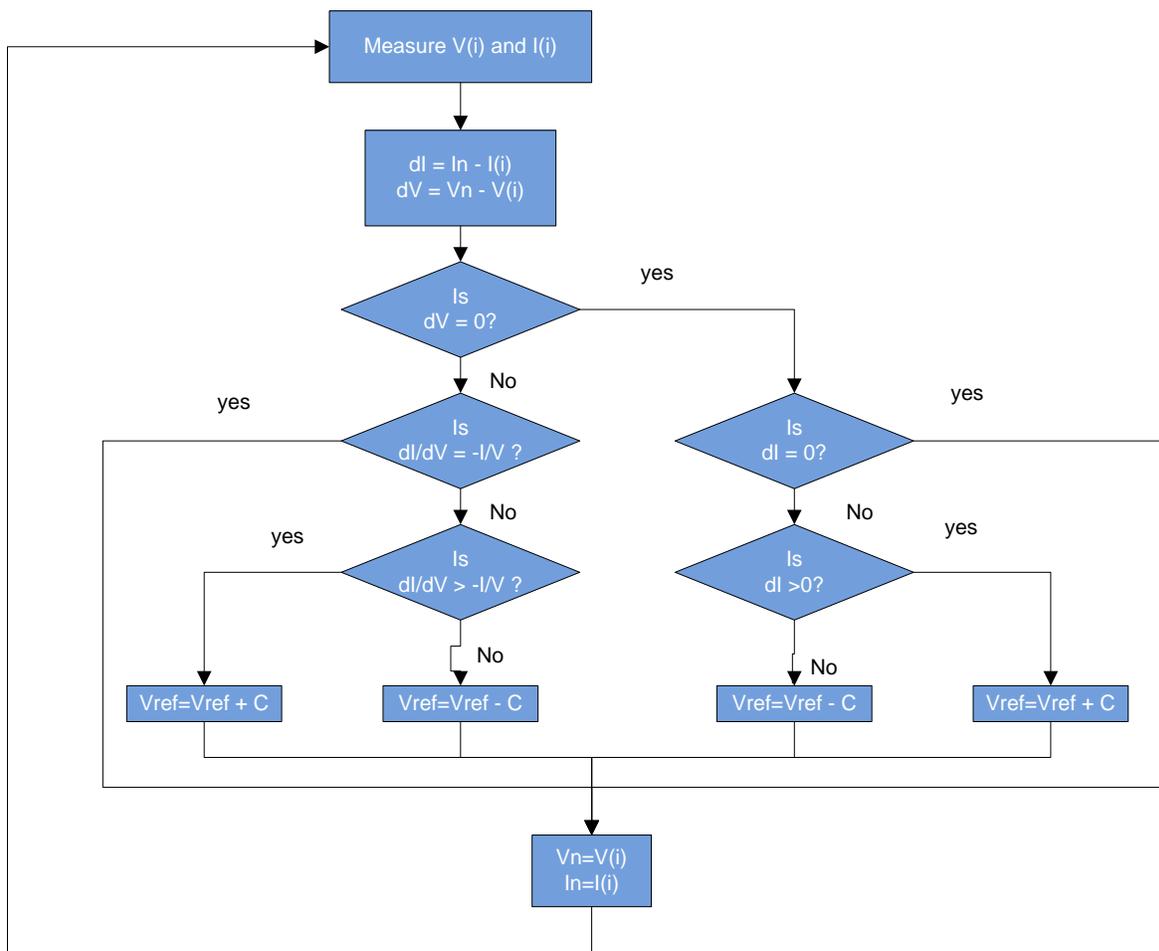


Figure 3.8 flow chart showing incremental conductance algorithm

Where I_n and V_n are stored value at the end of the preceding cycle. The V_{ref} is used by the DC-DC convertor to adjust the operating point of the generator. In this algorithm the change in the atmospheric condition (that is a change in the irradiation level) can be detected using the stage $dI \neq 0$.

Inverter Configurations

PV inverters, whose function is to convert DC into AC in addition, are responsible to extract maximum energy out of the PV generator. For this purpose most inverters have built in mechanism for maximum power point tracking.

Due to demands set by the different standard that has existed till present day, PV inverter technologies have evolved in various dimensions. Most references categorize them based on three major criteria:

1. **Conversion stage involved**
2. **Galvanic isolation - Transformer and Transformer less**
3. **Power decoupling**

1. Conversion stage involved

A single power conversion stage: In this topology, the task of MPP tracking, possible voltage boost (if necessary) and DC to AC conversion is all performed by one unit. This configuration is really common in most commercially available central inverters.

Dual power conversion stage: this involves a separate DC-DC conversion stage for MPP tracking and possible voltage boost and a DC-AC conversion stage for grid adaptation.

Dual Power conversion stage with numerous DC-DC stages: This involves individual DC-DC conversion where each string is equipped with individual MPP tracking with possible voltage boost that feeds to a common DC port. A single DC-AC inverter is responsible for grid adaptation.

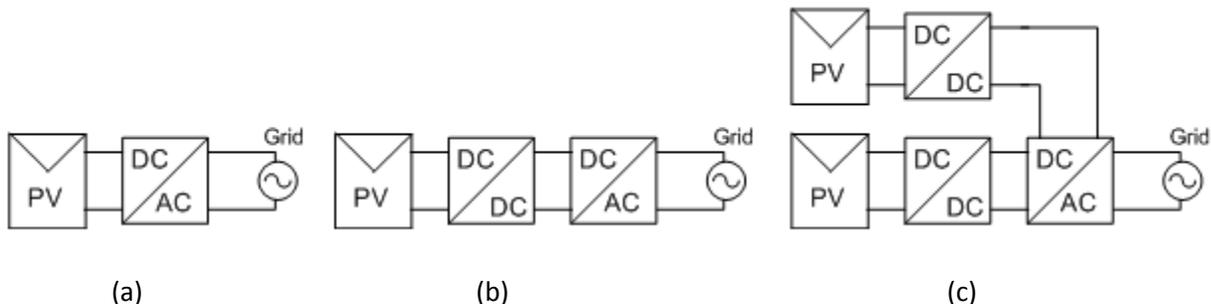


Figure 3.9 Inverter configuration (a) single conversion stage (b) double conversion stage with a single DC - DC stage (c) dual conversion stage with multiple DC-DC conversion stage

2. Galvanic isolation - Transformer and Transformer less

A stray capacitance exists between the PV module and the ground [26]. In large PV generator, the stray capacitance can be really significant causing severe oscillation with the stray inductance of the circuit [3]. To avoid this situation a galvanic isolation is required in the conversion stage. Some topologies involve a line frequency transformer that is placed between the grid and the inverter. Since it involves line frequency transformer, the size weight and cost associated is seen as a major disadvantage. Others topology involve a high frequency transformer that is embedded in the DC-DC converter which serves as

the MPP tracker. Although we get the advantage of smaller size and weight of using a high frequency transformer, the losses increase as a result of increased number of power processing stage. It should be pointed out that the existence of a transformer electrical decouples the PV generator from the grid.

There also exists transformer less configuration. This configuration has the advantage of lower losses, lighter weight and higher efficiency. This configuration in a single phase inverter is grounded on the AC side. This is due to the neutral of the grid been connected to earth somewhere. Grounding on the DC side can also occur due to two reasons. One is system grounding of the negative or the positive terminal of the module. The other is, in an ungrounded PV generator, stray capacitance that exists between the module surface and the ground creates a closed path for an undesired high frequency current. To avoid such problem different topologies that solidly ground the DC link is discussed in ref 4. There also exists the issue of safety standards in some countries that require galvanic isolation [4] between the grid and the PV generator.

3. Power Decoupling

It is the requirement in most grid code that the power that is feed to grid has a power factor of one. This requires a current that is inphase with the voltage. Therefore the power injected to the grid can then be written as

$$\begin{aligned}
 p(t) &= u(t).i(t) \\
 &= u_o \sin(wt) * i_o \sin (wt) \\
 &= u_o * i_o * \sin^2(wt) \\
 &= u_o i_o [1 + \sin (2wt)]
 \end{aligned}$$

It can be observed from above that the power on the AC side pulse at twice the grid frequency. If we assume the conversion stage as lossless, $P_{ac}=P_{dc}$, this pulsation is observed as a ripple on the dc side voltage. As a result all single phase inverter are equipped with a DC link capacitor so as to suppress the ripple in the voltage. The existence of this electrolyte capacitor decreases the inverters lifetime [3]. This is not a problem in case of 3 phase inverters since they feed power to the grid in a continuous manner [25].

PV Generator configuration

When it comes to medium and large size PV generator system, where several strings are connected to achieve higher power, the choice of plant design becomes important. Different PV generator configuration exist which are generally classified as

1. Central configuration
2. String configuration
3. Multi-string configuration
4. Modular configuration

1. Central configuration

Depending on the voltage requirement several PV modules are connected in series to form a string. Several strings then are connected in parallel to achieve a certain power level. In this configuration each

string feeds its out to a single DC bar. A central inverter capable of covering the whole range of input power of the PV generator is connected to the DC bar. This is illustrated in the figure below.

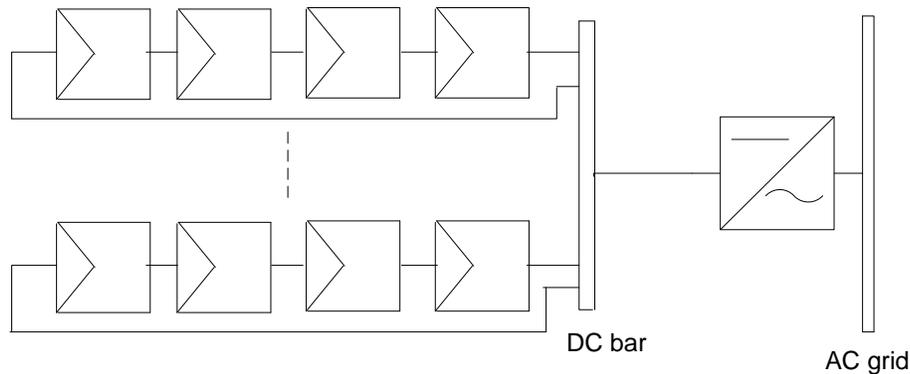


Figure 3.10 Central Configuration

In this system, a single MPPT that is incorporated within the inverter does the maximum power point tracking. The DC-AC conversion efficiency of PV inverters is very low in the low power range as a result of constant iron loss in the transformer. The efficiency of the system therefore falls drastically when the input from the PV generator falls low. This is one of the main demerits of this configuration.

Another disadvantage of the central inverter configuration is as a result of different operating condition (temperature and irradiation) along each string, especially in larger solar parks, the voltage associated with the maximum power point of each string doesn't necessarily coincide with the operating voltage at the DC bar. As a result we don't get to harness the maximum energy out of the PV generator. In addition, the requirement of a high voltage DC cable between the PV generator and the inverter and the reliability of the whole system on a single inverter is also some of the stated disadvantage of this configuration

2. String Configuration

In this configuration PV string, made of series connected PV modules are connected to individual inverter. The output from each inverter is then feed to a common AC bar. This is illustrated in figure 3.11. The advantage of this system is that the inverter equipped with an MPPT is able to extract the max energy out of each string. For large system this configuration would be really expensive as a result of increased number of string equipped with inverters. This configuration has more advantage for small installation where each string has different orientation, like installation on roof tops. In large installation where the shading and different orientation of PV modules has been avoided in the design stage, this configuration is not the best choice due to the associated higher price per KWh [6].

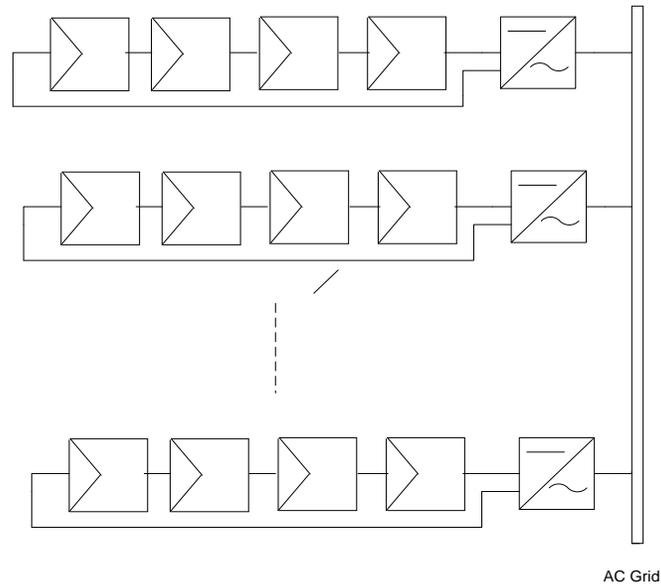


Figure 3.11 String configuration

3. Multistring configuration

This configuration is an intermediate between the string configuration and the central configuration. Here several strings are connected in parallel feeds into a DC box. A single inverter connected to the DC box performs the AC-DC conversion. Large commercial available PV inverters have Multiple MPPT as a feature. If such large inverters are employed, the output from the aggregated strings can be feed to individual DC input of the inverter. The advantage of this system as compared to the central inverter topology is the amount of reduced string operated under a single MPPT.

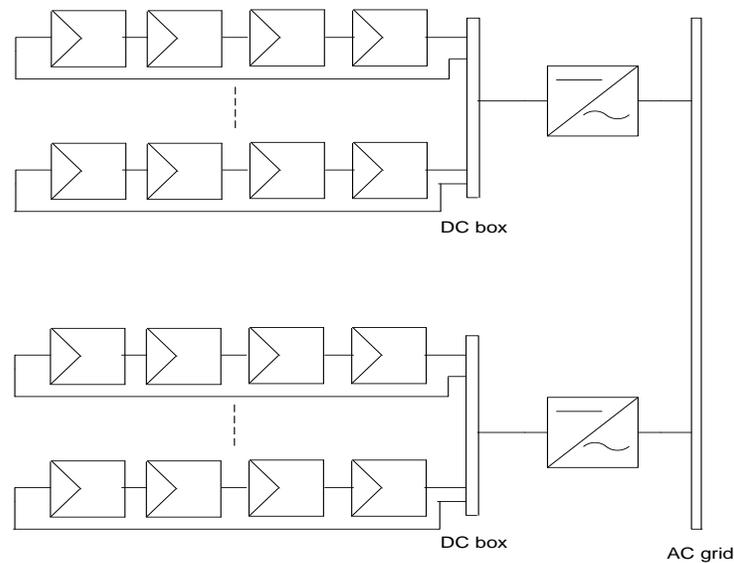


Figure 3.12 Multistring configuration

4. Modular Inverter topology

This topology is sometime also referred to as AC module. These are PV modules with built in inversion stage. Since each module is operated at its MPP, we are able to get the maximum energy out of the system. But the output of each module needs a further boost stage for the voltage to be compatible with the grid voltage. This usually consists of a line frequency transformer and its associated disadvantage. The advantage of this topology is that it is easily expandable. This technology to this day isn't applicable in large installation [3].

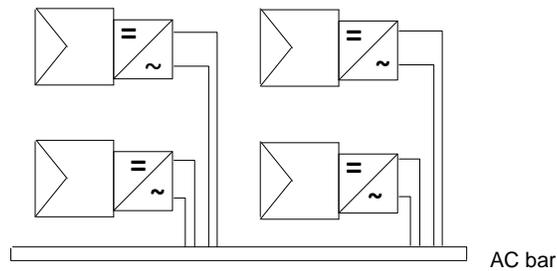
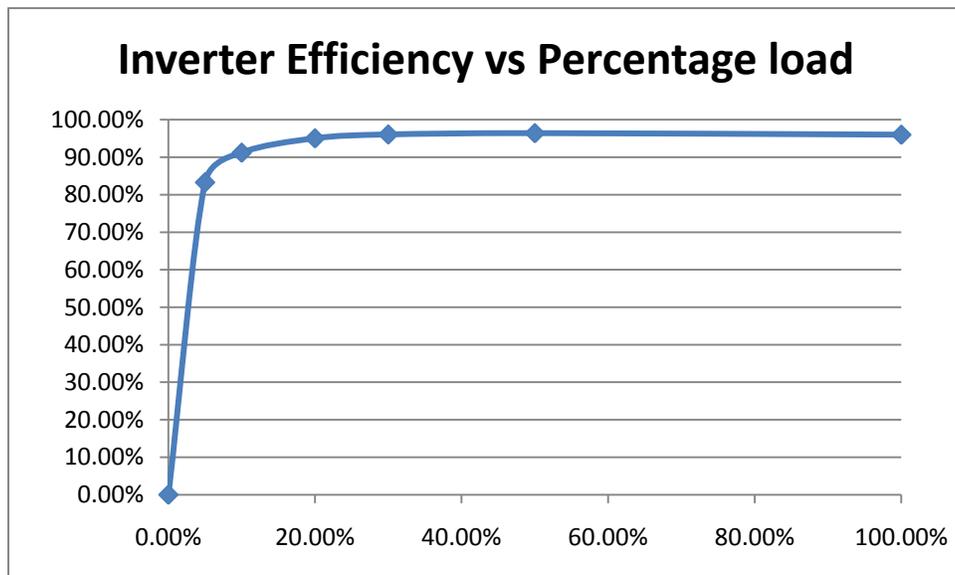


Figure 3.13 Modular configuration

3.1.3 Efficiency issues

Despite the different innovation in grid connected PV inverters, the fact remains that the efficiency of a single PV inverter in a partial load condition is really low [5]. This is due to the constant loss associated with the various inversion stages like constant iron loss in the transformer. A typical efficiency of a 100 KW Gamesa inverter is presented in the table 1 [5].



Load (%)	Efficiency (%)
5	83.30
10	91.21
20	95.04
30	96.06
50	96.41
100	96.00

Table 1 Efficiency as a function of nominal power for a 100KW Gamesa PV inverter

The low efficiency of the inverters during partial load has become a bottle neck. To avoid the operation of the inverters in their low efficiency region, different solution where proposed where the number of inverters serving a PV generator system were reduced during reduced output from the PV generator. Two concepts stand out, the master slave concept and the team concept.

Master – slave concept

Instead of having a single large inverter, several smaller inverters are operated in the master slave mode. When the PV generator starts to produce enough power, the master inverter switches on and takes over operation. As the produced power exceeds a certain threshold, the second inverter (1st slave) is switched in and for further increase of power the third inverter is switched. With increase in production more inverters are switched in so as all inverters are operated at their optimum efficiency level. When PV generator power output decreases due to significant variation in irradiation, the slave units are automatically disconnected. The advantage with this concept is avoiding operating inverters in their low efficiency regions.

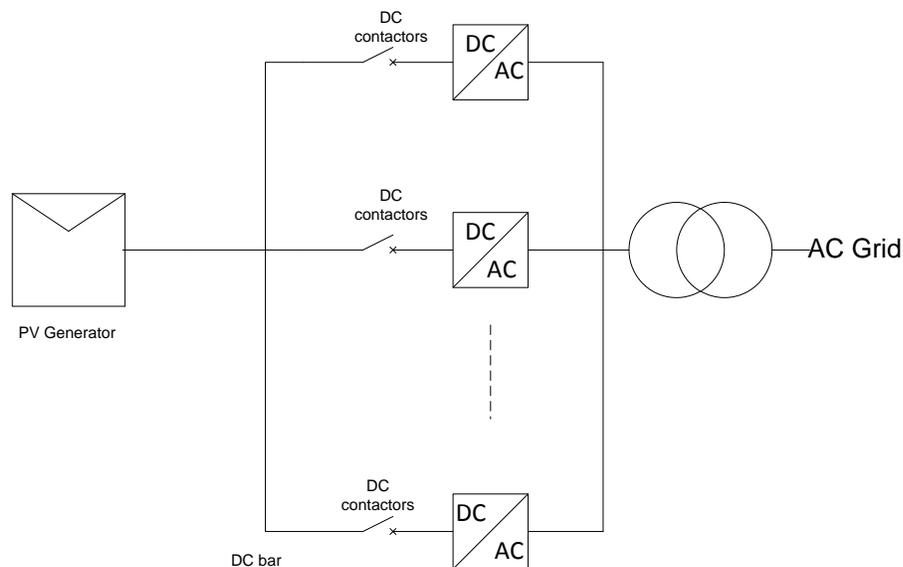


Figure 3.14 Single line diagram Master slave operation of inverters

Another stated advantage using this concept is the rotating master. When the PV generator system starts to operate the next day, the master inverter is freely chosen from among the slave inverters. This helps to evenly distribute the master inverter operating time among all inverters. If a master inverter fails any

inverter among the slaves can resume its task. The obvious drawback with this operation is it fails to utilize the maximum power point tracking capabilities of each inverter.

3.1.3.1 Team Concept

In some references this is put as the concept that brings string concept with that of master slave concept together. The PV generator is divided into parts. Each part feed its output to individual DC box. A DC switch exists for disconnecting the PV part during maintenance. When output power is high each part is connected to dedicated inverter and the park operates in a multi-string mode. When output is reduced, inverters can be disconnected and output from the parts can be rerouted to fewer inverters. The advantage with this operation is at high output, the maximum power tracking capabilities of each inverter is utilized. But on the other hand this concept requires additional hardware for routing during low output condition.

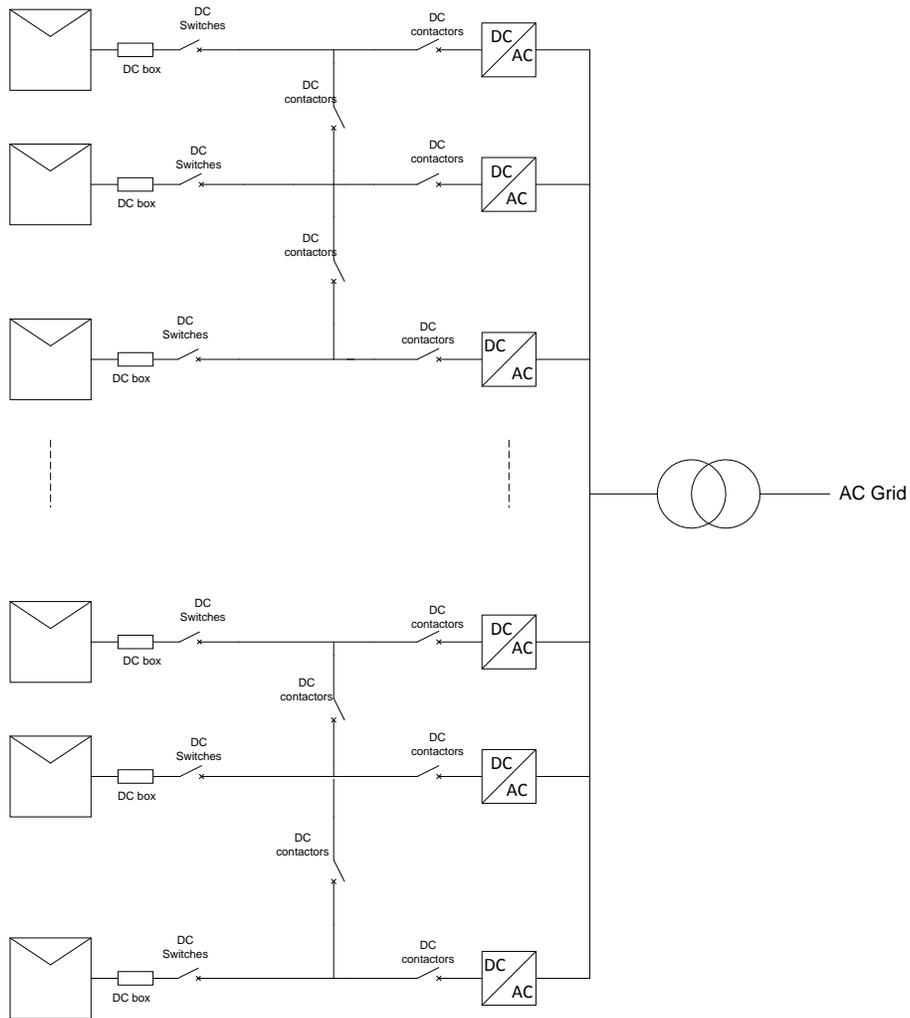


Figure 3.15 Single line diagram team operation of inverters

3.2 Modeling of PV Generator System

3.2.1 Basic PV Cell modeling

In the course of time various equivalent circuit model of a PV cell has been developed. The one diode model which is the most commonly used equivalent circuit for PV cell modeling will be discussed in this part. A small introduction in part 3.1.1 described the working of an ideal PV cell and the equivalent circuit of PV cell was discussed. A detailed derivation is presented in this section. Figure 3.16 is a repeated here for the convinces of the reader.

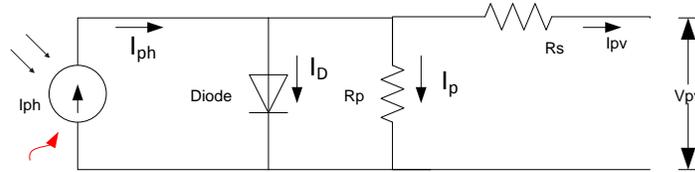


Figure 3.16 Equivalent circuit of a one diode model of a single PV cell

According to basic circuit equation, the cell current, I_{pv} can be described by equation 3.8

$$I_{pv} = I_{ph} - (I_D + I_p) \quad 3.8.$$

Using the basic equation for a diode, the diode current as a function of the diode voltage can be expressed as

$$I_D = I_o * [\exp\left(\frac{q * V_D}{A_o * k * T}\right) - 1] \quad 3.9.$$

A term known as the thermal voltage is used to simplify equation 3.10

$$I_D = I_o * [\exp\left(\frac{V_D}{V_t}\right) - 1] \quad 3.10.$$

$$\text{Where } V_t = \frac{A_o * k * T}{q}$$

The diode voltage, V_D in equation 3.9 and 3.10 can be easily derived from the equivalent equation as a function of PV cell's voltage and current as below

$$V_D = V_{PV} + I_{PV} * R_s \quad 3.11.$$

Inserting equation 3.11 into equation 3.10

$$I_D = I_o * \left[\exp\left(\frac{V_{PV} + I_{PV} * R_s}{V_t}\right) - 1 \right] \quad 3.12.$$

The current through the parallel resistance (I_p), can be expressed in terms of the diode voltage and the parallel resistance

$$I_p = \frac{V_D}{R_p} \quad 3.13.$$

$$I_p = \frac{V_{pv} + I_{pv} * R_s}{R_p}$$

Putting together equation 3.13, 3.12 and 3.8, we arrive at equation 3.14

$$I_{PV} = I_{ph} - I_o * \left[\exp\left(\frac{V_{PV} + I_{PV} * R_s}{V_t}\right) - 1 \right] - \frac{V_{pv} + I_{pv} * R_s}{R_p} \quad (a) \quad 3.14.$$

Equation 3.14 describes the current voltage characteristics of a PV cell using the one diode model representation. The above equation has five unknown values namely, R_s , R_p , I_{ph} , I_o and A_o which need to be determined before equation 3.14(a) can be used. To determine these values, a set of 5 equations is needed. Since none of these values are provided on the manufacturer's datasheet, some mechanism needs to be developed to determine this value for cell level. What we can get out of the manufacturer's data sheet is the total module short circuit current, module open circuit voltage and the module current and voltage value at the maximum power point. Equation 3.14(a) is then upgraded to a module level by adding a term N_s that represents the number of series connected cell in the module (refer to equation 3.14(b)). Provided that we know the short circuit current, open circuit voltage and maximum power point current and voltage value for the module, we can define 3 conditions for the equivalent circuit shown in fig 3.16. These conditions are discussed below. Later after solving the value of R_s , R_p , I_{ph} , I_o and A_o for the module, the cell values for I_o , I_{ph} and A_o would be the same as that for the module where as the R_s and R_p value equals the R_s and R_p value of the module divided by the no of cells in series.

$$I_{PV} = I_{ph} - I_o * \left[\exp\left(\frac{V_{PV} + I_{PV} * R_s}{N_s * V_t}\right) - 1 \right] - \frac{V_{pv} + I_{pv} * R_s}{R_p} \quad (b) \quad 3.14.$$

Condition 1: short circuit condition

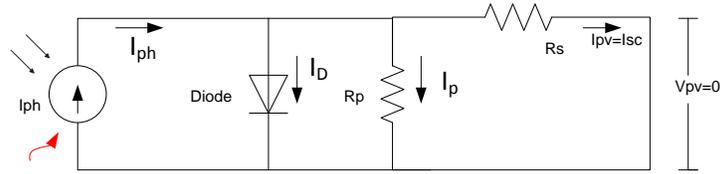


Figure 3.17 equivalent circuit of PV cell using one diode model under short circuit condition

Neglecting the diode current which is assumed to be really small compared to the I_{sc} , the photon current I_{ph} , can be expressed as the sum of the short circuit current and the current through the parallel resistance as below

$$I_{ph} = I_{sc} + \frac{I_{sc} * R_s}{R_p} \quad 3.15.$$

During short circuit condition, $V_{pv}=0$; equation 3.14(b) is then reduced to equation 3.16

$$I_{sc} = I_{ph} - I_o * \left[\exp \left(\frac{I_{sc} * R_s}{V_t * N_s} \right) \right] - \frac{I_{sc} * R_s}{R_p} \quad 3.16.$$

Condition 2: Open circuit condition

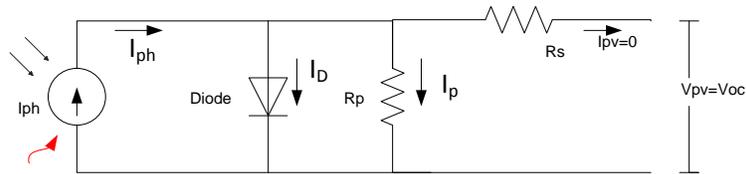


Figure 3.18 Equivalent Circuit of PV cell using one diode model under open circuit condition

Under open circuit condition the PV cell current, $I_{pv}=0$ and $V_{pv}=V_{oc}$. Applying this in equation 3.14(b), we arrive at equation 3.17

$$I_{oc} = 0 = I_{ph} - I_o * \left[\exp \left(\frac{V_{oc}}{V_t * N_s} \right) \right] - \frac{V_{oc}}{R_p} \quad 3.17.$$

Condition 3: Maximum Power Point condition

At the maximum power point $I_{pv}=I_{mpp}$ and $V_{pv}=V_{mpp}$. Inserting this conditions in equation 3.14(b), we get equation 3.18

$$I_{mpp} = I_{ph} - I_o * \left[\exp\left(\frac{V_{mpp} + I_{mpp} * R_s}{R_p}\right) \right] - \frac{V_{mpp} + I_{mpp} * R_s}{R_p} \quad 3.18.$$

The derivative of power with respect to voltage at the maximum power point is zero.

$$\left. \frac{dp}{dV} \right|_{V=V_{mpp}, I=I_{mpp}} \quad 3.19.$$

it can be observed from figure 3.17 that during short circuit condition the change in current with respect to voltage is mainly determined by the shunt resistance [11]. At short circuit condition, this can be expressed as

$$\left. \frac{dI}{dV} \right|_{I=I_{sc}} = -\frac{1}{R_s} \quad 3.20.$$

Taking equation 3.17 and solving for the photon current, we arrive at equation 3.21

$$I_{ph} = I_o * \left[\exp\left(\frac{V_{oc}}{V_t * N_s}\right) \right] + \frac{V_{oc}}{R_p} \quad 3.21.$$

By substituting equation 3.21 into equation 3.16, a new equation for the short circuit current is derived

$$I_{sc} = I_o * \left[\exp\left(\frac{V_{oc}}{V_t}\right) - \exp\left(\frac{I_{sc} * R_s}{V_t * N_s}\right) \right] + \frac{V_{oc} - I_{sc} * R_s}{R_p} \quad 3.22.$$

Since the term $\exp\left(\frac{I_{sc} * R_s}{V_t * N_s}\right)$ is really small compared to the other term in the same bracket, this term is neglected [11] and we arrive at equation 3.23

$$I_{sc} = I_o * \left[\exp\left(\frac{V_{oc}}{N_s * V_t}\right) \right] + \frac{V_{oc} - I_{sc} * R_s}{R_p} \quad 3.23.$$

Solving equation 3.23 for I_o

$$I_o = \left(I_{sc} - \frac{V_{oc} - I_{sc} * R_s}{R_p} \right) \exp\left(-\frac{V_{oc}}{V_t * N_s}\right) \quad 3.24.$$

Taking equation 3.21 and 3.24 and inserting it into equation 3.18, we get

$$I_{mpp} = I_{sc} - \frac{V_{mpp} + I_{mpp} * R_s - I_{sc} * R_s}{R_p} - (I_{sc} - \frac{V_{oc} - I_{sc} * R_s}{R_p}) \exp\left(\frac{V_{mpp} + I_{mpp} * R_s - V_{oc}}{N_s * V_t}\right) \quad 3.25.$$

Now considering the derivative of the power with respect to voltage at MPP

$$\left. \frac{dp}{dV} \right|_{V=V_{mpp}, I=I_{mpp}} = \frac{d(IV)}{dV} = I + \frac{dI}{dV} * V \quad 3.26.$$

The second term in equation 3.26 requires that the derivative of equation 3.25 with respect to voltage. But the equation of I_{mpp} needs numerical methods. As a simplification let us express equation 3.25 in the form below

$$I = f(I, V) \quad 3.27.$$

where equation 3.27 represents the right side of equation 3.25. Differentiating equation 3.27

$$\begin{aligned} dI &= dI \frac{\partial f(I, V)}{\partial I} + dV \frac{\partial f(I, V)}{\partial V} \\ \frac{dI}{dV} &= \frac{\frac{\partial}{\partial V} f(I, V)}{1 - \frac{\partial}{\partial I} f(I, V)} \end{aligned} \quad 3.28.$$

$$\frac{dP}{dV} = I_{mpp} + \frac{V_{mpp} \frac{\partial}{\partial I} f(I, V)}{1 - \frac{\partial}{\partial I} f(I, V)} \quad 3.29.$$

$$\left. \frac{dp}{dV} \right|_{I=I_{mpp}} = I_{mpp} + V_{mpp} * \frac{D}{1 + F} \quad 3.30.$$

Where $D = \frac{(I_{sc} * R_p - V_{oc} + I_{sc} * R_s) \exp\left(\frac{V_{mpp} + I_{mpp} * R_s - V_{oc}}{N_s * V_t}\right)}{N_s * V_t * R_p} - \frac{1}{R_p}$

$$F = \frac{(I_{sc} * R_p - V_{oc} + I_{sc} * R_s) \exp\left(\frac{V_{mpp} + I_{mpp} * R_s - V_{oc}}{N_s * V_t}\right)}{N_s * V_t * R_p} + \frac{R_s}{R_p}$$

Taking equation 3.20 and 3.28

$$-\frac{1}{R_s} \Big|_{I=I_{sc}} = \frac{-H - \frac{1}{R_p}}{1 + H + \frac{R_s}{R_p}} \quad 3.31.$$

$$\text{Where } H = \frac{(I_{sc} * R_p - V_{oc} + I_{sc} * R_s) \exp\left(\frac{I_{sc} * R_s - V_{oc}}{N_s * V_t}\right)}{N_s * V_t * R_p}$$

Now we have equation 3.25, 3.28 and 3.29 to solve for the 3 unknowns R_s , R_p and A_0 . Since it isn't possible to analytical solve for the 3 unknowns, some sort numerical method should be used. The acquired value of R_s , R_p and A_0 are then used to solve the value of I_{ph} and I_0 . The cell parameter is then determined as explained early by dividing the R_s and R_p values by the number of series connected cells in the module. Note however that all the above computation applies for STC condition. Since our aim is to determine the characteristics curve for different operating conditions i.e. irradiation and ambient temperature, the equations need to be modified taking into account the effect of both temperature and irradiation.

The dependency of the short circuit current and photon current on irradiance is considered to be directly proportional to the irradiation and can be expressed as [11]

$$\begin{aligned} I_{sc}(E) &= I_{sc} * E \\ I_{ph}(E) &= I_{ph} * E \end{aligned} \quad 3.32.$$

Where E is in watts/m².

The short circuit current depends linearly on the temperature and can be expressed as below [11]

$$I_{sc}(T) = I_{sc} \left(1 + \frac{k_i}{100} (T - T_{stc})\right) \quad 3.33.$$

Where k_i = temperature coefficient for the current

By considering the effect of irradiation and by taking equation 3.17, the open circuit voltage as a function of irradiation can be expressed as follows[11].

$$V_{oc}(E) = \ln\left(\frac{I_{ph}(E) * R_{sh} - V_{oc}(E)}{I_o * R_{sh}}\right) N_s * V_t \quad 3.34.$$

Equation 3.33 needs numerical methods to solve $V_{oc}(E)$. The open circuit voltage shows a linear dependency with temperature [11] and can be expressed as

$$V_{oc}(T) = V_{oc} + k_v(T - T_{stc}) \quad 3.35.$$

The dependency of saturation current on temperature $I_o(T)$ is derived by substituting the terms of equation 3.24 to include the temperature effect.

$$I_o(T) = (I_{sc}(T) - \frac{V_{oc}(T) - I_{sc}(T) * R_s}{R_p}) \exp\left(-\frac{V_{oc}(T)}{V_t * N_s}\right) \quad 3.36.$$

In a similar fashion, transforming the terms of equation 3.21 to include temperature effect, the photon current dependency on temperature can be represented as below

$$I_{ph}(T) = I_o(T) * \left[\exp\left(\frac{V_{oc}(T)}{V_t * N_s}\right) \right] + \frac{V_{oc}(T)}{R_p} \quad 3.37.$$

The current voltage characteristics can be expressed by inserting equation 3.33, 3.34, 3.35, 3.36, 3.37 into equation 3.14. The effect of temperature on value of series and parallel resistance is not accounted for in this modeling.

3.2.2 Simplified PV Generator Modeling

As the name indicates it is a simplified model as it assumes all modules connected in series to form a string are subjected to the same operating condition. The model also ignores any phenomena that occur in the cells making up each module.

Before proceeding let us say a few things about blocking diode and bypass diodes. In a PV generator system where several strings are connected in parallel, voltage variation among parallel strings causes the current produces by one string to be sunk by an adjacent string of a lower potential. To avoid back flow of current among adjacent strings, each string is equipped with a blocking diode in series. On a cell level; partial shadowing will have the same effect as receiving a reduced illumination [8]. Since in this model we assume that all the cells are operated under the same condition, it is fair to assume that partial shading will have the same effect as reduced illumination on the PV module. The current output of the shadowed module which is proportional to the illumination is thus reduced. Since all modules are connected in series, a situation occurs where the current from the unshaded modules which is greater than the short circuit current of the shaded module flows in the string. This causes the shaded module to operate in the 2nd quadrant and the module acts as a sink instead of a sources. To mitigate the problem bypass diode are connected anti parallel with the module. With bypass diode, when the current exceeds the short circuit current the diode is forward biased and all the current greater than the shaded module short circuit current is bypassed through the diode. The string output voltage is reduced by the amount equivalent to the bypassed module output voltage plus forward voltage drop of bypass diode. The diode is

connected in reverse bias to that of the PV module. Figure 3.19 illustrates the effect of having a bypass diode in parallel with a module

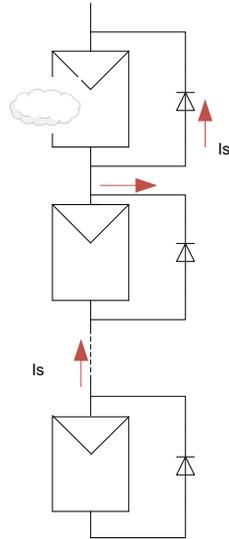
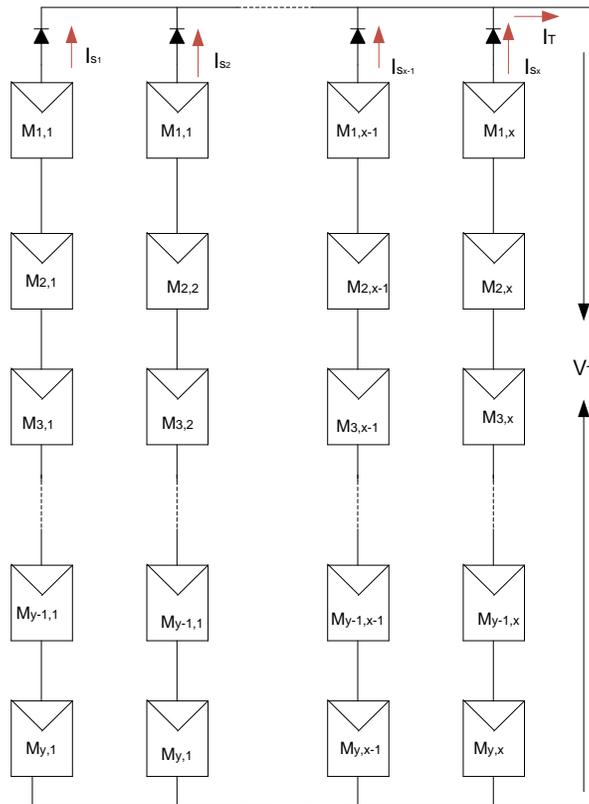


Figure 3.19 Shows working of a bypass diode



3.190 PV generator representations: Simplified model

Coming back to the description of the simplified model, the model ignores the presence of a bypass diode. Under the assumption that all modules that are connected in series are identical and operated under the same operating condition, including the effect of bypass diode in the model is really irrelevant. If y no of PV modules is series connected to form a string, then the terminal voltage of the PV generator is easily expressed as below

$$V_T = \sum_{i=1}^y V_{M_{i,1}} \quad 3.38.$$

Since each module with in a string contribute equally to the terminal voltage of the PV generator, the voltage of the modules can be expressed as below

$$V_{M_{i,j}} = V_T/y \quad 3.39.$$

Having determined the voltage, the related current can be expressed using equation 3.14(b). It is observed from the figure that each string is connected to a blocking diode. The existence of the blocking diode in the model decouples the possible current relation among parallel string. The total current produced by the array can be expressed as the contribution of current from each string. If x number of strings are parallel connected to form the PV generator, then the terminal current of the generator is expressed as below

$$I_T = \sum_{j=1}^x I_{S_j} \quad 3.40.$$

Where I_{S_j} = current output of j^{th} string

Using this approach the PV generator's output when its individual Strings are operated under varying operating condition can be modeled. Since in reality there is little or no chance that all modules along a string are subjected to the same operating condition, this model is not the best option if we are to model realistic situation.

3.2.3 Cell based Modeling

In this modeling approach, the equivalent circuit modeling of a solar cell is the tool that is used to simulate the I-V characteristics of PV module. The PV module is modeled as connection of solar cell. The PV generator model is then an aggregate of PV module model that are connected in series and parallel to achieve a certain power level. This modeling technique is really efficient in modeling the effects of shading on the performance of PV array. Since shading effect is highly dependent upon the direction or shape of the shadow, this technique provides a more accurate result. But on the other hand, modeling of large PV array down to a cell level comes with a value, the obvious drawback begin the need for a long computation time.

To model the entire PV module, which is an interconnection of solar cell a method employed in one of the reference was chosen [9]. In this approach Kirchhoff's law is applied to relate all current and voltage in the network. In the circuit the elements marked as A represent the cells were as the element marked as B represents switches. Different configuration of cell interconnection exists. Series- parallel (SP) configuration where all the switches are turned off, total cross tied (TCT) where all the switches are turned on and bridge like (BL) where switches form a bridge like character are switched on [28].

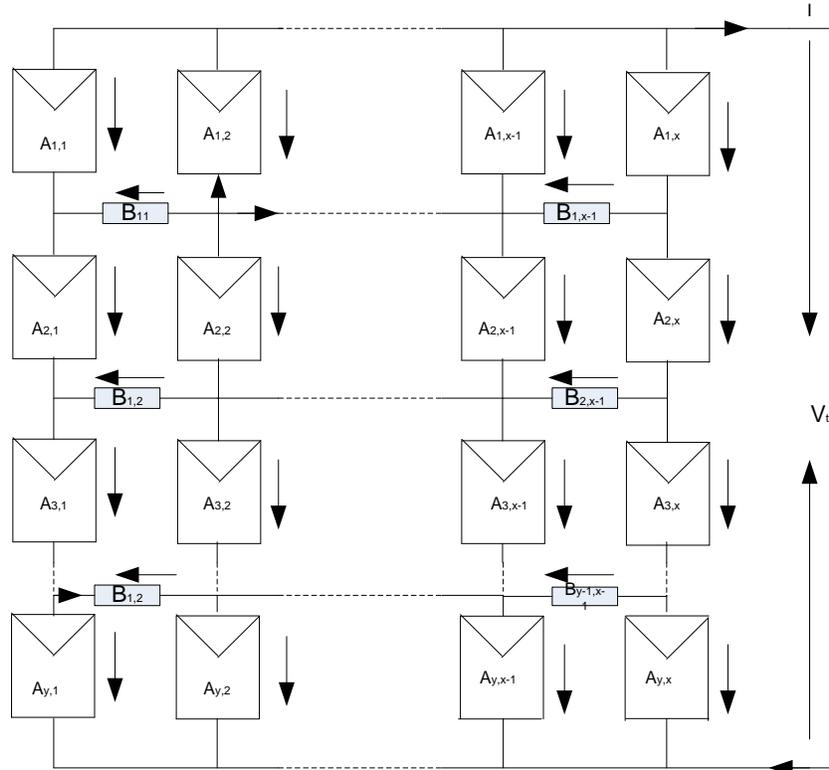


Figure 3.21 A general model representing a network of solar cell making a module

The number of elements in a column is represented by y whereas the element number in a row is represented by x. Each element of A is described by the mathematical equation describing the current voltage relation of a cell as described in equation 3.14(a). For the B term, the relationship can be described as below

$$I_{B_{i,j}} = g * V_{B_{i,j}} \quad 3.41.$$

Where g = conductance

The model assumes the total voltage output of the network is known. Based on the total voltage the current and voltage of each element is to be determined. For each sub voltage ($V_{A_{i,j}}$ and $V_{B_{i,j}}$), the related sub current can be determined using equation 3.14(a) and equation 3.38 respectively. This leaves the subvoltages and the total current as unknown. If z subvoltages exist then we have z+1 unknown value to solve.

$$z = (V_{A 1,1}, \dots, V_{A y,x}, V_{B i,j}, \dots, V_{B y-1,x-1}, I) \quad 3.42.$$

One equation can be defined using the total voltage of the network

$$f_1 = \sum_{i=1}^y V_{A i,1} - V = 0 \quad 3.43.$$

In the network, we can define $m=y*(x-1)$ meshes. According to Kirchoff's Voltage law the sum of current in voltage in each mesh equals to zero. Based on this m number of equations can be defined

$$f_{2\dots m+1} = V_{A i,j} - V_{B i,j} - V_{A i,j+1} + V_{i-1,j} = 0$$

Where $i = 1, 2, \dots, y$
 $j = 1, 2, \dots, X-1$
 $V_{B i,j} = 0$ for $i=0$ and $i=y$

3.44.

Another equation for the total current can be defined as below

$$f_{m+2} = \sum_{j=1}^x I_{A 1,j} - I = 0 \quad 3.45.$$

Again, we can define $n=(y-1)*x$, nodes. According to Kirchoff's Current rule, the sum of current into a node must be zero. Using this law we define n number of equation

$$f_{m+3\dots m+n+2} = I_{B i,j} - I_{A i,j} - I_{A i+1,j} + I_{B i,j-1} = 0$$

Where $i = 1, 2, \dots, y-1$
 $j = 1, 2, \dots, x$
 $I_{B i,j} = 0$ for $j=0$ and $j=x$

3.46.

Having equal equation and equal unknown the subvoltage and total current can be solved using numeric methods. In the reference, the suggestion is to use Newton Raphson method due to its fast convergence. [9].

3.2.4 Module based Modeling

In this modeling approach the cell making up the modules is not the focus of the point. Instead it is assumed that each cell making up the module is subjected to the same operating condition. It ignores any

sort of possible electrical mismatch that exists among the cells. Considering these assumptions, and assumption previously stated in section 3.2.2, equation 3.14(b) to equation 3.37 can be used to mathematical represent a PV module characteristics. Modeling of a PV module with a bypass diode in this approach considers a single diode that is connected in parallel with the PV module.

If the condition of a bypass diode is included in the modeling, equation 3.14(b) is transformed to equation 3.47 to include the effect of the bypass [13].

$$I_{PV} = I_{ph} - I_o * \left[\exp\left(\frac{V_{PV} + I_{PV} * R_s}{N_s * V_t}\right) - 1 \right] - \frac{V_{pv} + I_{pv} * R_s}{R_p} + I_{OBP} \left[\exp\left(\frac{-q * V_{pv}}{A_{OBP} * k * T}\right) - 1 \right] \quad 3.47.$$

The last term in equation 3.43 describes the diode characteristics in parallel with the module. Once the characteristics equation describing the non linear relation between the current and voltage for PV module is described, the same circuit network configuration as in the cell based modeling can be used to model a PV generator system.

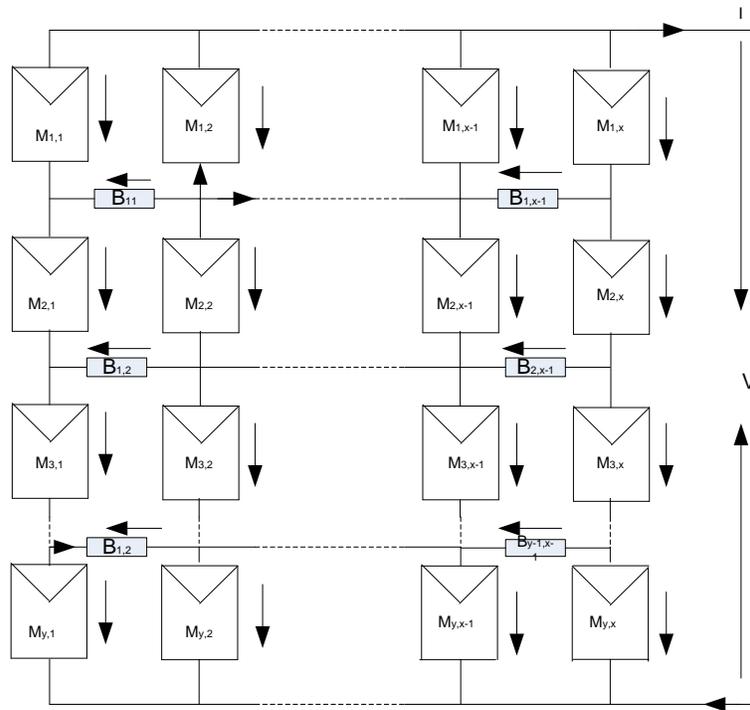


Figure 3.20 A general model representing a network of solar modules making PV Generator

In the figure the component marked as A represent individual PV module, where as the component marked as B represents switches element. Since in the PV generator model, no cross ties between adjacent modules exist, the conductance of the element represented as B can be set to a really low value in the order of 10^{-20} . In a similar fashion by applying Kirchoff's current law and Kirchoff's voltage law, a set of

equation can be found. In this modeling scheme, the terminal voltage of the PV generator is assumed to be known.

The number of elements in a column is represented by y whereas the element number in a row is represented by x . Each element of A is described by the mathematical equation describing the current voltage relation of a PV module with bypass diode as described in equation 3.44. For the B term, the relationship is described as below

$$I_{B i,j} = g * V_{B i,j} \quad 3.48.$$

Where g = conductance

For each subvoltage (module voltage and voltage along term B), the related subcurrent can be found using equation 3.44 and 3.45. Similar to the case in the cell network, this leaves out the subvoltage and the total PV generator's current as unknown. Following this step equation 3.39 to eqn 3.43 applies here too. To avoid redundancy only the equation will be placed below.

$$f = \sum_{i=1}^y V_{A i,1} - V = 0 \quad 3.49.$$

$$f_{2\dots m+1} = V_{A i,j} - V_{B i,j} - V_{A i,j+1} + V_{i-1,j} = 0 \quad 3.50.$$

Where $i = 1, 2, \dots, y$

$j = 1, 2, \dots, X-1$

$V_{B i,j} = 0$ for $i=0$ and $i=y$

$$f_{m+2} = \sum_{j=1}^x I_{A 1,j} - I = 0 \quad 3.51.$$

$$f_{m+3\dots m+n+2} = I_{B i,j} - I_{A i,j} - I_{A i+1,j} - I_{B i,j-1} \quad 3.52.$$

Where $i = 1, 2 \dots y-1$

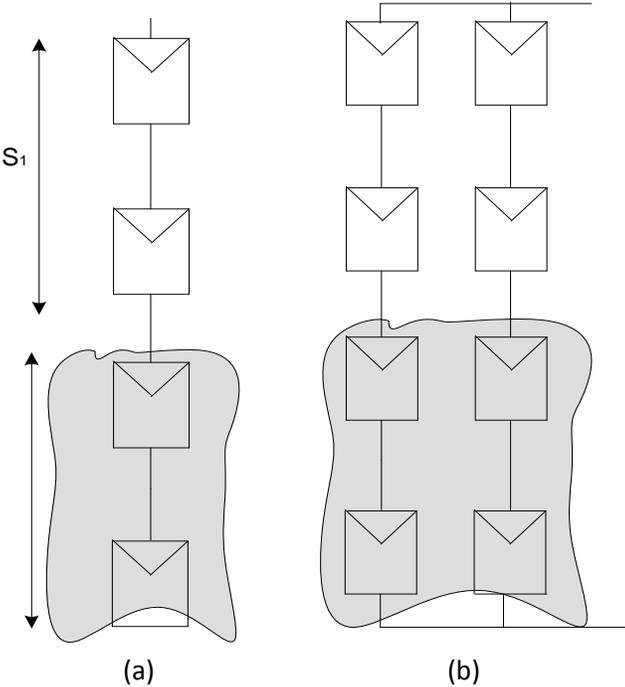
$j = 1, 2 \dots x$

$I_{B i,j} = 0$ for $j=0$ and $j=x$

Using the set of equations 3.44 to 3.49, the unknown module voltages, including the PV generator's output current can be determine

3.2.5 Partial Shaded PV Generator Modeling

This model is suitable in studying the I-V and P-V characteristics of a PV generator subjected to non uniform shading. This modeling approach is a middle ground between the module based modeling and the simplified modeling. The smallest building block in this module is a PV module. The modeling approach is a technique described in ref 22. To make the description easy, certain terms are defined with the aid of a diagram.



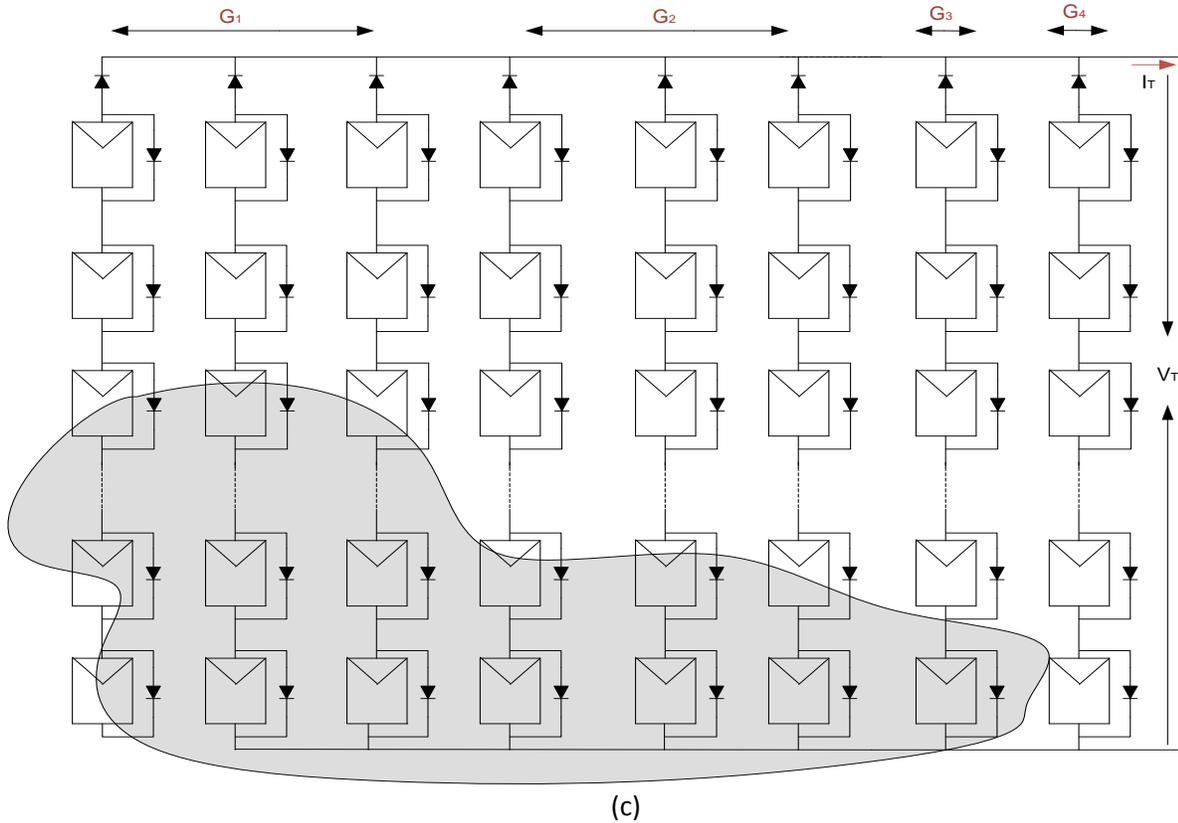


Figure 3.21 Terminology used in partial shaded PV generator modeling (a) string with 2 substring (b) group with two strings (c) PV generator

Modules that are connected in series that are subjected to the same operating condition are referred to as a substring. This is shown as S_1 in figure 3.23 (a). A “String” is then several such series connected substrings that are subjected to different operating conditions (fig 3.23 (a)). Strings that have similar shading pattern connected in parallel make up a “Group” (fig 3.23(b)). Various groups subjected to different shading pattern connected in parallel make up the PV generator.

The irradiation level (E) and working temperature (T) of each substring created as a result of a specific shading pattern over the PV generator should be known. Based on the E and T data and using a range of voltage value between zero and open circuit voltage, the related current value is obtained using equation 3.47. This gives the I-V characteristics of a single module (with bypass diode) within a substring. Since a substring is a series connection of modules under the same operating condition, the module’s voltage value is upscaled by a factor equivalent to the number of module in the substring, while the current remains the same. In that manner the I-V curve for all the substring making up a string can be acquired.

A string’s I-V curve is then created by the summation of the voltage value of each substring within the string for a common current value. The group’s characteristics can be obtained by multiplying the current value with a factor equivalent to the number of strings making up the group while the voltage value remains the same. Finally for a common voltage value, the related current value from each group is summed up to generate the I-V characteristics of the PV generator.

4 Solution

Background knowledge and possible methodology has been discussed in previous chapter. This chapter covers the implementation part. The little knowledge that was gathered will be presented in a similar order as carried out. This chapter first discusses the approach that was used to analyze the loss reduction potential of the different inverter reconnection scheme discussed in part 3.1. The second part covers the method chosen, the approaches taken and the challenges faced in modeling a large PV generator. Possible methodologies implemented in the second part of this chapter are discussed in part 3.2.

4.1 Inverter Reconnection

The loss reduction potential for different reconnection was evaluated in this section. The inverter reconnection chosen for evaluation were

1. **Classical inverter connection scheme:** in this scheme it is assumed all output from the PV generator was feed to a single DC bar and all nine inverters were always connected in parallel.
2. **Master – Slave reconnection (minimum) scheme:** here the number of slave inverters switched is decided upon the maximum current loading of the inverters. This allows for minimum number of inverters to be operated but each inverter is loaded to their maximum capacity.
3. **Master –Slave reconnection (optimum) scheme:** here the number of slave inverters connected is based on the optimum loading of the inverters. When power output exceeds the optimum load of connected inverters more slave inverters are switched in.
4. **Team reconnection scheme:** here input to adjacent inverters are checked, during low load inverters are switched out and their dedicated input is redirected to the nearby inverters. During high production, the output is directed to delegated inverters. Redirection to adjacent inverter is done by checking the maximum current loading.

As a test case two locations were chosen, 1MW park layout located in Totana, Spain and another 1 MW park located in Pöcking, Germany. The simulated generator output was used in the calculation. The plant specification is presented in table below.

PV modules	Zytech Monocrystalline Silicon 175 W
Inverters	GAMESA 100 KW 9 Inverters
PV generator	18 Module/ String 37 String/ DC box 9 DC box (1 per inverter) 333 Strings in total 5994 Modules in total
Trackers	Biaxial, 0.1 accuracy

Table 2 Specification of park layout in PVSyst for Totana, Spain and Pöcking, Germany

Two professional software program to simulate the output from a PV generator were at our disposal. PVSyst was chosen for its relability and wide use and INSEL due to its modular capabilities. PVSyst is widely used as a simulation tool both for grid connected as well as standalone system. The user can generate the annual irradiation level for a location from a large database of metrological sites. It also

provides the functionality of estimating the number of inverters needed based on the PV generator layout (i.e. based on the selected module, no of series and parallel connection). The output from the simulation result include loss breakdown among the various conversion stages, current and voltage output before the inverter stage, power loss within the inverter and wiring loss are also accounted for. The connection consideration, how losses are calculated and the coefficient used are not really clear when it comes to PVSyst. INSEL on the other hand is more modular Software. It consists of building blocks for the different component of a solar PV generator like modules, inverters. Blocks exist for generating meteorological data for a location which provides the global irradiation on a horizontal surface and blocks that can generate the irradiation on a tilted surface based on irradiation on a horizontal surface. All wiring connection among the different blocks is done by the user which gives the user more freedom for modification.

The models of both parks in PVSyst were already developed and the PV generator hourly output current and voltage for the entire year was acquired by running the models.

For evaluating the first 3 inverter reconnection case, the result we simulate using PVSyst is acceptable with little error. For performing any calculation for the fourth connection scheme, the output for each DC box needed to be known first hand. This becomes a limitation since PVSyst only generates current and voltage value for the entire generator. To mitigate these two simplified approaches were taken.

Approach 1: was to build a model in PVSyst taking parameters equal to part of the generator connected to a single DC box. Table 3 below shows the used specification for simulation of a single DC box in PVSyst.

PV modules	Zytech Monocrystalline Silicon 175 W
Inverters	GAMESA 100 KW 1 Inverters
Arrays	18 Module/ String 37 String 666 Modules in total
Trackers	Biaxial, 0.1 accuracy

Table 3 Specification part of PV generator feeding a single DC box : PVSyst

The whole generator output was then taken by multiplying the current value acquired from PVSyst with total number of DC box used by the PV generator. The result has limitations since it neglects any sort of variation among DC box output.

Approach 2: The other sought solution was to use a more modular PV Generator simulation program introduced earlier (INSEL). This is mainly because the program gives us the freedom to simulate the park down to the DC box level. A screen shot of model is shown in fig 4.1.

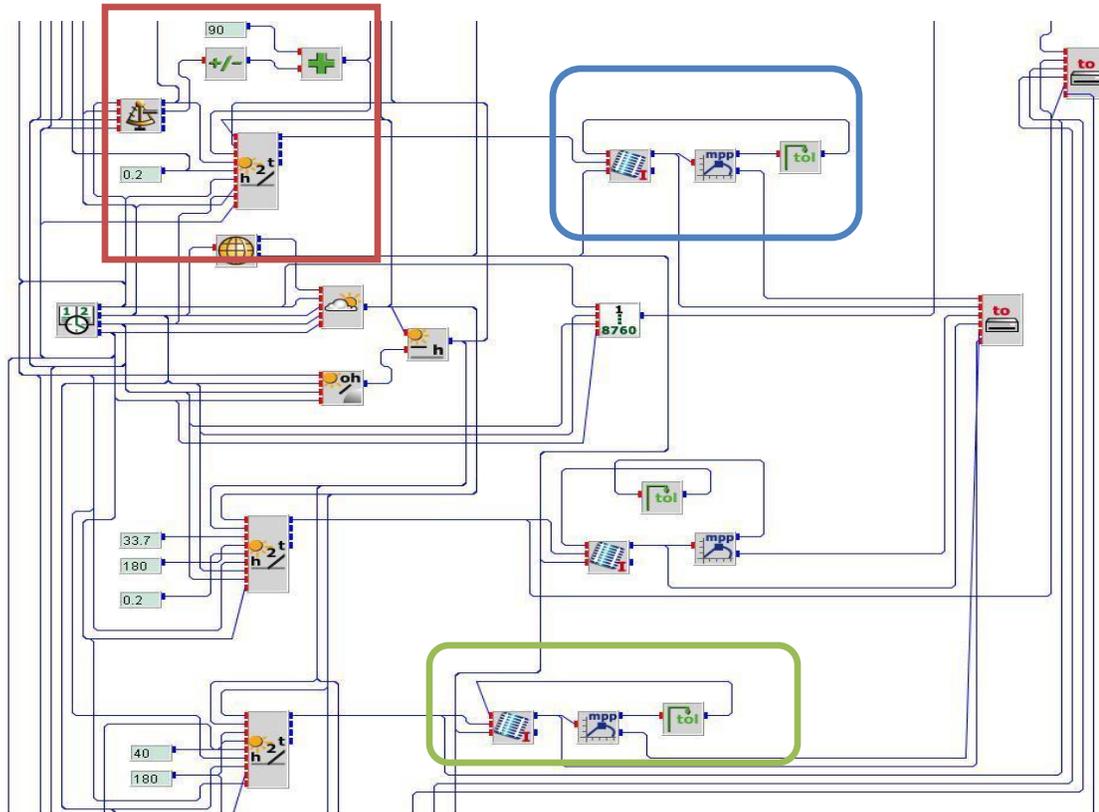


Figure 4.1 Screen shot of Part of a 1MW PV generator: INSEL 8

The figure shows part of a model developed in INSEL 8 (the whole model is too big to get a full screen shot). The block marked by a blue box represent part of the PV generator with 18 modules in series and 37 strings in parallel connected to a single maximum power point tracker. The modules are suntracking modules. The portion marked with green also resembles the same arrangement but the modules used are fixed angle modules. Different modules were used in the building the model was so as to create a variation in the output among DC box. The suntracking modules have the capability to track the sun position where as if fixed modules are chosen, then there is a specific tilt angle of the module that is optimum for a particular location.

To resemble the situation where all the output from each DC box is feed into a single DC bar, another model with a single maximum power point tracker for the entire park was also developed (not shown here). The benefit of having individual maximum power point tracking for each DC box during team operation can be more represented using this model. Using the models developed in both PVSyst and Insel, the hourly current and voltage output of the PV generator system was generated.

The losses characteristics of the inverter used for all the case are taken from a data that is provided by the inverter manufacturer. The inverter here is assumed to be a black box. We have a defined efficiency of the inverter as a function of nominal load and input voltage provided in the datasheet. A program in MATLAB is used to calculate the inverter power loss characteristics as a function of both input voltage and current. Figure shows the loss power for a single 100 KW inverter.

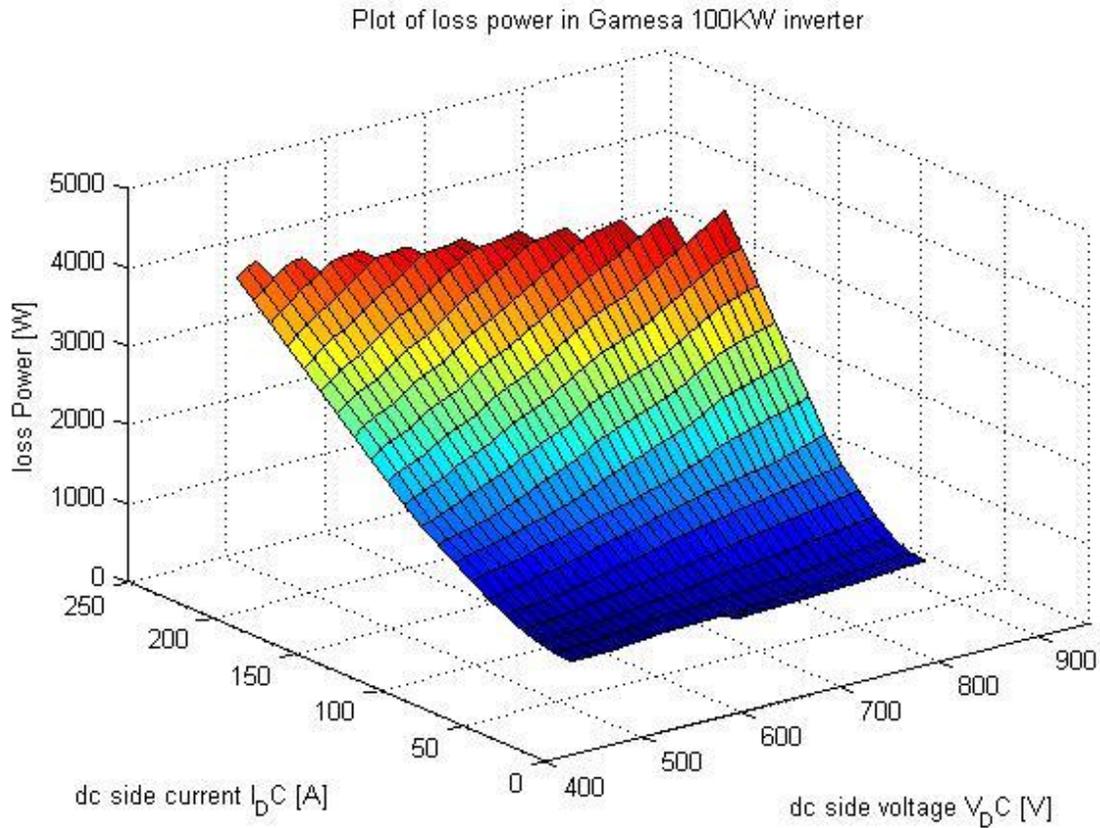


Figure 4.2 Loss characteristics of a 100 KW Gamesa Inverter

For quantify the power loss binning is applied. The average power loss from the generator is then presented as a function of voltage and current input. The input current can range from 0 to 1800 and this is divided into 90 groups. While the voltage range from 430 to 670 V and this is divided into 24 groups. A total of 2160 bins were created. The average of the values that falls within each group is calculated. The average power for each bin is then calculated by multiplying the average value of the group making up the bin. Average power value of each bin is represented below.

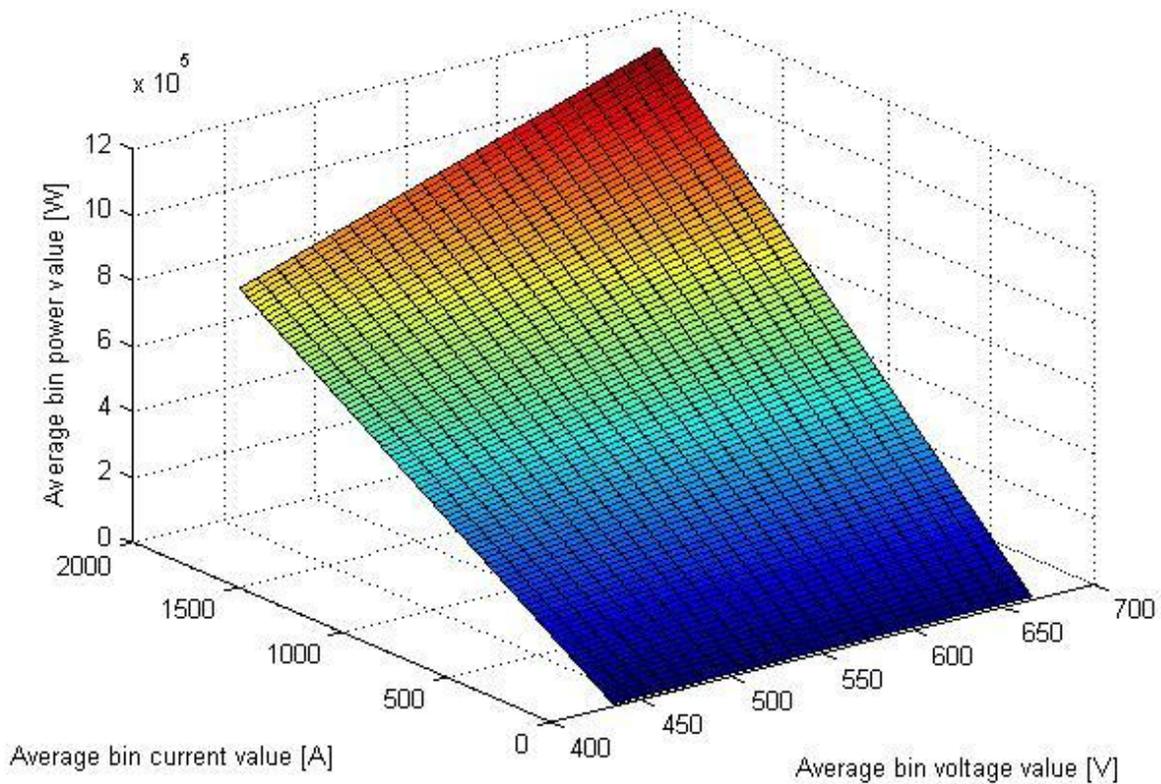


Figure 4.3 Average power output profile of PV generator.

The loss power for a single inverter for the voltage and current value of each bin is obtained through interpolation. The total power loss for the generator system then can be calculated using the number of inverters used and the loss power in each inverter. Following the procedure used in calculating the inverter losses for the different inverter connection scheme will be explained, we start with the classical inverter connection scheme

Classical inverter connection scheme:

In this scheme, the average voltage and current value representing a bin is taken. The current value is divided by the total inverters connected (in this case 9). This is assuming that each inverter shares the load equally. The current and voltage value is used to determine the loss power within the inverter. The total power loss is then the aggregate loss of each inverter.

Master – Slave reconnection (minimum) scheme:

The average voltage and current value representing a bin is taken. From the current value, the number of inverter to be operated for the bin is calculated by rounding the ratio between the bin average current value and the max current capacity of the inverter to the nearest whole number. Once the number of inverters to be operated is determined, the average current is divided by the number of operated inverters. This is again assuming the number of operated inverters share the load current equally. The acquired current value and voltage value is used to determine the loss power in a single inverter for the particular

bin. Total power loss for the bin is then the power loss in a single inverter multiplied by the number of operated inverters for the bin.

Master –Slave reconnection (optimum) scheme:

The average voltage and current value representing a bin is taken. From the current value, the lower bound for the inverter combination for the bin is calculated by rounding the ratio between the bin average current value and the max current capacity of the inverter to the nearest whole number. The upper bound is set to the max number of inverters (in this case are 9). For each inverter combination in the range corresponding input current for a single inverter is calculated. The power level is also calculated using the average bin voltage and current for each inverter combination. The inverter combination with power level closest to the optimum power level of a single inverter is chosen as the best inverter combination. Once the number of operated inverter to be operated is determined, the bin average current value is divided by the number of inverters operated to get a single inverter current value. The acquired current value and average voltage value of the bin is used to determine the loss in a single inverter. The total loss for the bin is calculated by multiplying the loss by the number of operated inverters.

Team reconnection scheme:

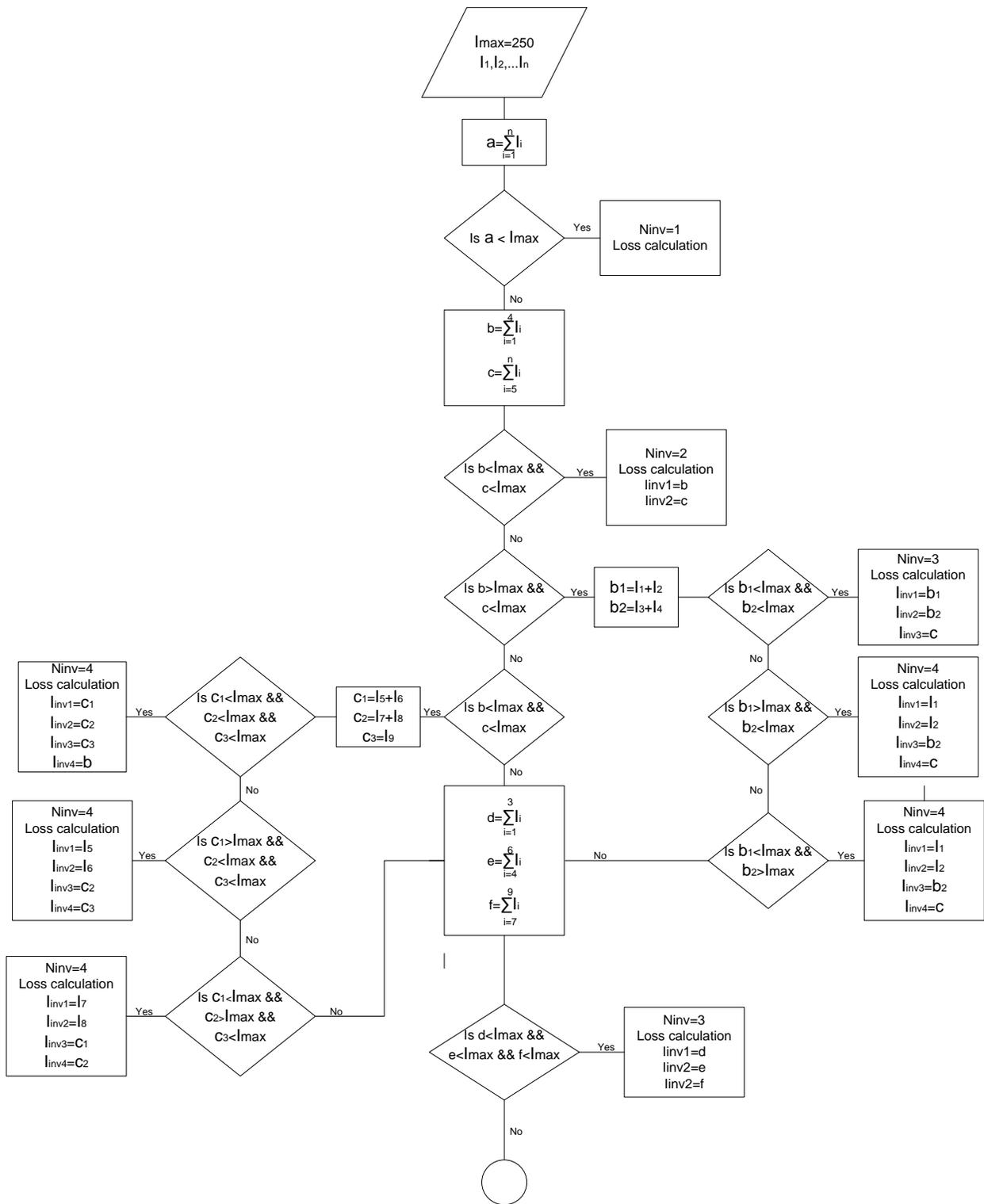
A flow chart is used to explain how the algorithm calculates the number of inverters operated for certain input.. If not all inverters are operated, the voltage value input for each inverter need to be determined. The program checks the average voltage value from each bin redirected to a single inverter and picks the maximum. This way the highest possible average power is represented. The loss power for each inverter is calculated individually and finally summed to get the total loss power for the bin.

Terms used in the flow chart

I_n = the current from the nth DC box, $n=1,2,\dots,9$

I_{max} = maximum input current to a single inverter

N_{inv} = number of inverters



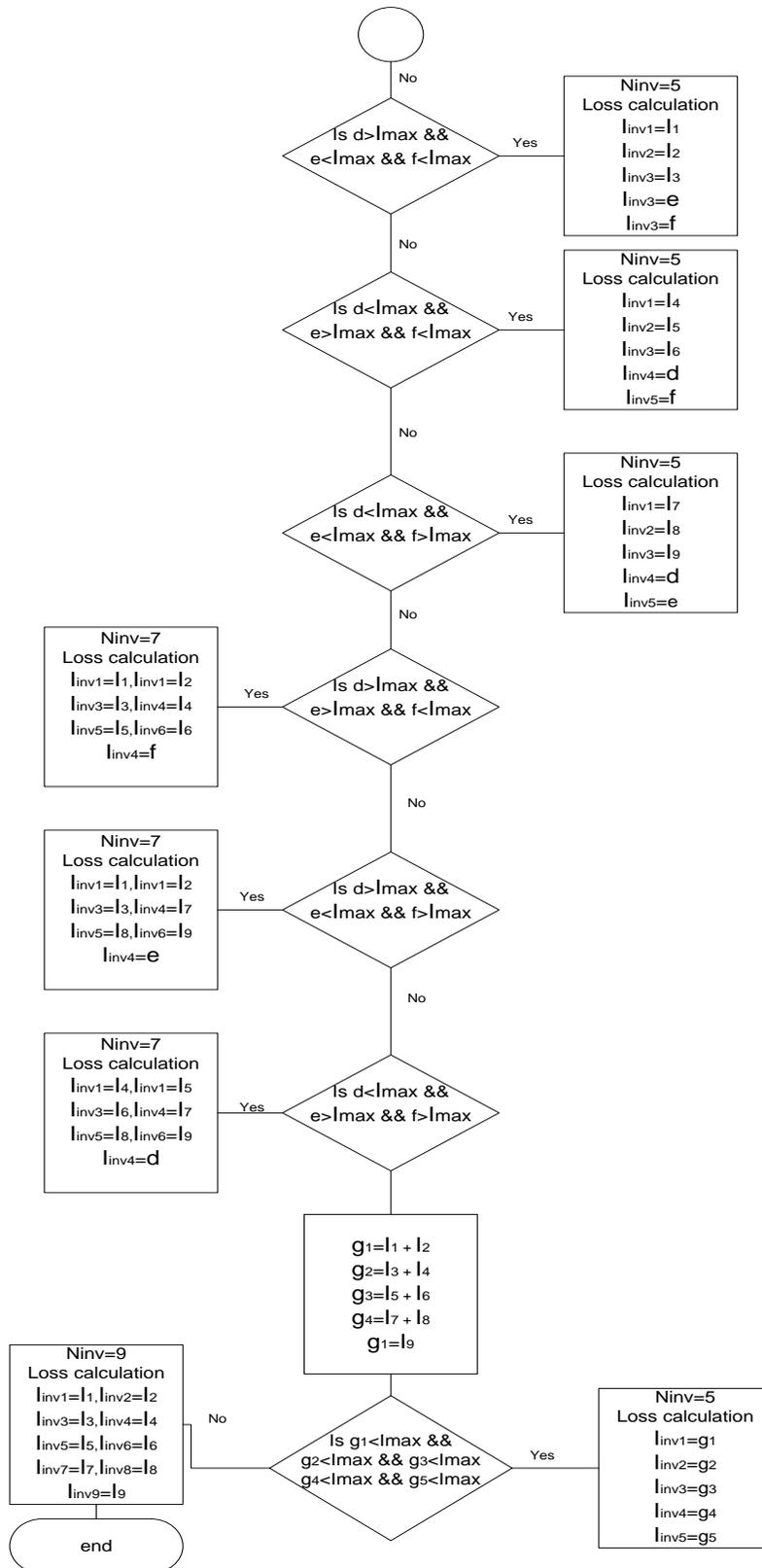


Figure 4.4 Algorithm for calculating the number of inverter operated: Team Scheme

4.2 PV generator modeling

4.2.1 Module Based Modeling

The implementation was started with the module based model. The precondition was previously done thesis work on PV module modeling based on the one diode model. To generate a varying irradiation condition, a solution in reference 13 was used. It relates the passing of a cloud to a change in the short circuit current. The author in his approach, calculates the distance R_{ij} between the solar cell $S_{i,j}$ at a certain time instance, t_n using equation 4.1

$$R_{i,j} = \sqrt{(i - t_n * v)^2 + (j - t_n * v)^2} \quad 4.1.$$

Where v = Speed of cloud
 t_n = time instane

Since the irradiance is proportional to the short circuit current, the effect of a passing cloud on a solar array can be modeled as a change in the short circuit current. The author defines a relationship between the short circuit current at STC and short circuit of the specific cell using a sin function as shown below

$$\frac{I_{SC\ i,j}}{I_{SC\ 0}} = 0.5 + \frac{\sin(R_{i,j})}{1 + R_{i,j}} \quad 4.2.$$

Taking the average speed of a cloud to be 10m.p.h, the variation on a 10 by 10 configuration is plotted in MATLAB.

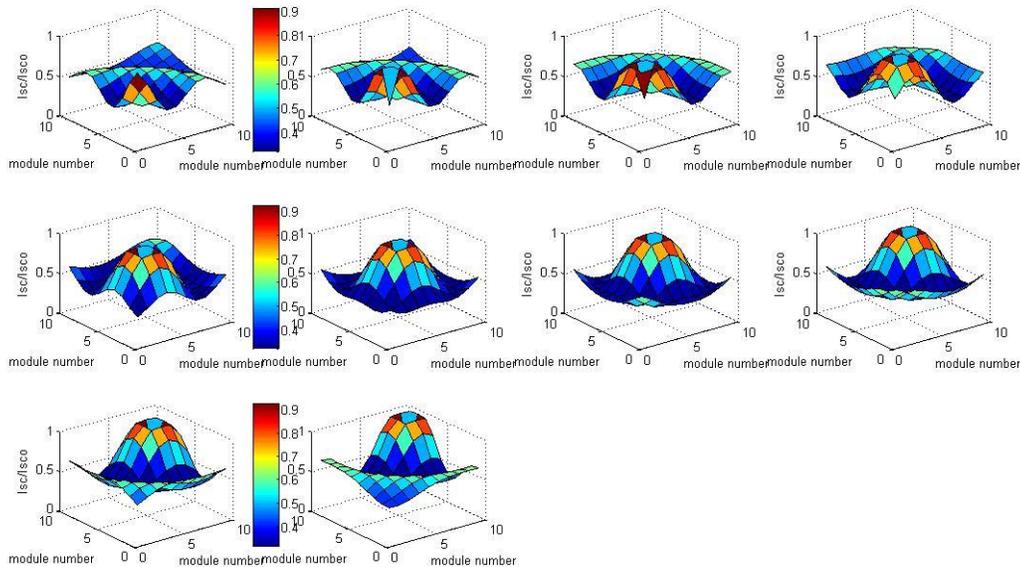


Figure 4.5 Changing irradiation effect due to a passing cloud on a 10 by 10 configuration: each for a time instance t_i

Although the above equation as stated in paper is for PV cell in a module, it is acceptable to use it for a module level based on our assumption that each cell in the module based modeling is subjected to the same irradiation level. Although it doesn't reflect real time situation, the result can be thought of creating a random irradiation along a surface which could be similar to that created by a passing cloud.

The problem was started at a small level having 4 modules in total, two modules in series forming a string and two strings in parallel. Equation 3.47 is used to define voltage relation in each mesh. Equation 3.48 is used to define each string output contribution to the total current. Equation 3.49 is used to write the current for two nodes. The current output for each module is calculated by passing voltage value to a function that uses the one diode mathematical model representation of the module. Fsolve in MATLAB was used to solve the equations for voltage values and total current. Unfortunately the program reaches max iteration before it can solve the problem.

The PV generator was up scaled to contain 6 modules and another solution was tried. Two conditions were used to define an objective function

Condition1: The same current flows through all modules in the string.

Condition 2: The sum of voltage from each module in a string gives the terminal voltage

The objective function defined in MATLAB is shown below.

$$\begin{aligned} x(1) &= (I1 - I2)^2 + (I2 - I3)^2 + (I3 - I1)^2; \\ x(2) &= (I4 - I5)^2 + (I5 - I6)^2 + (I6 - I4)^2; \\ x(3) &= (Vt - (V(1) + V(2) + V(3)))^2 + (Vt - (V(4) + V(5) + V(6)))^2; \end{aligned}$$

I1, I2 and I3 are current produced by module 1, module 2 and module 3 making up the first string. I4, I5 and I6 are current produced by module 4, module 5 and module 6 making up the second string. The objective function is then to minimize the sum of x. A function that uses the Levenberg Marquardt algorithm to arrive at a solution found from the web was used. The result didn't converge to a solution.

As a last resort, the current voltage relationship was redefined, to define the objective function. Index is used to differentiate the voltage value and current output of a module. "n" indicates the number of modules connected in series to form a string and "m" indicates the number of strings connected in parallel. Based on the condition that the difference of the current among series connected module should be zero a set of equation is defined

$$I_{ij} - I_{(i+1)j} = 0 \quad 4.3.$$

Where $i=1,2,\dots,n-1$ and $j=1,2,\dots,m$

The voltage output of a string should equal the total voltage of the PV generator

$$\sum_{i=1}^n V_{ij} - V_T + V_{bd} = 0 \quad 4.4.$$

For $j=1,2,\dots,m$

V_{bd} =voltage drop across blocking diode

The model assumes a bypass diode exists in parallel with each module and a blocking diode in series with each string. The total current of the PV generator can be expressed as the contribution of current from each string.

$$\sum_{j=1}^m I_{1j} - I_T = 0 \quad 4.5.$$

Where I_T and V_T corresponds to the PV generator output at the terminal. The results from using this approach is presented in part 5.5

4.2.2 Simplified PV generator modeling

Each module along the string is subjected to the same operating condition and is assumed to contribute equally for the value of the terminal voltage. The developed model was PV generator with a 1MW capacity. Each string consists of 18 modules in series and 360 strings in parallel. Two layout of the PV generator was tried.

First layout was the central layout where all the output from each string is assumed to feed a single DC bar. All strings are operated at the DC bar voltage. The second layout was a string layout where the park is grouped into 2 groups, each group with 180 strings in parallel. Each group has its own independent operating voltage. The algorithm in both layouts takes the percentage shading value as an input from the user.

The purpose was to actually simulate the PV generator's output when subjected to shading condition. A set of irradiation values that are incident upon the PV generator module needed to be determined. As a simplification of a very complex process, the assumption taken was that two irradiation levels exist; one representing unshaded condition and the other representing a shaded condition. For the sake of not choosing a random value for the irradiation level, the values were taken to be the hourly global in plane irradiation and the diffused inplane irradiation of a particular area. An excel file is made to provide the algorithm with two irradiation levels for solar hours within a year.

The algorithm asks the user to choose between central or team layout. If a central set up is selected, the program proceeds as follows. Initially the algorithm solves to find the operating voltage of the PV generator. For this it calls a function to calculate the MPP of the PV generator for the provided shading condition.

The function goes to compute for the unshaded portion first and saves the data for further calculation. It starts at a string level, by taking the hourly irradiation level to generate the I-V characteristics of the string. Using the percentage shading data provided from the user, the portion of the whole park that isn't shaded is determined. Based on this value, the I-V curve of unshaded group is determined and saved. The algorithm does the above 3 steps for every global irradiation level provided in the excel sheet. To reduce the computation and since no energy is harnessed during night time, no computation is done during night hours.

Next, it calculates for the shaded portion with the similar procedure as that of the unshaded portion but taking the diffused inplane irradiation value into account. The total I-V characteristic of the PV generator for each hour is then computed by summing the contribution from the shaded and unshaded portion. Based on the generated hourly I-V curve of the PV generator, the PV generator's MPP voltage values can be calculated for each hour. The algorithm then returns the hourly operating point for the range hourly irradiation level provided in the excel spread sheet assuming that the PV generator is always operated at

its MPP. The program then calls a second function that takes the saved hourly operating point voltage to generate the operating current for the defined shading condition and irradiation level.

When the user selects the team layout of the park, the algorithm assumes the park is divided into two parts each with 180 strings that operate independently. It should be pointed out that the unshaded part in each portion of the PV generator are subjected to same irradiation level (i.e. global inplane irradiation). The above statement also holds for the shaded part. The two parts thus differ only in the percentage shading provided by the user. The algorithm then calls a function that performs the MPP tracking to determine each portion operating point. What the function does is perform the same procedure explained above but does it for the two parts separately. From the function the operating voltage for the two parts is generated and saved. The algorithm then calls another function to compute the operating current for the saved operating voltage point. It does this for the two portion of the PV generator separately. Finally the algorithm saves the generated hourly current and voltage value into an excel sheet. Another down side of this method that is not stated in chapter 3 is that it is really computational expensive.

4.2.3 Partially shaded PV Generator Modeling

The Algorithm can intake a shading pattern from the user and produce I-V characteristics curve for one instance of time. The implementation of the algorithm in MATLAB is as follows. The program starts by taking the shading pattern from the user. The outlook is shown below

```

////////////////////////////////////
please enter the number of groups 4
Enter no of substring for group No1 =3
Enter No of module in each substring enclosed in square bracket([])separated by comma = [8,6,4]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,.5,.2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,21,18]
Enter no of string for group No1 =80
Enter no of substring for group No2 =2
Enter No of module in each substring enclosed in square bracket([])separated by comma = [12,6]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,18]
Enter no of string for group No2 =100
Enter no of substring for group No3 =2
Enter No of module in each substring enclosed in square bracket([])separated by comma = [16,2]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,.2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,18]
Enter no of string for group No3 =120
Enter no of substring for group No4 =1
Enter No of module in each substring enclosed in square bracket([])separated by comma = [18]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25]
Enter no of string for group No4 =60
////////////////////////////////////

```

It first calculates and generates the I-V curve of all substrings with in a group. This is achieved by up scaling the I-V characteristics of a module under the same operating condition as the substring. The program performs the above step for each substring within the string. Each string I-V characteristics is generated from the I-V curve of the substrings. The program does an interpolation of the voltage value for a current range from zero to the resulting maximum short circuit current among the substrings. The interpolated voltage value for each point in the current range is summed to generate the I-V curve of the string. The group I-V characteristic is then achieved by up scaling the current value of the string by a

factor equal to the total number of strings making up the group. Then the program goes to interpolate the current value for a common voltage for each group. Then the program generates the I-V curve for the generator by summing the current contribution of each group for a common voltage value. The voltage range is set from zero to maximum open circuit voltage from the group.

The down side of this model is that it can only generate the I-V curve of the PV generator for a single instant of time. The user needs to input the shading pattern for each instant. It is a good approach to visualize the effects of partial shading on the general characteristic curve of a PV generator. The implementation alongside little description is presented in section 5.4. In section 3.2.5, terms used to describe the parts of the generator using this modeling approach was described. The 4 curves below shows the I-V characteristics of each group. A group's operating condition defines part of the total operating condition of the PV generator at a time instance t . The array output is thus the aggregate contribution from each group

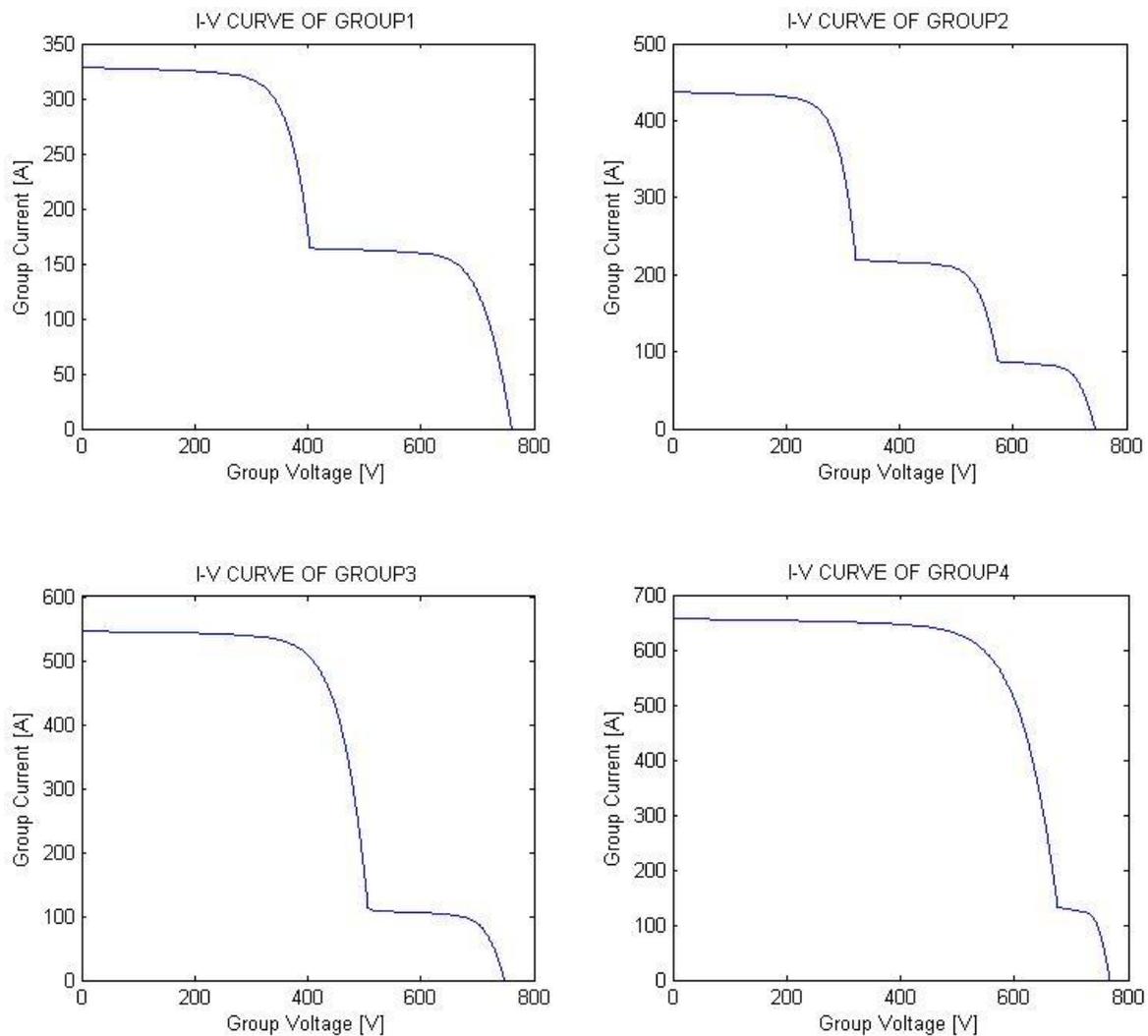


Figure 4.6 I-V characteristics of individual group corresponding to a shading condition

5 Results

The results are presented in accordance to the steps followed in the solution part of this report. A small description in each section is included. Analysis is presented alongside results. The first part of the chapter presents the result for the loss calculation for the inverter reconnection scheme. The second part

5.1 Loss calculation for different Inverter Reconnection Scheme

In the initial stage two locations were chosen, a 1 MW solar power plant in Totana, Spain and a similar 1MW plant in Germany. The choice of location is because both region have the high potential with regards to solar irradiation [27]. The data for the park is simulated in PVSyst V 5.12 . The extracted data from PVSyst was the array's hourly current and voltage output for an entire year. Similarly the hourly current and voltage for the Poking solar power plant in Germany was extracted. The chosen size and number of inverter is based on the actual no of inverters employed in the plant. But due to the missing efficiency data of specific inverter used, a 100KW inverter from Gamesa was used for the calculation.

First batch of test was based on hourly current and voltage output generated using PVSyst. The result will be presented side by side for the individual park.

The PV array voltage and current distribution for the park in Totana, Spain and for the park Poking in Germany is plotted in figure 5.1 and 5.2 below

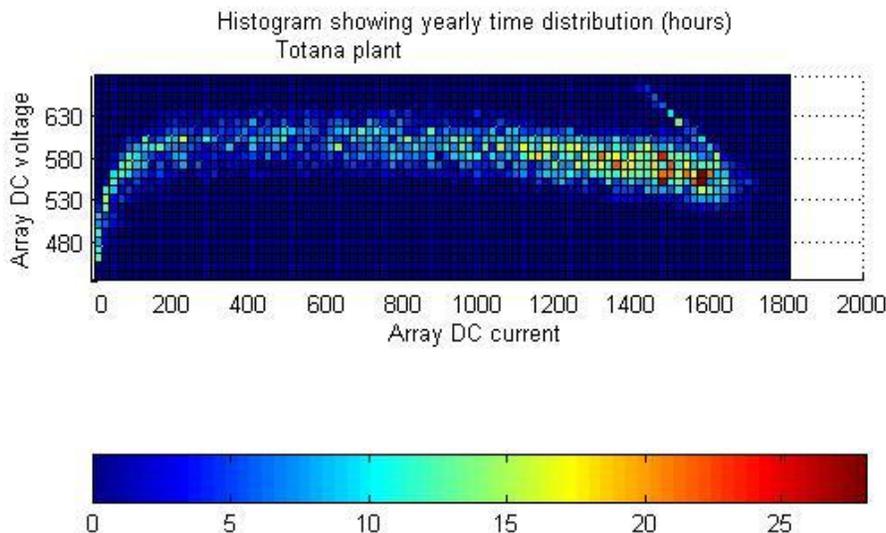


Figure 5.1 Histogram showing yearly time distribution : Totana, Spain

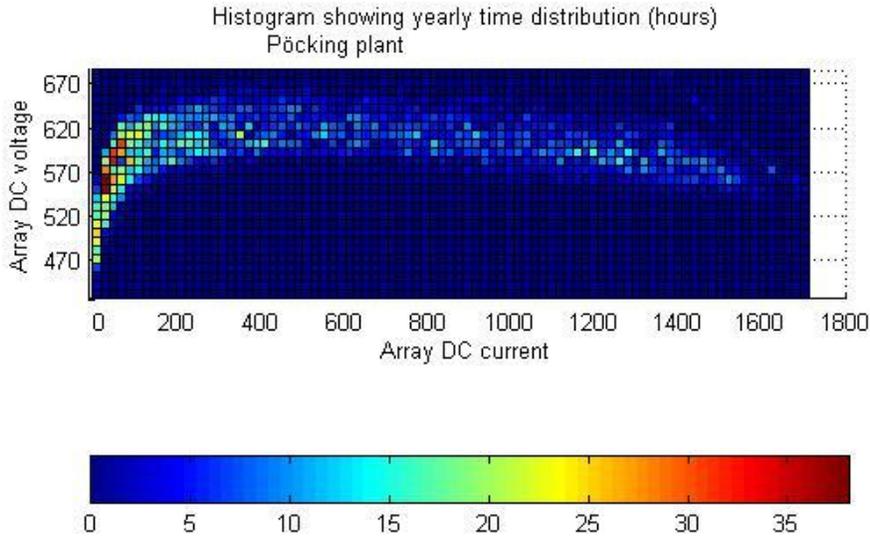


Figure 5.2 Histogram showing yearly time distribution, Pöcking, Germany

The metanom data that is used in PVSyst runs from jan 1990- December 1990. This is one of the down sides of using PVSyst. Assuming the data from PVSyst is fairly accurate, the losses for the different inverter reconnection scheme is computed.

Result for inverter reconnection Scheme 1

In this scheme, there exists a single DC bar and all the array output is feed to the DC bar. The 9 inverters are then connected to the DC bar and they share the load current equally. All the inverters stay connected during the entire operating hours

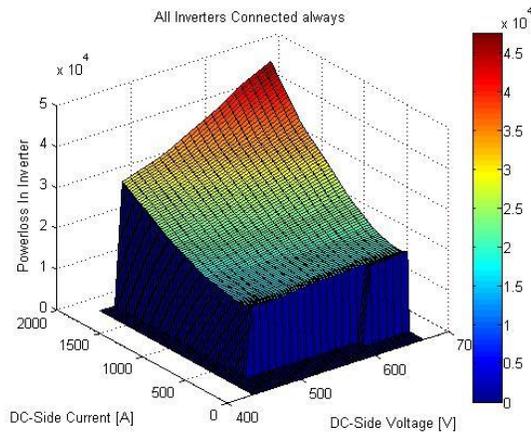


Figure 5.3 Cumulative powerloss distribution when all nine inverters are operated: Totana Park

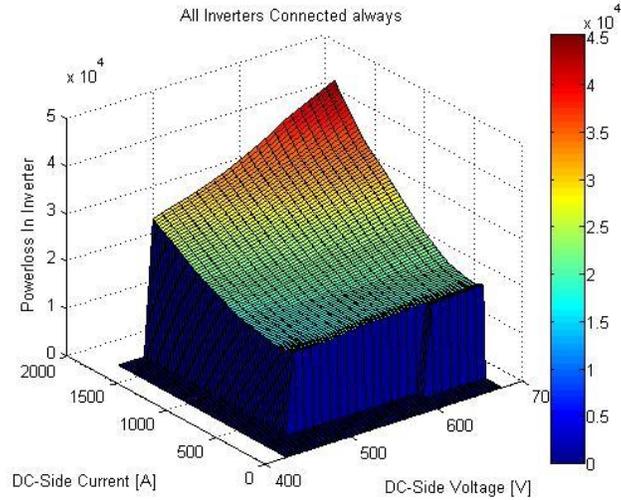
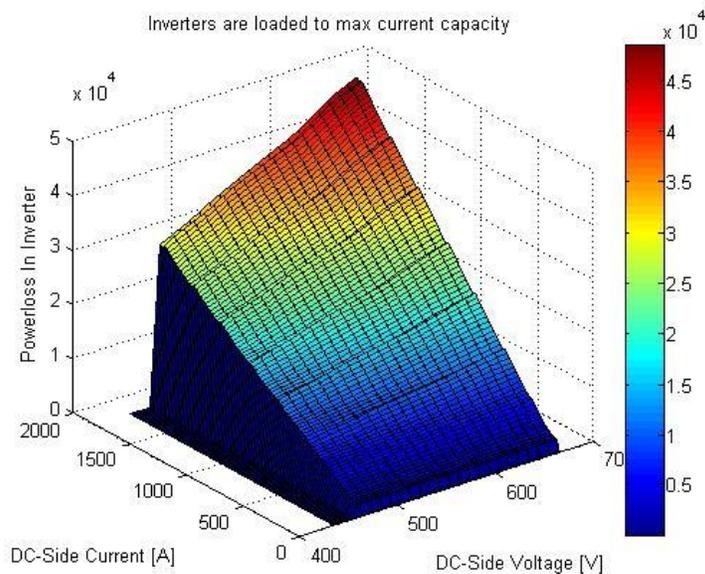


Figure 5.4 Cumulative powerloss distribution when all nine inverters are operated: Pöcking Park

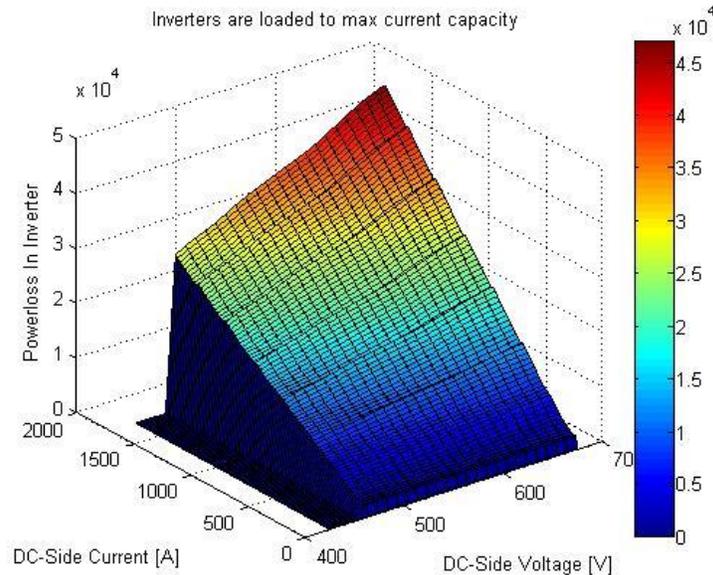
When the PV generator's output is low, all the inverters stay connected and share the output equally. During low PV generator output each inverter works in its low efficiency region and therefore the cumulative losses appear to be larger

Result for inverter reconnection Scheme 2:

In this scheme, there exists a single DC bar and all the array output is feed to the DC bar. The number of inverters that are operated is based on the current output of the PV generator. Here each inverter that is connected is operated to their maximum current capacity. In other words, each time, minimum no of inverters are connected and each inverter is forced to operate to their maximum current loading. The power loss distribution for this scheme is shown below.



(a)



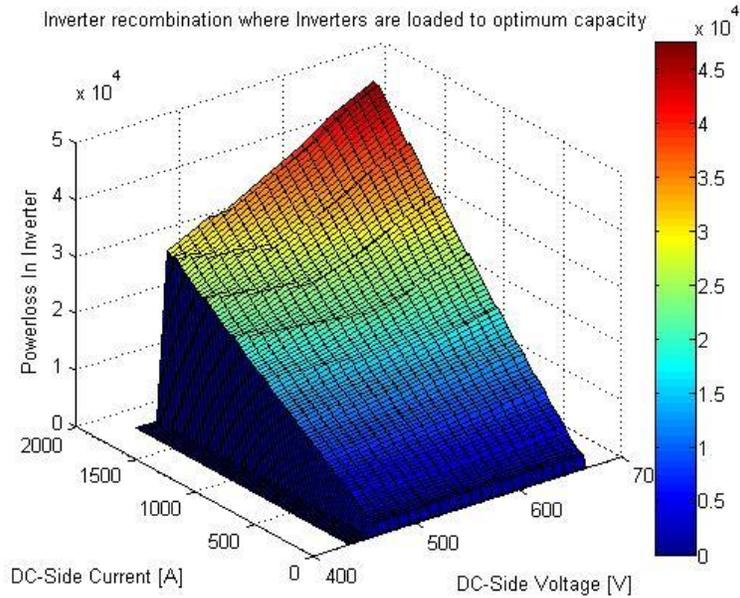
(b)

Figure 5.5 the cumulative powerloss distribution when each inverter loaded to max current capacity.(a) Totana Park, Spain (b)Poking Park, Germany

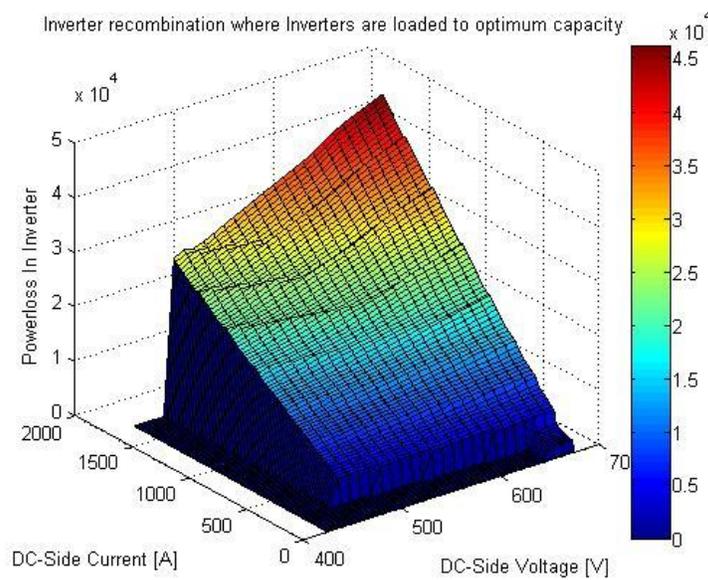
At low PV generator output inverters are disconnected while the connected inverters are loaded to their maximum current capacity. When the output from the generator exceeds the connected inverter's capacity, more inverters are switched in. comparing figure 5.4 and 5.5, a lower power loss during low PV generator output is mainly because the lower number of inverters operated (which indicates less additive losses). During maximum generation, the loss distribution is similar since the operated numbers of inverters are the same in both schemes.

Result for inverter reconnection Scheme 3:

In this scheme, there exists a single DC bar and all the array output is feed to the DC bar. The PV generators output is shared among the inverters so that each inverters are loaded to their optimum operating point. No inverter is loaded to the maximum operating capacity. The value of the optimum power used for the computation is the one provided by the manufacturer. The power loss distribution for this case is shown figure 5.6.



(a)



(b)

Figure 5.6 Cumulative powerloss distribution when each inverter loaded to optimum power capacity.(a) Totana Park, Spain (b)Poking Park, Germany

The steps observed in the power loss distribution diagram is an indicative of the increase in the number of inverters operated.

Comparison between the 3 schemes can be done by a means of annual energy loss in the system. During the night, when the inverters are disconnected a constant loss of 35W as specified by the manufacturer is accounted for.

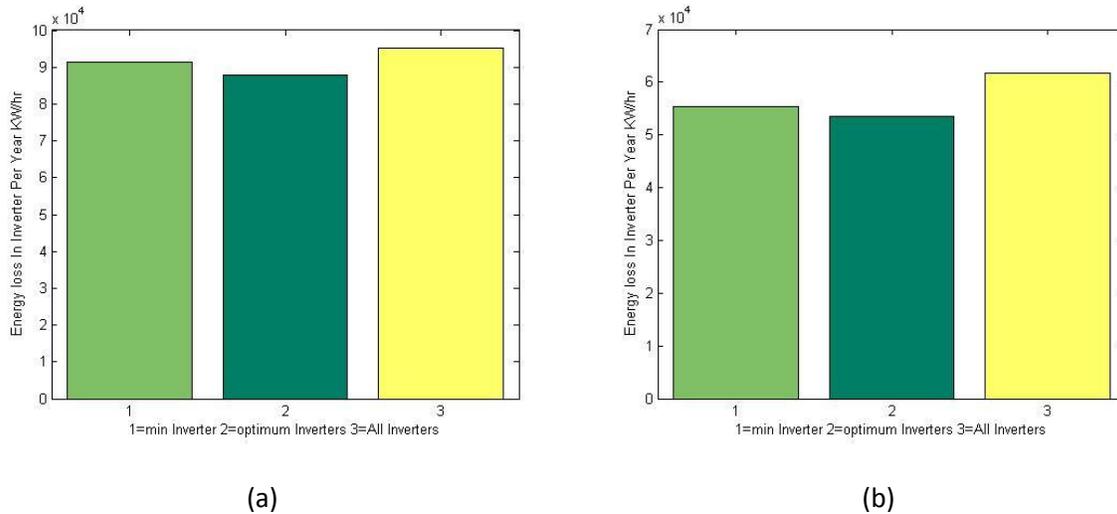


Figure 5.7 The Energy loss for the 3 reconnection scheme (a)Totana park, Spain (b)Pöcking Park, Germany

The result indicates the scheme where all inverters are operated as having the max loss. Among the master slave operation, the scheme where inverters are switched based on their optimum capacity bring up the least loss in both parks.

Result for inverter reconnection Scheme 4:

In this scheme, unlike the others mentioned above no common DC bar exists for all inverters. Each inverter is operated individually during high output. At low generator output, the input to the inverter can then be rerouted so that lower numbers of inverters are operated. For ease of reference the scheme will be called team concept. To be able to represent the powerloss distribution using the team concept and at the same time be able to compare the result with the rest of the scheme, the output of the PV generator for a single individual inverter was generated by PVSyst. The approach is explained in section 4.1. The histogram showing yearly time distribution for a single inverter input is shown figure 5.8.

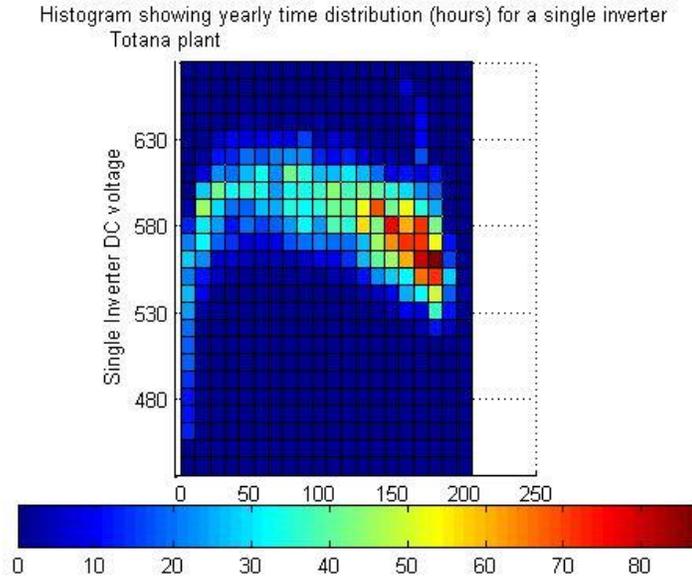


Figure 5.8 Histogram showing yearly time distribution for a single inverter: PVSyst result for Totana park

The assumption taken for the 3 scheme above is the data generated for the individual inverter is feed into a single DC bar. The voltage current distribution used for this calculation is shown below.

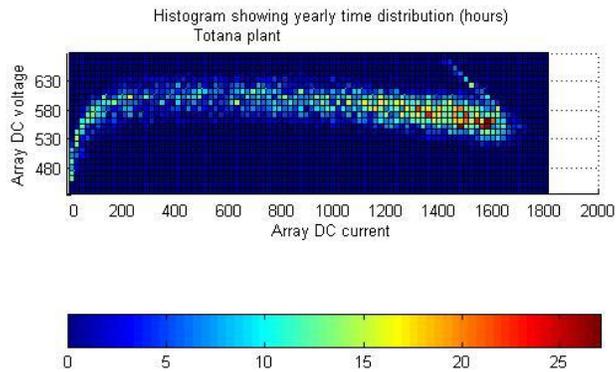
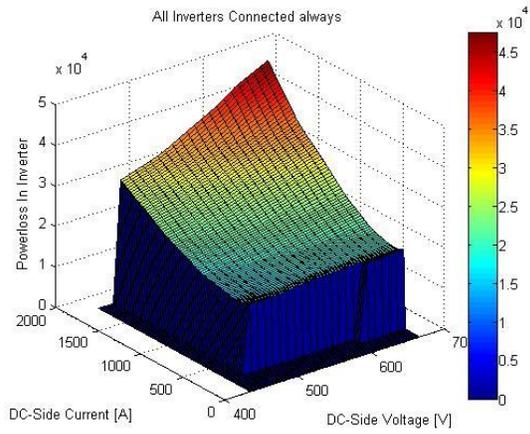
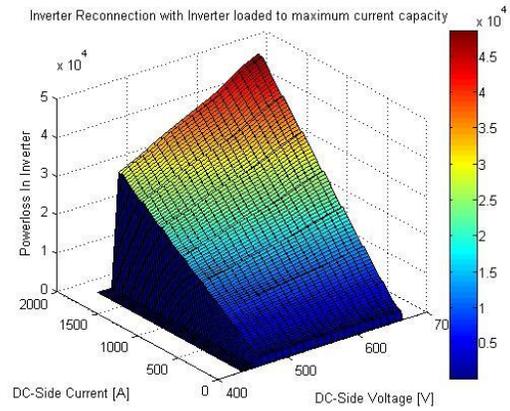


Figure 5.9 Histogram showing yearly time distribution generated using single inverter data

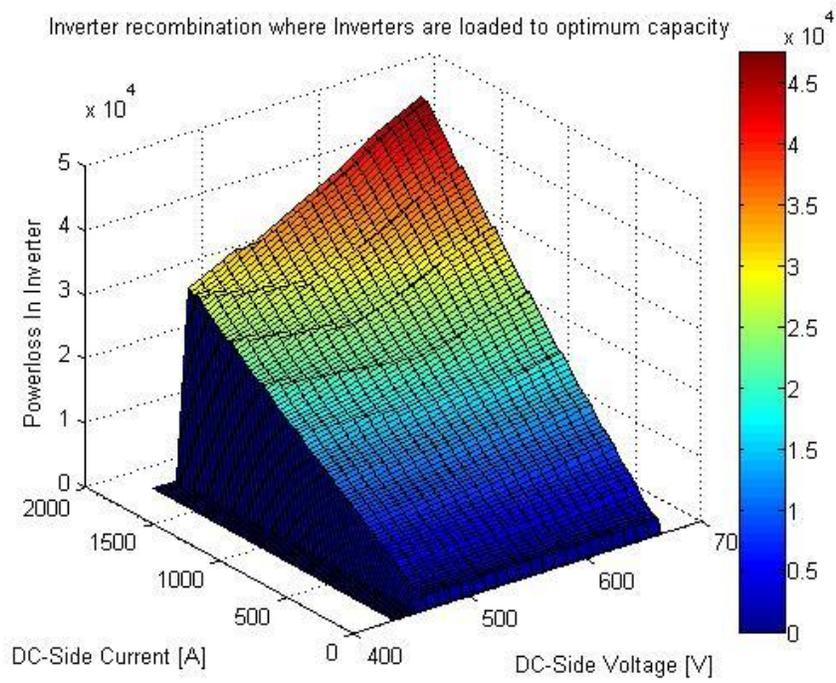
The result of power loss distribution for the 4 inverter reconnection scheme, for the plant in Totana, Spain is presented below.



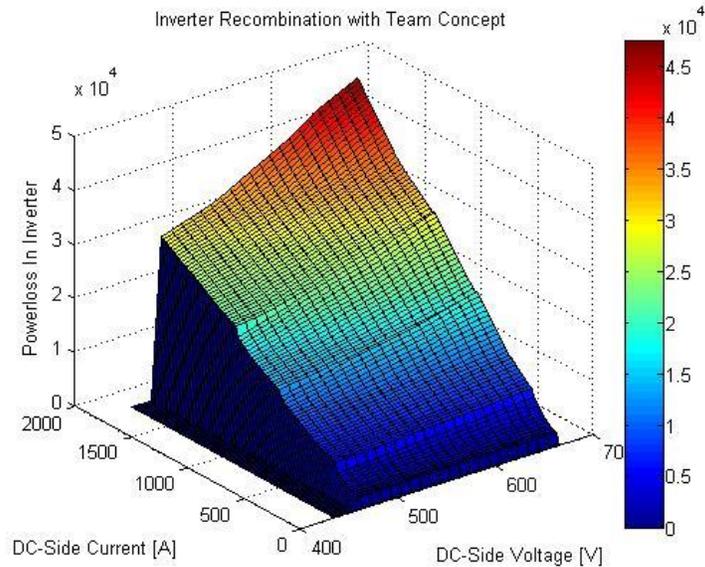
(a)



(b)



(c)



(d)

Figure 5.10 Cumulative powerloss distribution for 4 inverter reconnection scheme in Totana plant(a)All inverters connected always(b)inverter reconnection based on max current loading(c)inverters reconnection based on optimum loading of inverter(d)team Concept

Part (d) in figure 5.10, since output of a individual inverters can be rerouted to adjacent inverters, the possible combination steps are a single inverter, two inverters, 3 inverters, 5 inverters and 9 inverters. The cumulative power loss is therefore the sum of losses in each inverter that is operated.

The energy loss per year is plotted out as a tool for comparison.

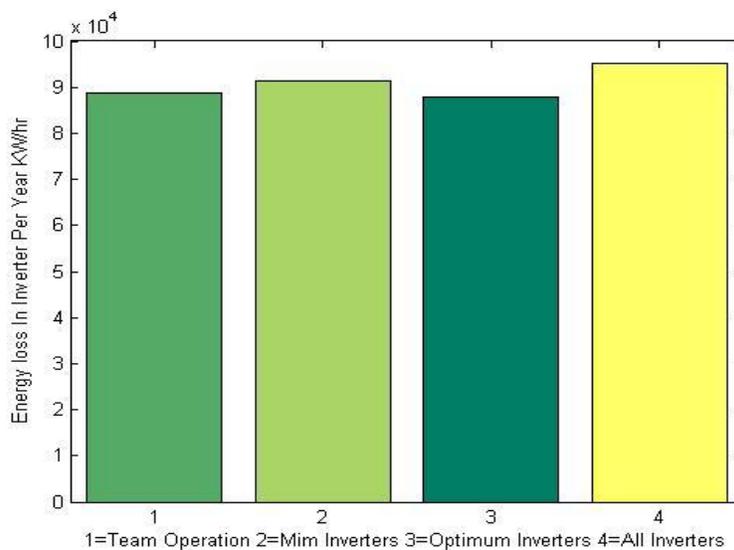


Figure 5.11 The Energy loss for the 4 reconnection scheme, Totana Park, Spain

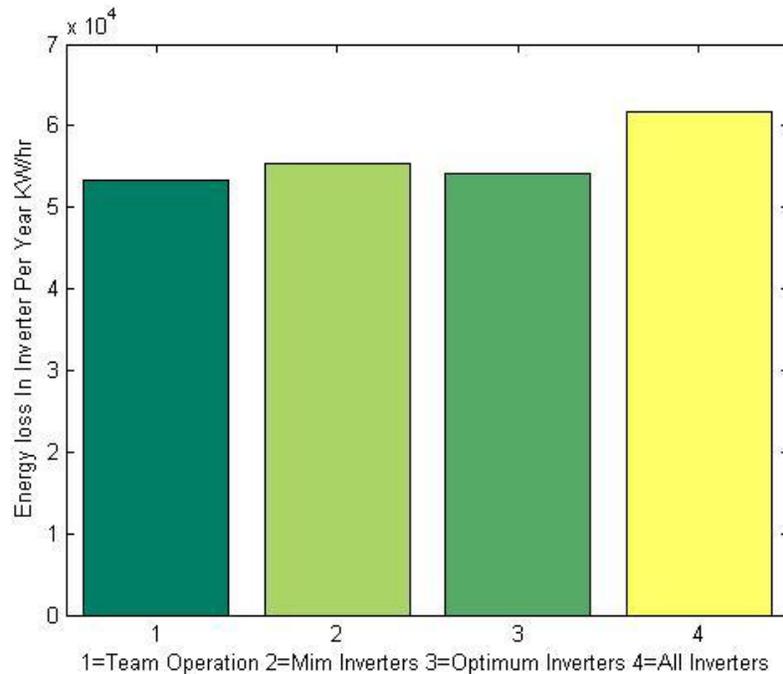


Figure 5.12 The Energy loss for the 4 reconnection scheme, Poking Park, Germany

From the figures considering the overall energy losses in the different inverter reconnection scheme, the inverter reconnection where each inverter is loaded to its optimum loading shows promising results.

5.2 Test on General Model

Following this step, a general function for calculation of the power loss distribution and the corresponding energy loss for 1 year of a 1MW plant employing 9 inverters was developed. For testing the function, a model of a 1 MW park was developed in the INSEL8. Detailed description of the model is found in the section 4.1. Note that the model developed in INSEL has no resemblance to any park, the model is made in such a way that the variation exists among DC box output. As a reminder the inverters are assumed to be equipped with an MPP tracker and model developed has individual MPP trackers involved. For the case of the single DC bar connection the model built is generated using a single MPP tracker of the whole PV generator. Histogram of the yearly time distribution of PV generator's output is shown in figures below.

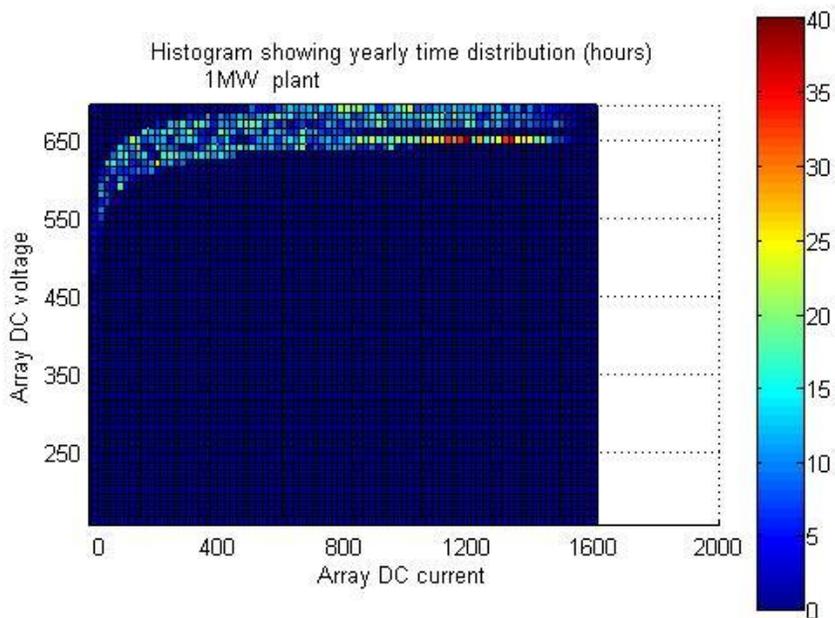


Figure 5.13 Histogram showing the yearly time distribution of PV generator :model built in INSEL 8

For the case where individual MPP trackers were employed, the yearly time distribution for some DC box is shown below. 9 DC box exists, out of which 4 DC box each aggregating 37 string with sun tracking modules. The remaining 5 DC box each aggregating 37 strings with fixed angle module. The tilt angle for the modules within a single DC box was uniform but a variation was introduced among modules of different DC box. The used tilt angles for the modules were 33.7 deg, 60 deg, 40 deg, 22 deg and 15 deg (not all is presented in the figures)

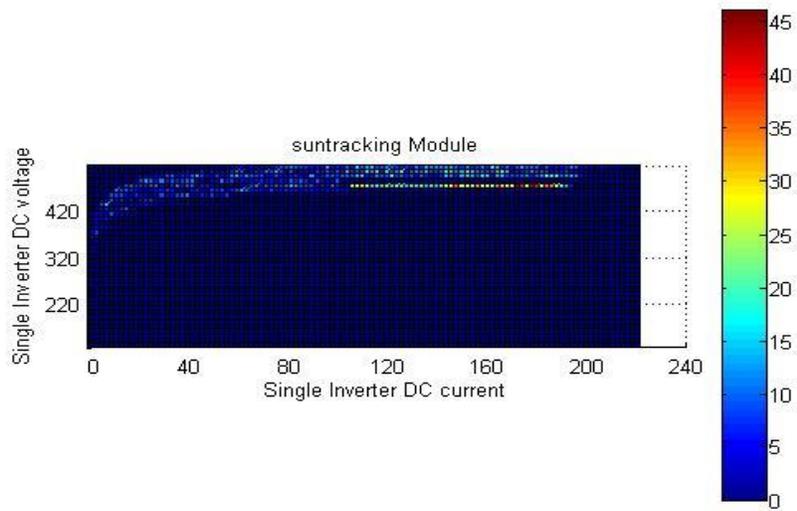


Figure 5.14 Histogram showing the yearly time distribution: single DC box feed from string of suntracking modules

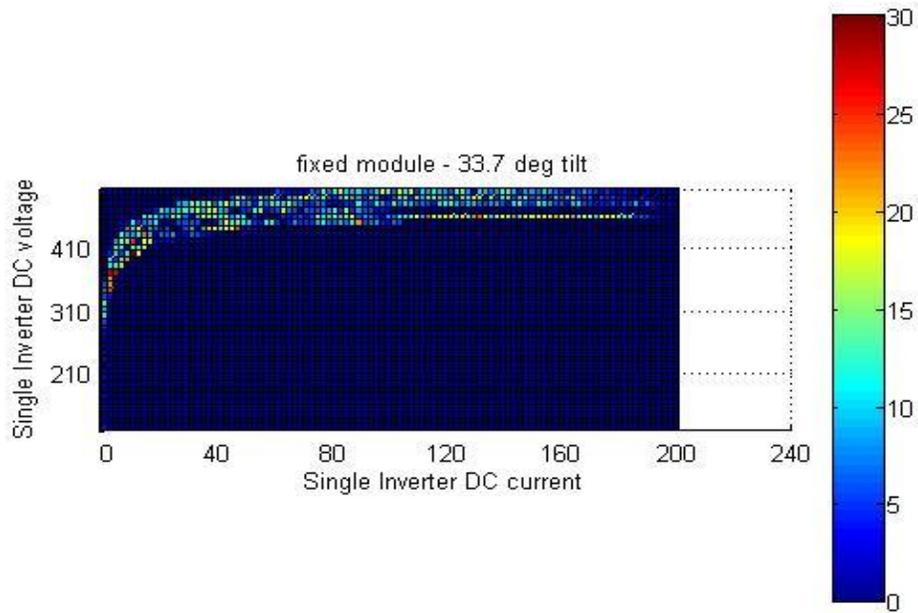


Figure 5.15 Histogram showing the yearly time distribution: single DC box feed from string of fixed modules with 33.7 deg tilt

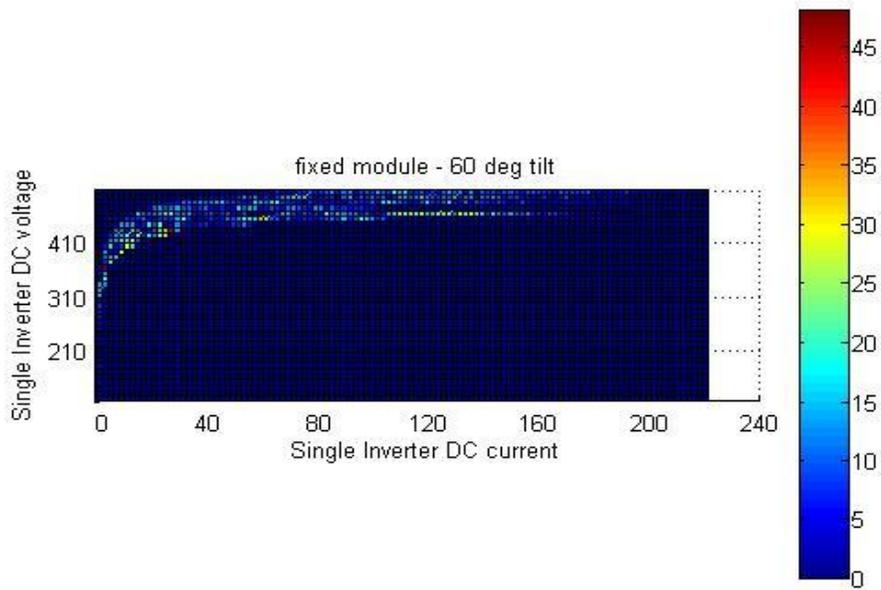
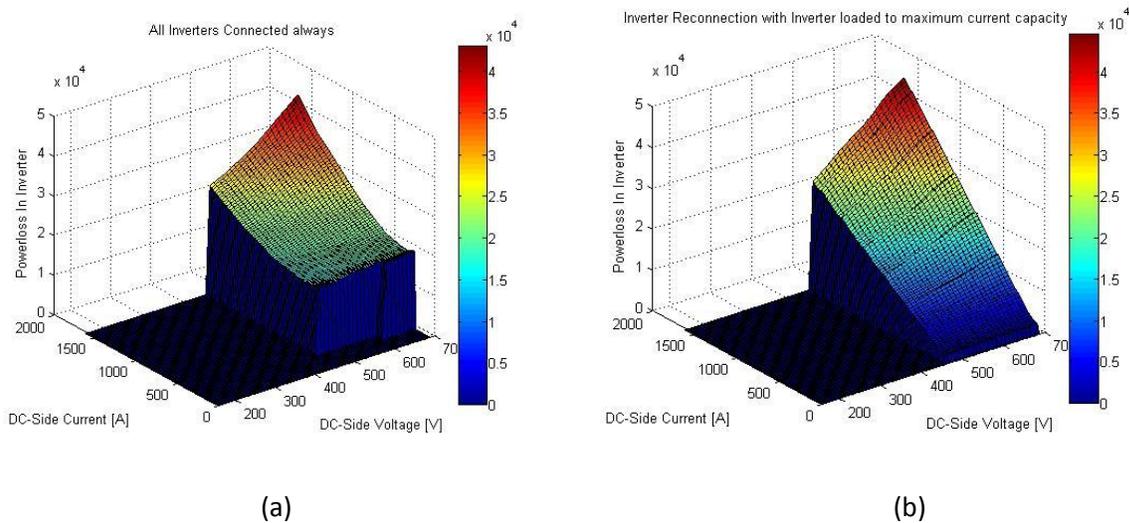
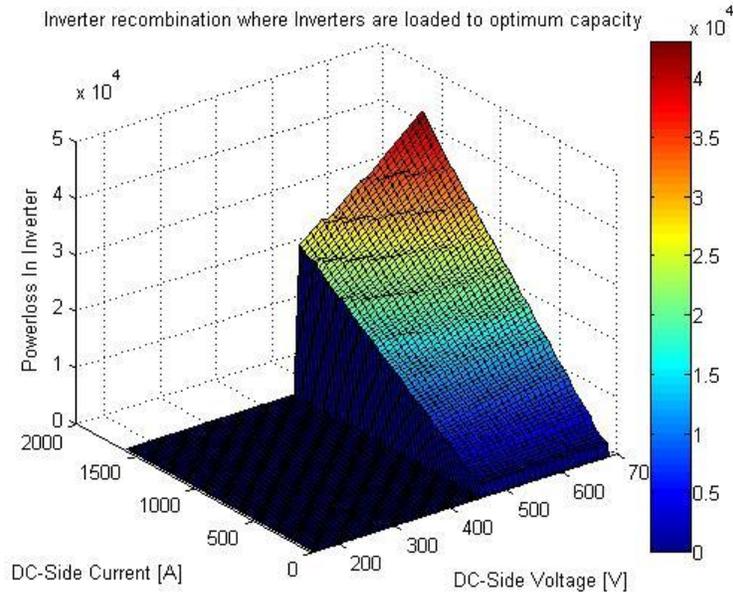


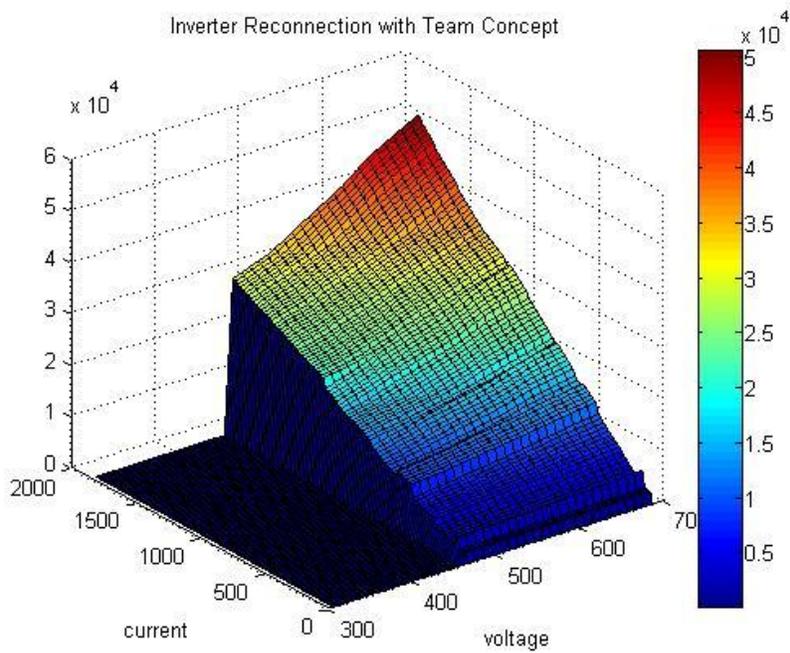
Figure 5.16 Histogram showing the yearly time distribution: single DC box feed from string of fixed modules with 60 deg tilt

From the model, the generated PV generator voltage and current with individual MPP tracker for every 37 strings connected in parallel (which corresponds to one DC box) is used to test the team concept. On the other hand the generated array voltage and current for the whole PV generator with a single MPP tracker was used to test the 3 other inverter reconnection scheme. The result is presented below





(c)



(d)

Figure 5.17 Output of the general model for calculating power loss distribution for 1MW park (a)All inverters connected (b)Inverter reconnection with max current loading(c) Inverter reconnection with optimum inverter loading(d)Inverter reconnection using team concept

The result of energy loss calculation per year using the general model is presented below.

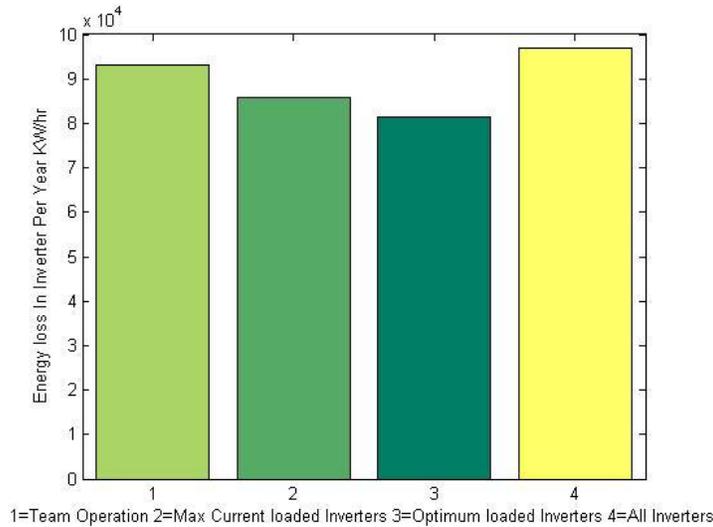


Figure 5.18 The Energy loss for the 4 reconnection scheme:Test for General model

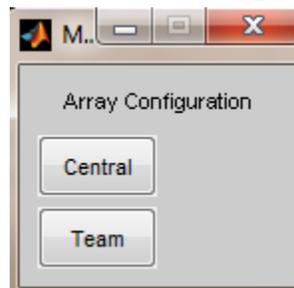
It is observed that as the combination of inverter connection during the team operation is increased the energy loss also increases. In theory the team concept gives the flexibility of operating less number of inverters when output is lower. The downside is the inverters that are switched out can't freely be chosen since rerouting is only possible among adjacent inverters. This limits rerouting options if further apart portion experience lower production.

The condition where inverters are operated to the maximum capacity shows a promising result as compared to team operation is from the fact the max number of inverters operated was 7 inverters. The master slave reconnection scheme based on maximum current loading can be good choice where the yield of the park is low compared as compared to its installed capacity. The master slave operation with inverters loaded to their optimum loading shows the best result.

5.3 Simplified PV Generator Modeling for Inverter reconnection Analysis

The data generated using the simplified PV generator model was used to calculate the power loss distribution and total energy loss for the 4 inverter reconnection schemes discussed previous section

The simplified PV generator model developed has two options, the central or team. Assumption taken is that all modules with in a string are subject to the same shading condition and same temperature. The selection menu is shown below



The header of the program used to simulate the array is shown below

```

%% To generate output of an array under shading condition
%
% Assumption :
%(1) Plant is divided into 2 parts, each part consists of 180 strings
% connected in parallel. Each string has 18 modules in series
%(2)All modules along the string is subjected to uniform
% irradiation
%(3)Temperature effect between shaded and un shaded portion isn't considered
%
% INSTRUCTION:
% - Choose option "central" for the condition that the entire output of the
% array is feed into a single DC bar.
% - Choose Option "Team" for the condition that 2 DC bar exist and the output
% from first 180 parallel strings are connected to the first DC bar and the
% output of the last 180 strings is connected to the 2nd DC bar.
% - The current and voltage output is saved in the excel file with a file
% name "Result--%shading.xls" for option central and file name
% "ResultArrayPart1 --%shadingArrayPart2 --%shading"

```

The irradiation data taken for result presented here is a generated data of the global in plane and the diffused in plane for a location with latitude of 36.3. The header file of the program used for power loss distribution is shown below

```

%% To make Loss Calculation for Different Inverter Reconnection
% Case Considered: 1MW plant
%
% This algorithm for loss calculation using data generated from an array
% model. The array model is static with two options Central or Team. The
% result generated using the "Central" option is used when inverter
% reconnection which involves a single DC bar. The result generated using
% "Team" option is used where inverters are connected independently.
% No of Inverters=2, 500 KW Inverters

```

The generated data used for the calculation considered a 30% shading of the whole PV generator when the Central option was chosen. To generate equivalent shading, a 20% shading on the first 180 string and a 40% shading in the 2nd 180 string was used when option “Team” was selected. The program plots the I-V and P-V Curve based on the shading condition and the irradiation level. As a demo the program is run for one day with 30% shading of the array. The plots are presented below

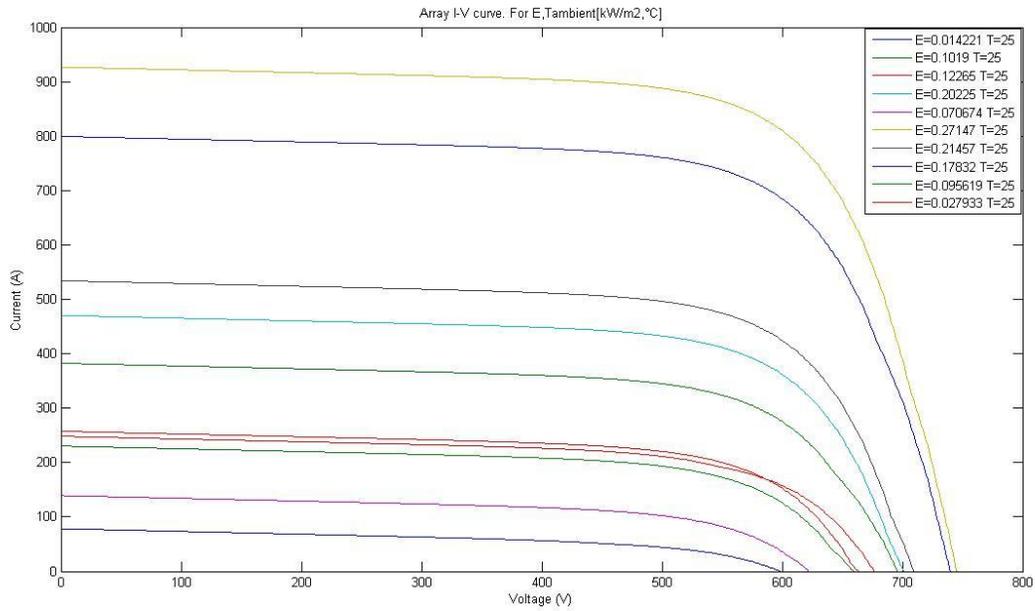


Figure 5.19 PV generator I-V curve for a day with 30% shading: simplified PV generator model used (central option)

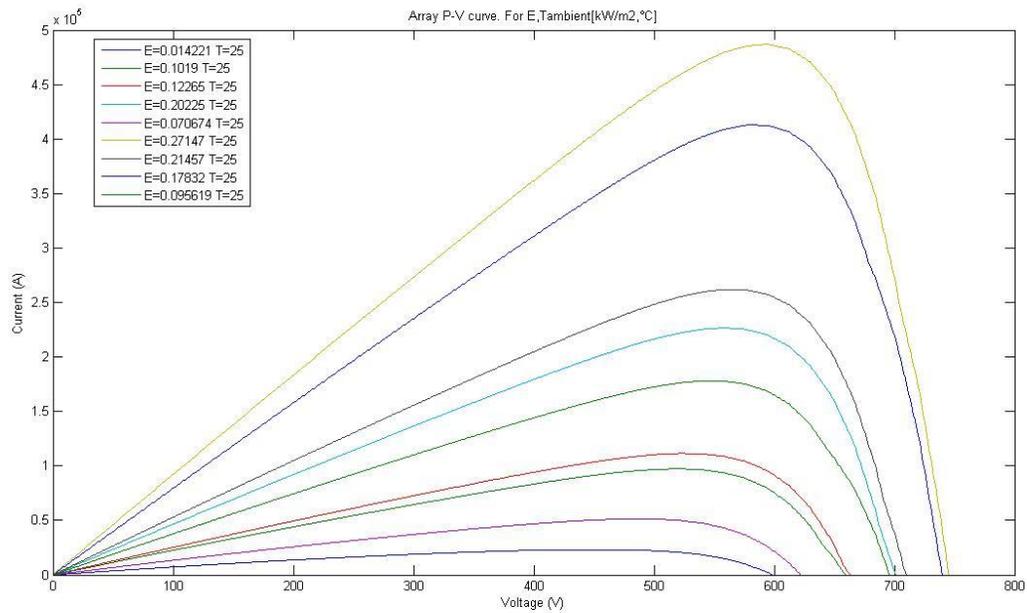
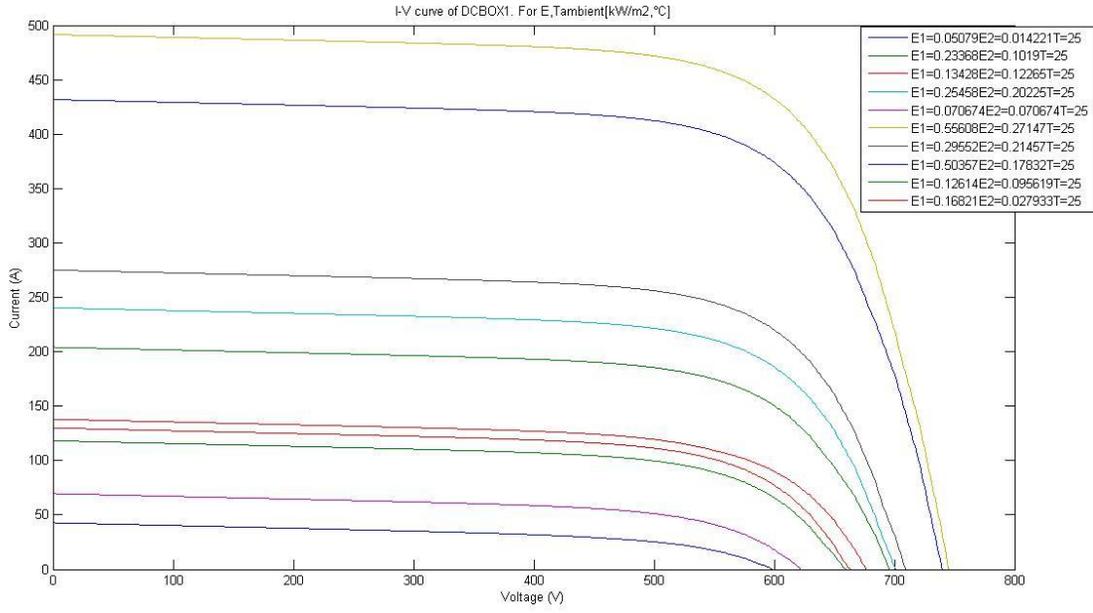
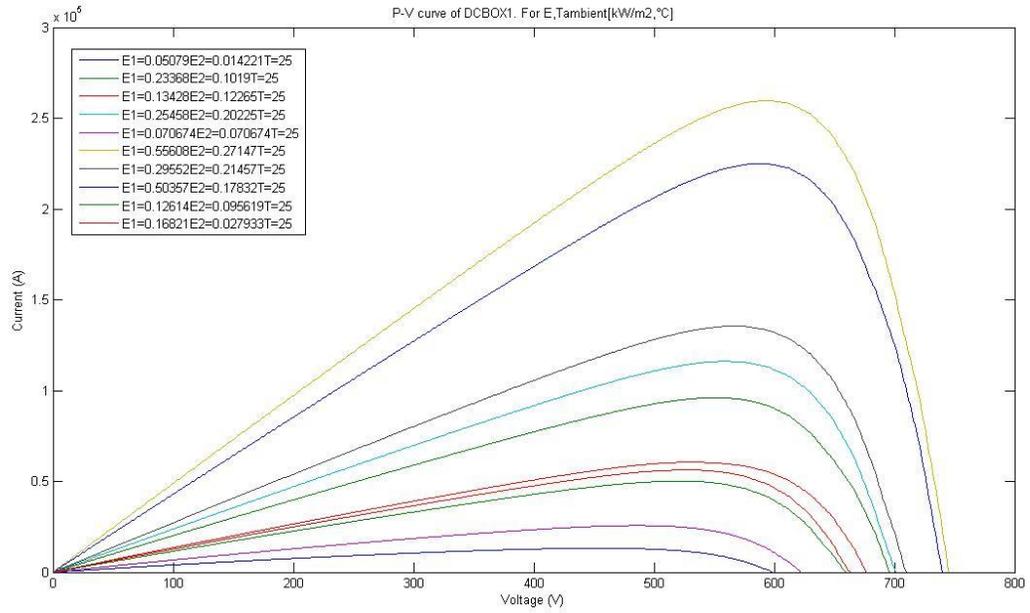


Figure 5.20 PV generator P-V curve for a day with 30% shading: simplified PV generator model used (central option)

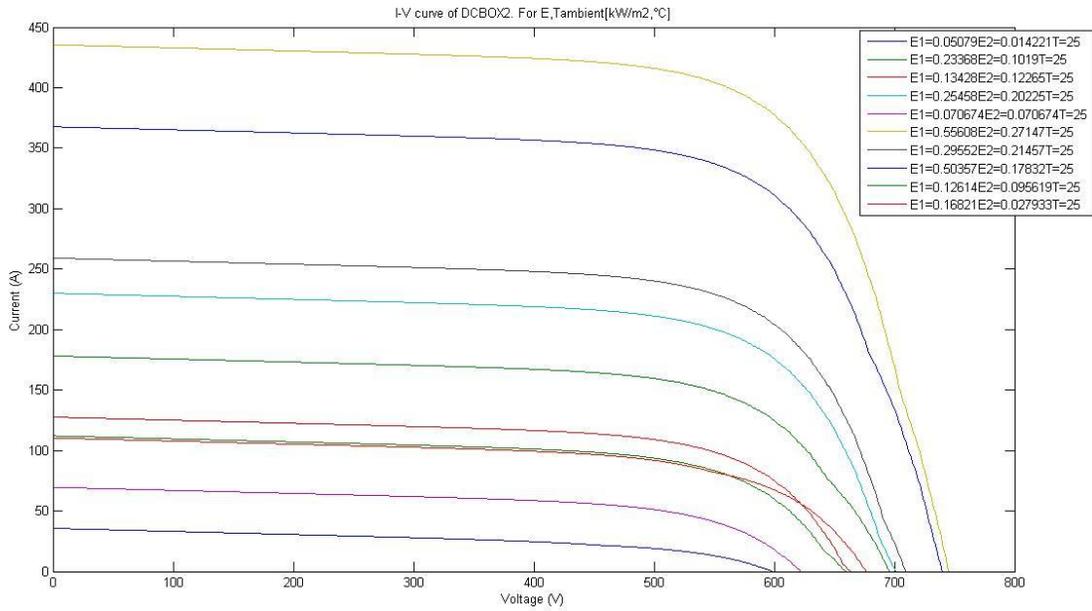
The program then continues to compute the operating point current of the array using the MPP voltage as the operating voltage. The acquired current voltage value for each pair of irradiation value is then saved on to an excel file. The generated I-V and P-V curve of the same day using the team option is shown figure 5.21



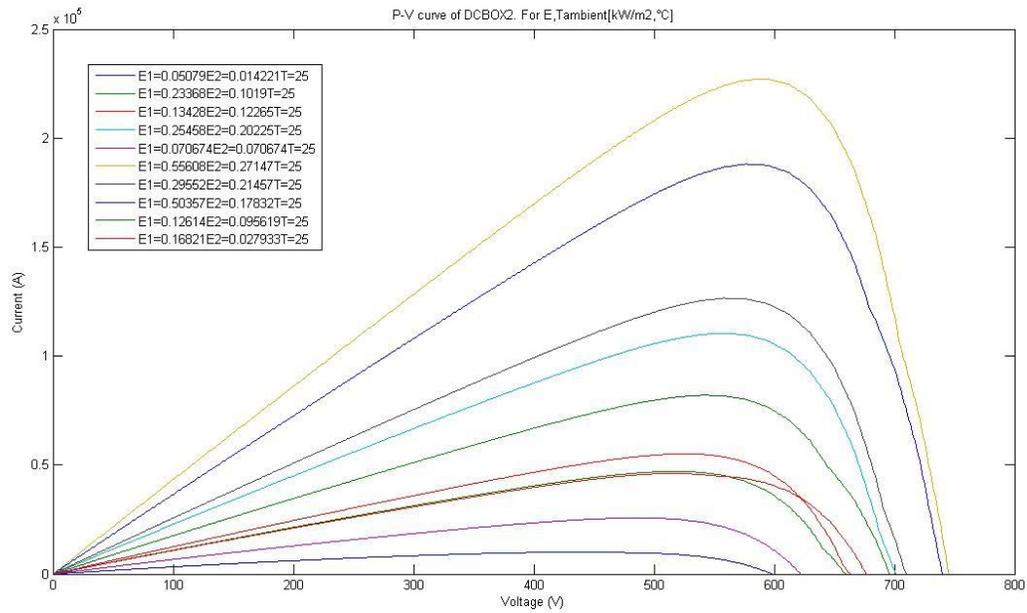
(a)



(b)



(c)



(d)

Figure 5.21 Generated I-V and P-V curve for 20% shading of part 1 and 40% shading on part 2. (a) I-V curve for part 1 (b) P-V curve for part 1 (c) I-V curve of part 2 (d) P-V curve of part 2

The yearly time distribution of the data generated is shown below. Figure 5.22 shows the result when the central option is chosen whereas figure 5.23 shows the result when the team option is selected

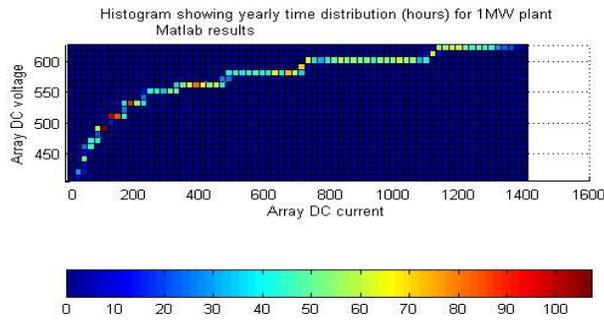
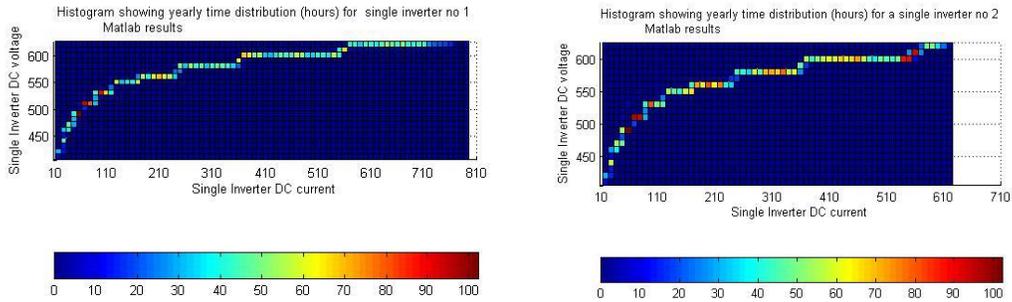


Figure 5.22 The yearly time distribution generated in MATLAB using Central option

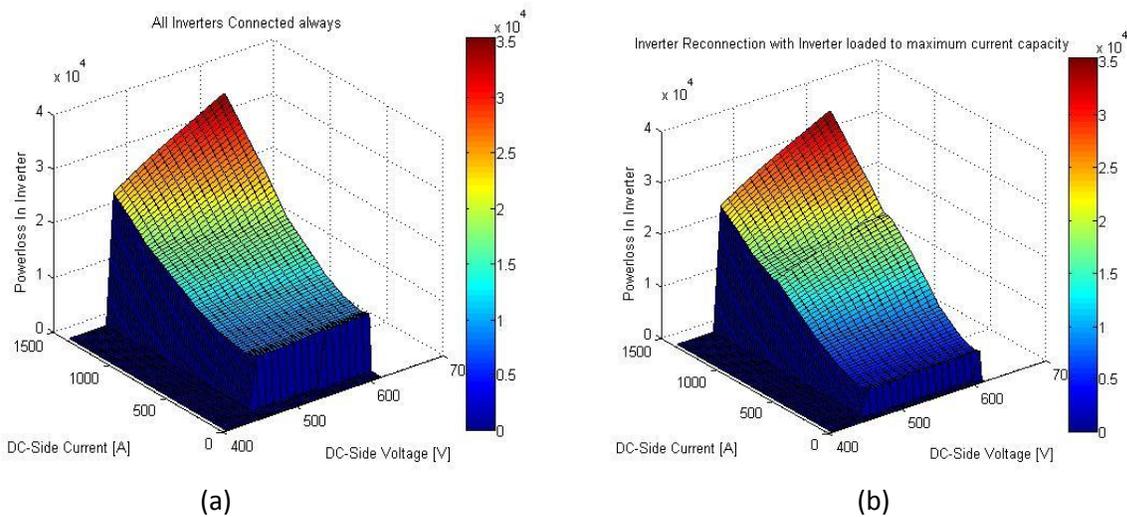


(a)

(b)

Figure 5.23 Shows the yearly time distribution generated in MATLAB using Team option (a) first 180 strings with 20% shading and (b) last 180 string with 40% shading

Quantifying the power loss for the 4 inverter reconnection scheme discussed the power loss distribution as a function of voltage and current is plotted below. The inverter employed are 2, 500 KW inverters.



(a)

(b)

Figure 5.24 Power loss distribution based on data generated using simplified PV generator model (a) All inverters always connected (b) Inverter reconnection with max current loading

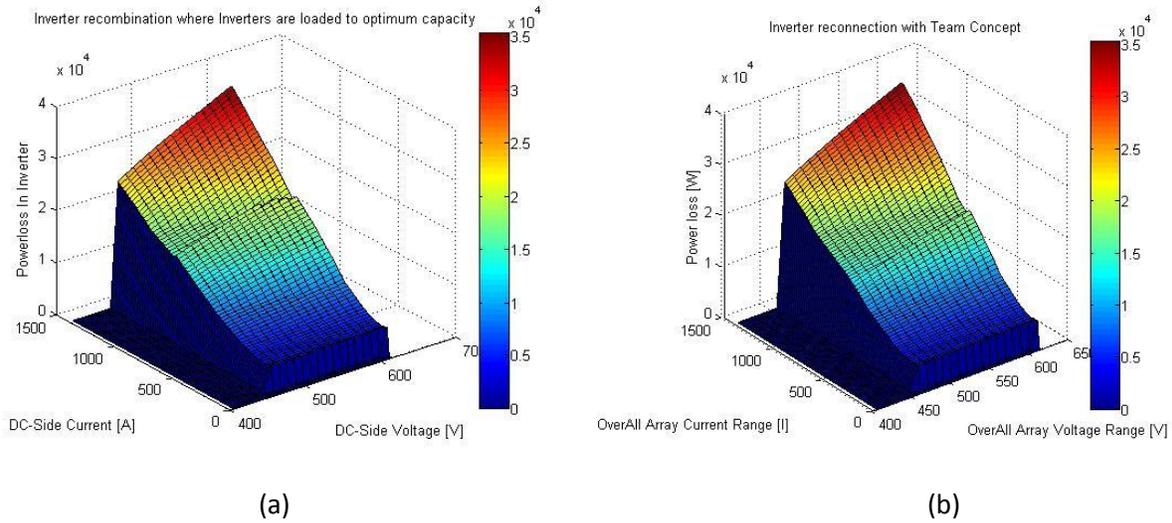


Figure 5.25 Power loss distribution based on data generated using simplified PV generator model (a) Inverter reconnection with optimum inverter loading (b) Inverter reconnection using team concept

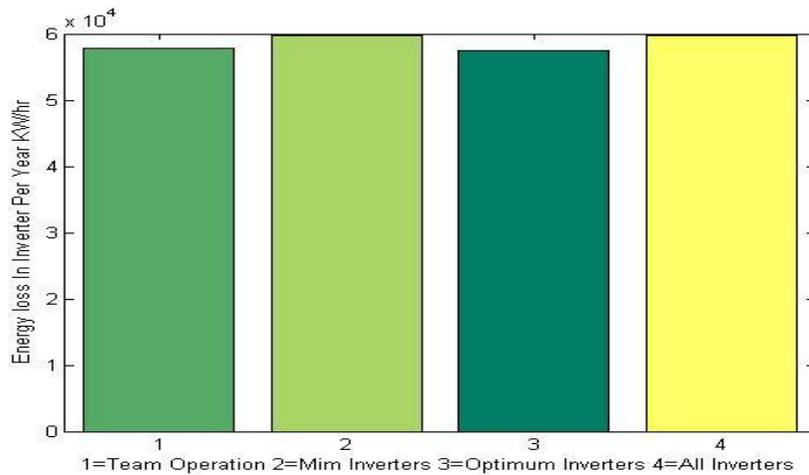


Figure 5.26 The Energy loss for the 4 reconnection scheme: generated data from a simplified array model

The master slave operation where inverters are loaded to their maximum current capacity fails to minimize losses. This is because inverters operated at max capacity have a higher loss and in this scenario the possibility that some inverters remain ideal doesn't exist. The master slave operation where inverters are operated at their optimum capacity shows a good result when few inverters with large rating are employed.

5.4 Partially Shaded PV Generator Modeling

The results for the model developed to generate the I-V curve and P-V curve of a partially shaded PV generator will be presented in this section. Description of terms used to explain the shading condition of the PV generator will be briefly reviewed.

Substring: is composed of series connected modules that are subjected to the same operating condition (equal irradiation and temperature)

String: composed of series connection of substrings which are subjected to different operating condition.

Group: string that have similar shading pattern is termed as group

Array: then several group elements with their respective shading pattern which are connected in parallel making up the solar array

Group No	1	2	3	4	Total
No of substring	3	2	2	1	4
Module in substring	[8 ,6, 4]	[12, 6]	[16, 2]	[18]	
Irradiation	[1, .5, .2]	[1, .2]	[1, .2]	[1]	
temperature	[25, 21, 18]	[25, 18]	[25, 18]	[25]	
No of String in group Group	80	100	120	60	360

Table 4 Shading description input to program: time instant t1

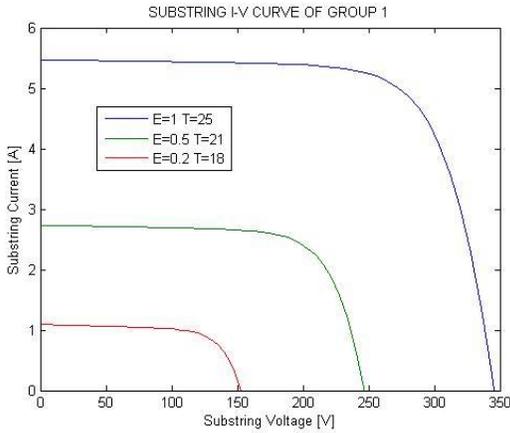
The table above describes the irradiation over the PV generator for one instance of time. The values that is presented in the table is in the same format that is input into the m-file that generates the characteristics I-V and P-V curve of the PV generator. The outlook in MATLAB looks like this

```

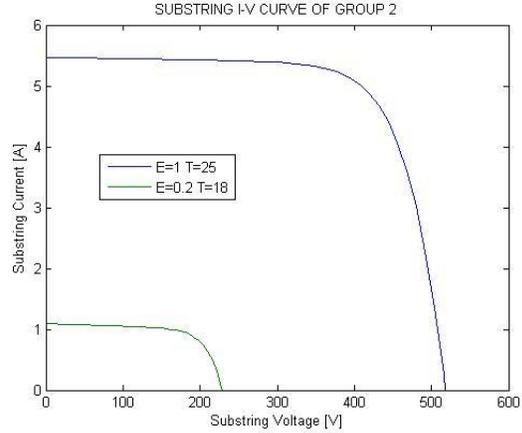
////////////////////////////////////
please enter the number of groups 4
Enter no of substring for group No1 =3
Enter No of module in each substring enclosed in square bracket([])separated by comma = [8,6,4]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,.5,.2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,21,18]
Enter no of string for group No1 =80
Enter no of substring for group No2 =2
Enter No of module in each substring enclosed in square bracket([])separated by comma = [12,6]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,18]
Enter no of string for group No2 =100
Enter no of substring for group No3 =2
Enter No of module in each substring enclosed in square bracket([])separated by comma = [16,2]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1,.2]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25,18]
Enter no of string for group No3 =120
Enter no of substring for group No4 =1
Enter No of module in each substring enclosed in square bracket([])separated by comma = [18]
enter irradiation for each substring enclosed in square bracket([])separated by comma = [1]
Enter the temp for each substring enclosed in square bracket([])separated by comma = [25]
Enter no of string for group No4 =60
////////////////////////////////////

```

The generated I-V curves of all substrings within a string of all 4 Group is shown in figure 5.27



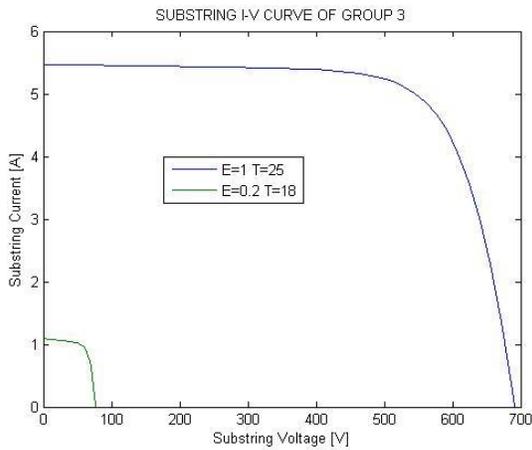
(a)



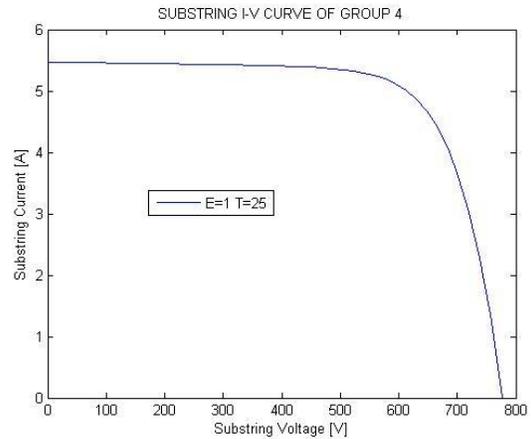
(b)

Figure 5.27 Individual I-V curve of substrings making up a string (a) Group 1 (b) Group 2

The blue curve in figure 5.27 (b) is the resulting I-V curve of 8 modules in series subjected to irradiation equal to 1000W/m² at the temperature of 25 degrees. The pink curve on the same fig represents the I-V curve of 4 modules in series subjected to irradiation of 200W/m² at a temperature of 18 degree. Curves for group 3 and 4 are shown below. Note that in group 4 (fig 5.28 (b)), all modules receive the same irradiation therefore curve in blue represent I-V curve of 18 modules in series subjected to irradiation of 1000W/m² and temperature of 25 degree.



(a)



(b)

Figure 5.28 Individual I-V curve of substrings making up a string (a) Group 3 (b) Group 4

The resultant I-V curve for each group is presented in figure 5.29

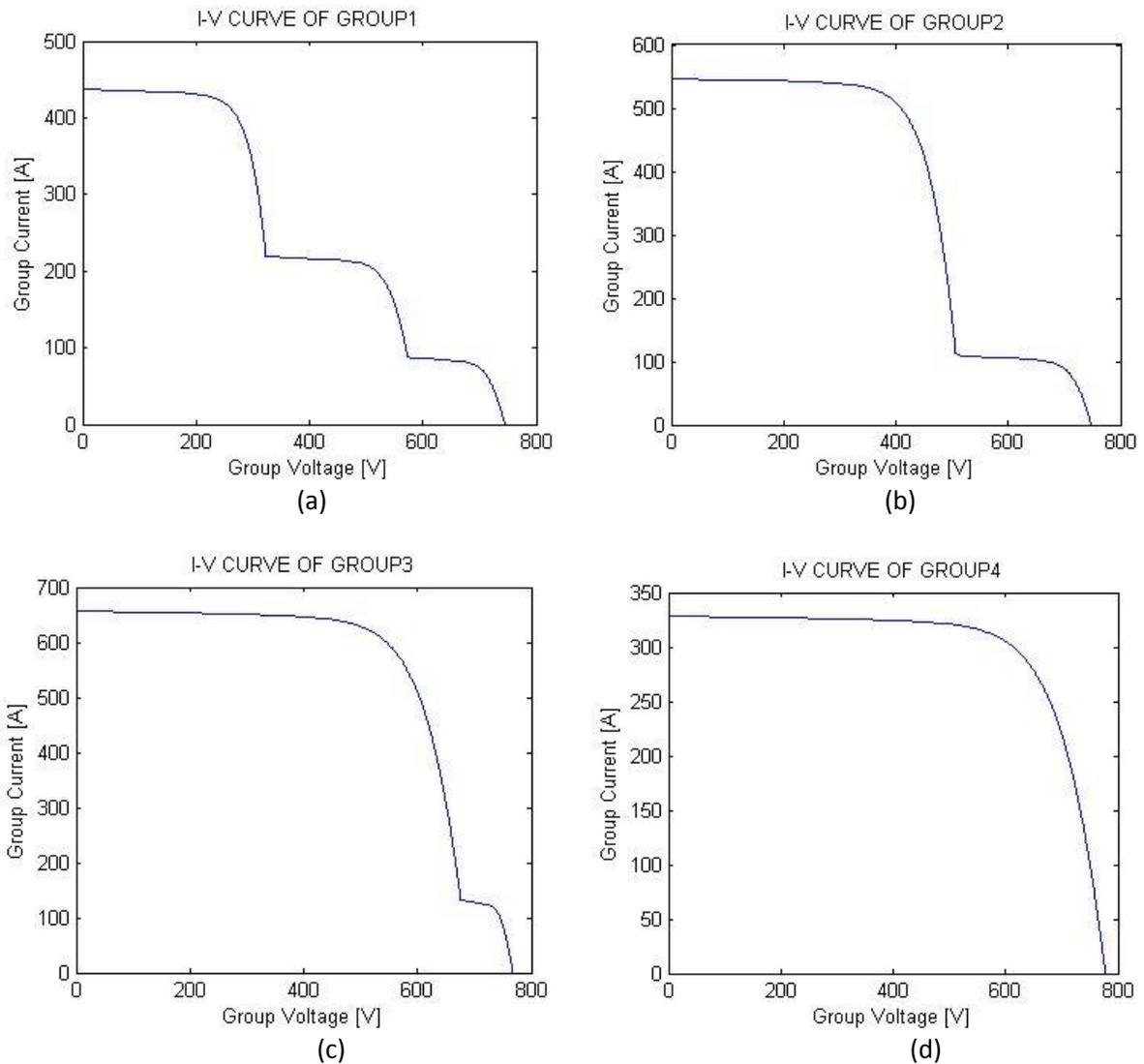


Figure 5.29 Individual I-V curve of each group making the PV generator (a) Group 1 (b) Group 2 (c) Group 3 (d) Group 4

The resultant characteristics I-V curve and P-V curve for the PV generator system is shown in figure 5.30

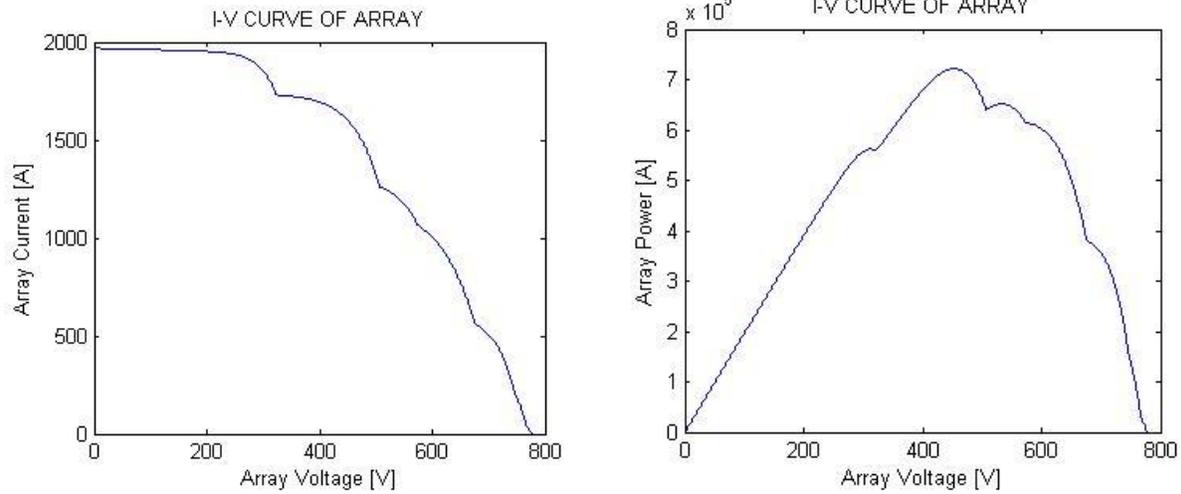


Figure 5.30 The I-V curve of the PV generator for a shading condition described in table 4(left),P-V curve of the PV generator (right)

The output from the program is presented below

```

%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1292.2688 A
% Array Operating Point voltage = 456 V
% Array Operating Point Power = 589.2746 KW
%%%%%%%%%%

```

To create a simplified dynamic shading scenario, a shifting shading condition for 5 time instance following the one illustrated above was simulated. The shading condition was made to shift along the PV generator system until condition of no shading. Table 5 to table 9, describe the shading information that is feed to the m-file to generate the I-V,P-V curve , operating point voltage(V) , Current(I) and power

Group No	1	2	3	4	Total
No of substring	2	3	2	2	4
Module in substring	[10, 8]	[8 ,6, 4]	[12, 6]	[16, 2]	
Irradiation	[1, .5]	[1, .5, .2]	[1, .2]	[1, .2]	
temperature	[25, 21]	[25, 21, 18]	[25, 18]	[25, 18]	
No of String in Group	60	80	100	120	360

Table 5 Shading description input to program: time instant 2(t2)

Group No	1	2	3	4	Total
No of substring	1	2	3	2	4
Module in substring	[18]	[10, 8]	[8 ,6, 4]	[12, 6]	
Irradiation	[1]	[1, .5]	[1, .5, .2]	[1, .2]	
temperature	[25]	[25, 21]	[25, 21, 18]	[25, 18]	
No of String in Group	120	60	80	100	360

Table 6 Shading description input to program: time instant 3 (t3)

Group No	1	2	3	Total
No of substring	1	2	3	3
Module in substring	[18]	[10, 8]	[8 ,6, 4]	
Irradiation	[1]	[1, .5]	[1, .5, .2]	
temperature	[25]	[25, 21]	[25, 21, 18]	
No of String in Group	220	60	80	360

Table 7 Shading description input to program: time instant 4 (t4)

Group No	1	2	Total
No of substring	1	2	2
Module in substring	[18]	[10, 8]	
Irradiation	[1]	[1, .5]	
temperature	[25]	[25, 21]	
No of String in Group	300	60	360

Table 8 Shading description input to program: time instant 5 (t5)

Group No	1	Total
No of substring	1	1
Module in substring	[18]	
Irradiation	[1]	
temperature	[25]	
No of String in Group	360	360

Table 9 Shading description input to program: time instant 6 (t6)

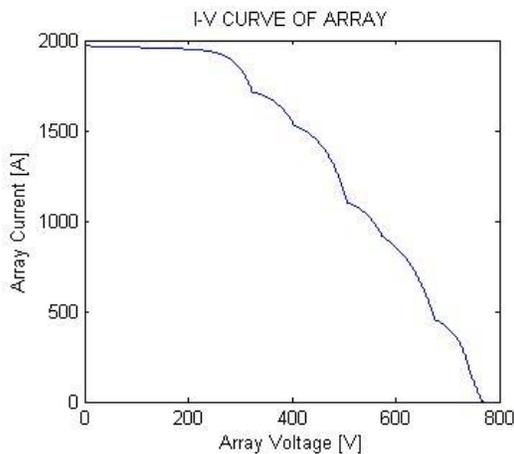
The Generated operating point value, the I-V and P-V curve of the PV generator for the each time instance is shown in the rest of this section

Time instance 2

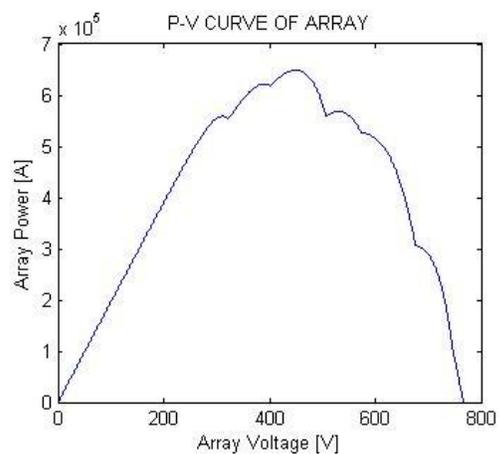
```

-----
%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1428.9802 A
% Array Operating Point voltage = 454.3 V
% Array Operating Point Power = 649.1857 KW
%%%%%%%%%%

```



(a)



(b)

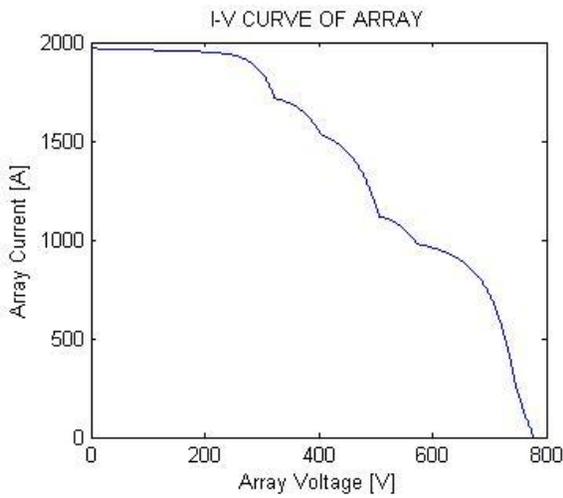
Figure 5.31 The I-V curve of the PV generator for time instance 2 described in table 5(left),P-V curve of the PV generator (right)

Time instance t3

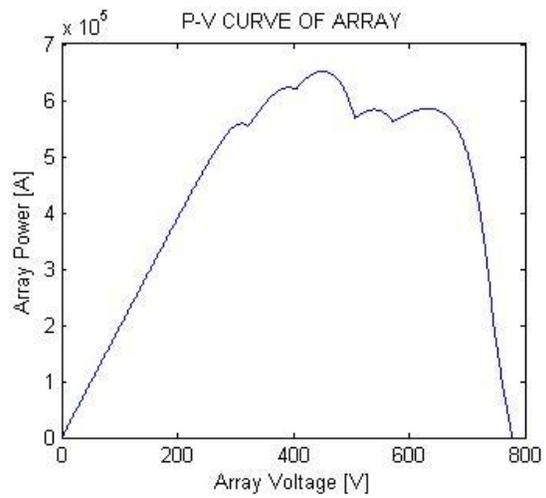
```

-----
%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1430.3112 A
% Array Operating Point voltage = 455.7 V
% Array Operating Point Power = 651.7928 KW
%%%%%%%%%%

```



(a)



(b)

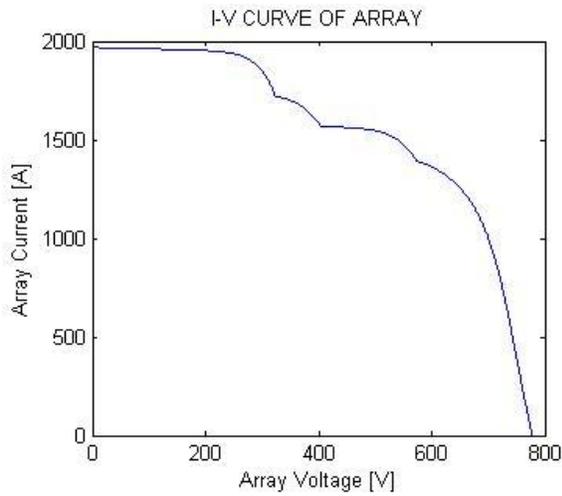
Figure 5.32 (a)The I-V curve of the PV generator for time instance 3 described in table 6(b) P-V curve of the PV generator

Time instance t4

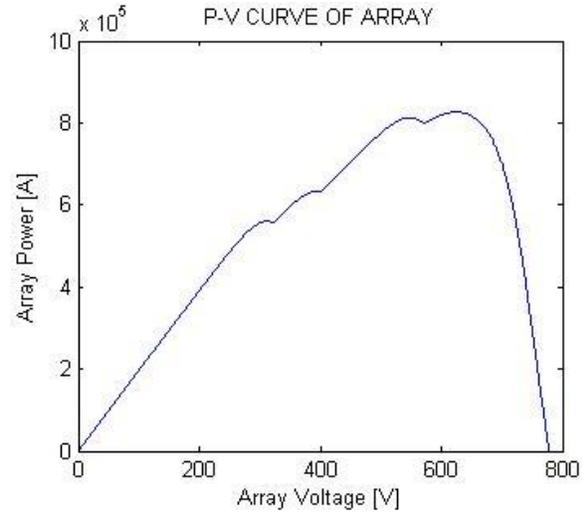
```

%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1313.365 A
% Array Operating Point voltage = 629.7 V
% Array Operating Point Power = 827.0259 KW
%%%%%%%%%%

```



(a)



(b)

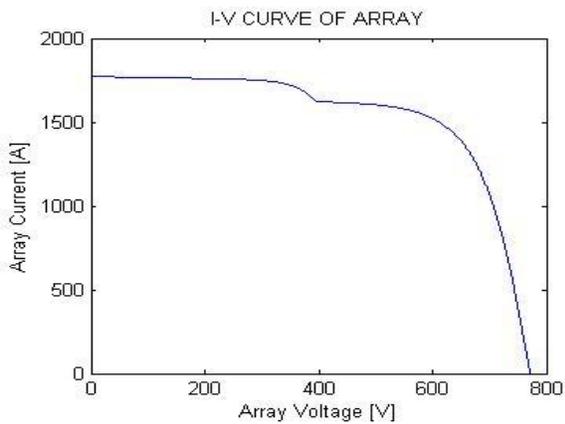
Figure 5.33 (a)The I-V curve of the PV generator for time instance 4 described in table 7(b) P-V curve of the PV generator

Time instance 5

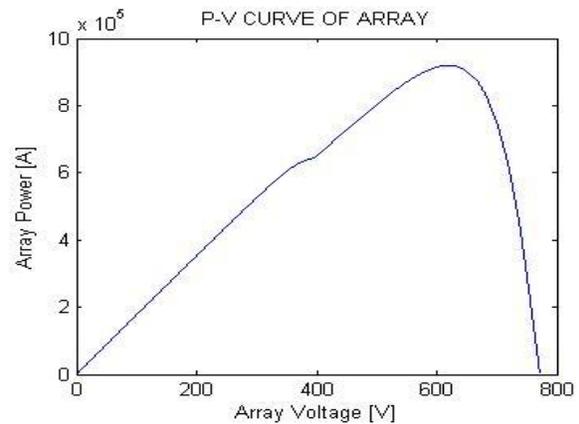
```

-----
%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1486.6802 A
% Array Operating Point voltage = 618.6 V
% Array Operating Point Power = 919.6604 KW
%%%%%%%%%%

```



(a)



(b)

Figure 5.34 (a)The I-V curve of the PV generator for time instance 5 described in table 8(b)P-V curve of the PV generator

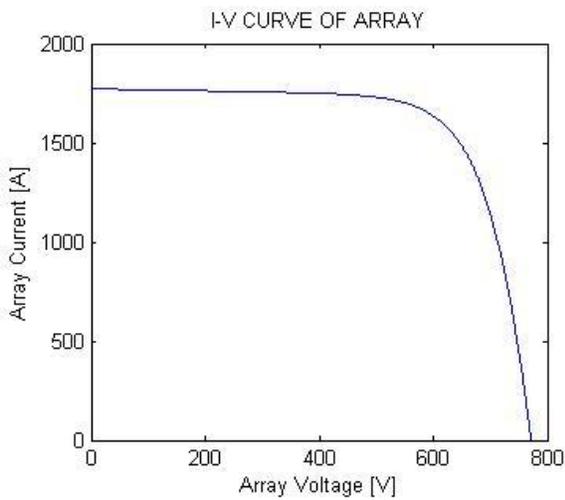
Time instance 6

During time instance 6, it is assumed that no shading exists. The plot represents the output of the array for a uniform shading condition of 1000W/m²

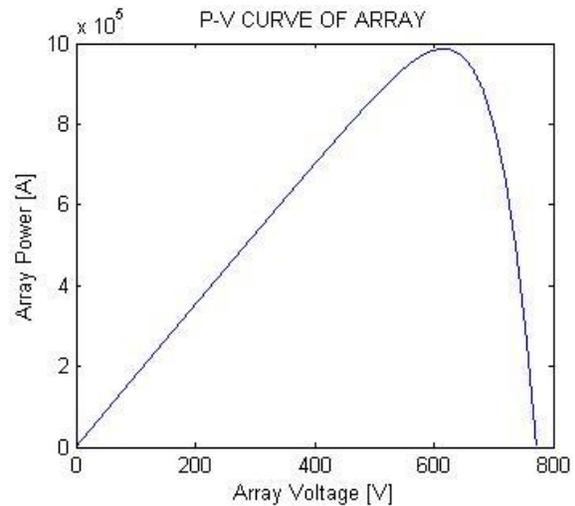
```

-----
%%%%%%%%%%
%      Generated operating point value
%-----
% Array Operating Point current =1612.6285 A
% Array Operating Point voltage = 612.1 V
% Array Operating Point Power = 987.0899 KW
%%%%%%%%%%

```



(a)



(b)

Figure 5.35 (a)The I-V curve of the PV generator for time instance 6 described in table 9(b)P-V curve of the PV generator

5.5 Module Based Modeling

The result taking the last approach explained in section 4.2.1 will be presented below. The model was developed for a 4 module PV generator, 2 modules in series forming a string with 2 strings in parallel. The first module of the first string and the 2nd module of the 2nd string received full irradiation of 1000W/m² where as the 2nd module of the 1st string and the 1st string of the second module received reduced irradiation of 500W/m². The result of the simulation is presented below

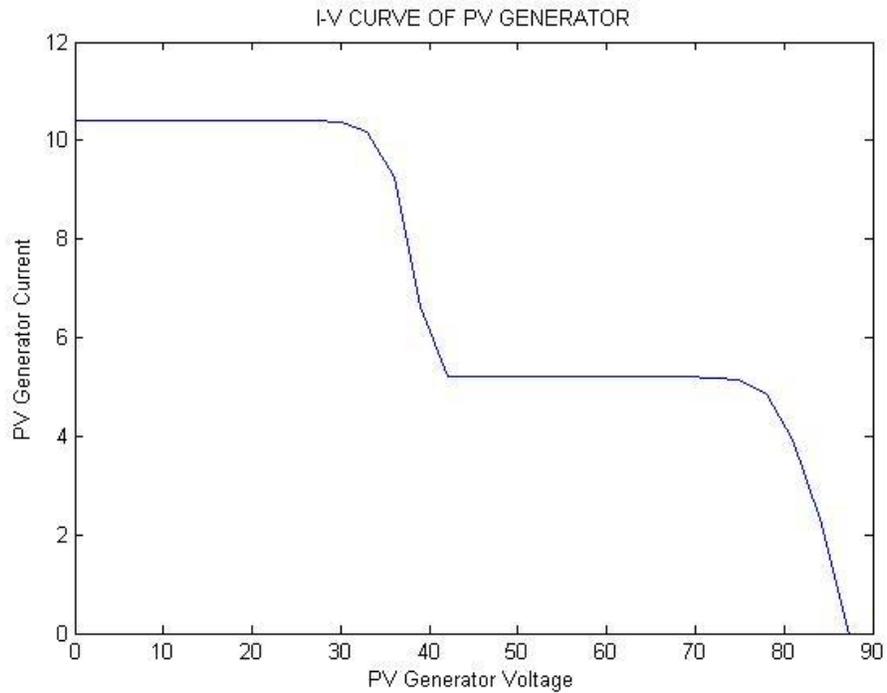


Figure 5.36 I-V characteristics Curve of a 4 module PV Generator: using Module based model

The I-V characteristic of the PV generator was simulated using the partial shaded PV generator model using the same shading pattern. Both curves are plotted in the same figure.

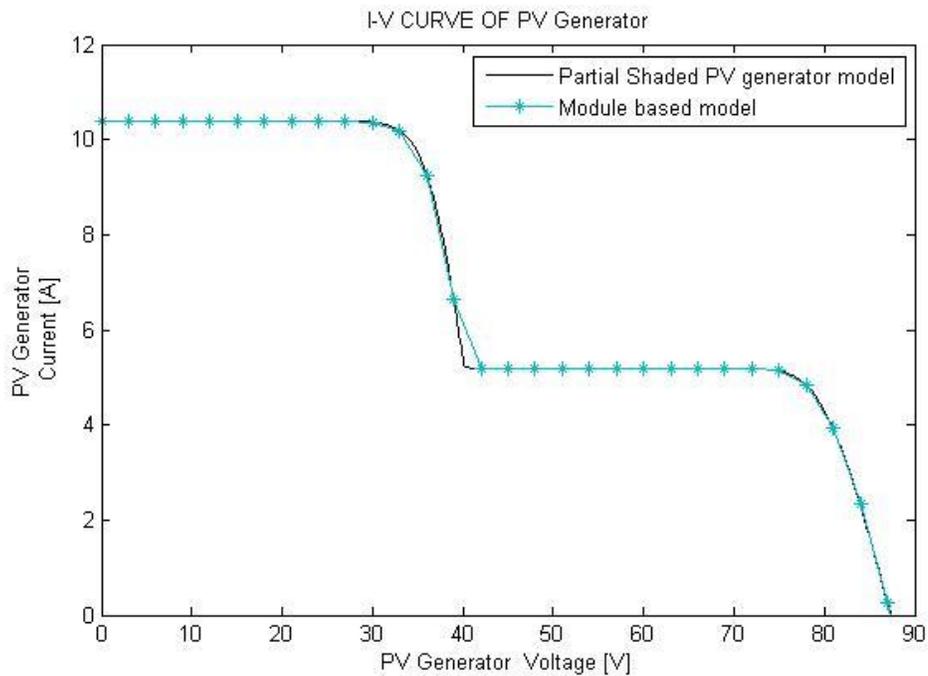


Figure 5.37 I-V Characteristic curve of 4 module PV generator: black line using partial shaded PV generator model, blue line using module based model

A little fitting error can be related to large increment value of voltage used when running the module based model. This was done to reduce the computational time; a better fit is expected if the smaller voltage increment is used.

6 Conclusion and Future work

Inverter reconnection methods

The classical inverter connection method where all inverters are connected in parallel shows the worst power loss profile especially in the low generation region. The master-slave reconnection based on maximum current loading shows the best profile when generation is low, but is seen to produce higher loss under full power production. The master slave reconnection based on optimum loading of inverters shows the most promising results since in this method it is so that the inverters are operated around their highest operation point. The data generated using PVSyst or any other PV simulation program cannot be sufficient to do loss calculation and arrive at a solid decision which reconnection scheme has the best benefit. The loss reduction potential of the team reconnection method based on generated data isn't so promising. This can be because under this operation power rerouting is limited among adjacent inverters. The overall loss reduction potential between the different methods would be more represented if actual generation data from the park is used instead of software generated data.

Module based modeling.

To develop a model for a large PV generator considering each module equivalent circuit parameter dependency on irradiation and temperature becomes computationally complicated. If a mechanism for determining the value of $I_{ph}(E,T)$, $I_o(E,T)$, R_s , R_p and A_o without having to solve the five implicit equation, the number of function to be minimized can be reduced. One suggestion could be developing an artificial neural network that can take irradiation and temperature as input and produce this value as output. The neural network can be trained based on measured data or generated data using the two diode model of a PV module [12].

The simplified PV generator modeling can be modified to include variation of irradiation along the string. This improves the model's ability to simulate partial shading over a PV generator system.

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Appendix A: Research on Cloud Effects on PV Generator system

A study performed based on 28 PV system installed on house which all feed to the same feeder [19]. The study was performed to verify no serious problem arise when high penetration of distributed PV generation occurs in the electrical distribution system. Measurement of irradiation was done using five pyranometers distributed across the area of observation. From the measurement of the five pyranometer, the time when the area was shaded and illuminated can be determined. As described in his method, the cloud shadow passage over all the sensors were thereby described by five pair of time measurements. A model for the site irradiance is developed and it assumes that cloud shadow created are always circular and the cloud moves at a constant speed. According to the author a least square method was used to determine the cloud diameter, the velocity at which it moves and the position of cloud center when the edge is detected. Based on this, the developed model is used to reconstruct the irradiance for a point in the site. The irradiance is at a point is assumed to take the value corresponding to cloud coverage or full sunlight

This is a method used to develop a model to estimate isolation under cloudy sky conditions [15]. It first defines 6 characteristics that describe a cloud pattern.

1. Size of cloud
2. Shape of cloud
3. Percentage of sky coverage
4. Direction of movement and speed of cloud
5. Optical transmission of cloud
6. Optical variation of cloud from its center to its edge.

The work down was considering cumuliform clouds although the author claims can be applicable to other type of cloud.

Determining of cloud size and shape: For small, large and stormy weather cumuliform clouds, the size of the cloud and their occurrence frequency within a cloud pattern was observed and recorded. It was conducted based on statistics done by the aerospace corporation on cumuliform cloud [20]. Equation describing the discrete probability (Q) of a cloud of area A of occurring for small, large and stormy weather cumuliform clouds was derived.

$$\begin{aligned} Q &= 16.086 - 16.256 \ln A & 0.100 < A < 2.690 & \quad (a) \\ Q &= 14.754 - 6.363 \ln A & 0.100 < A < 10.163 & \quad (b) \\ Q &= 10.500 - 3.061 \ln A & 0.100 < A < 30.884 & \quad (c) \end{aligned} \quad 3.53.$$

Area expressed in square nautical miles. To estimate the cloud size, a stochastic model was developed. In the stochastic model a cloud area will be generated for each simulated cloud. For this a cumulative distribution function which gives the probability of a cloud of size a or less is occurring is derived.

$$\begin{aligned}
F(a) &= a(0.880 - 0.442\ln a) - 0.180 & 0.100 < A < 2.690 & \quad (a) \\
F(a) &= a(0.346 - 0.104\ln a) - 0.059 & 0.100 < A < 10.163 & \quad (b) \\
F(a) &= a(0.147 - 0.033\ln a) - 0.022 & 0.100 < A < 30.884 & \quad (c)
\end{aligned}
\tag{3.54}$$

A random generator will be used to generate a number between 0 and 1 and that value is substituted for the value of $F(a)$ in one of the equation of 3.54. The equation is then solved for the value of “a” which is the area of the cloud. Iterative method is used to determine the value of a. As a simplification the shape of a cloud was assumed to be rectangular. The width (W) to length (L) ratio of each cloud was chosen to be

$$W = 0.582L \tag{3.55}$$

Percentage coverage: which is the percentage of cloud covered, can be made to vary from a very low value representing few clouds to 100% representing total coverage. **Cloud speed:** range will be estimated based on wind speed and height of cloud. **Optical transmission:** The mean transmittance of cloud of type i is given by

$$transmittance = x(i)' + y(i)' m \tag{3.56}$$

Where $x(i)'$ and $y(i)'$ are transmittance coefficient of a cloud [21]. Their value for cumulus cloud is $x'=0.366$ and $y'=0.015$. m Stands for air mass which is dependent on the sun’s angle and is given by

$$m = \frac{35}{(1224\cos^2 Z + 1)^{1/2}} \tag{3.57}$$

Where Z = zenith angle of the sun. The irradiance with the shadow is then determined by multiplying the clear sky isolation with the transmittance value.

Optical variation of cloud from edge to center: the assumption taken was a transition from a condition of full sun to full cloud. Using the 6 characteristics a cloud pattern is generated; once this is generated it is made to move across the service area. This helps in determining the isolation level of any point within the service area.

The other work related to shadow evaluation was done to evaluate the reduction of irradiance due to shading by surrounding objects [16]. The model calculates the irradiance on a tilted surface taking into consideration the shading reduction.

Assumption taken is that the irradiance on a horizontal or tilted plane is measured on a surface without any shading. The method first explains how to describe a surrounding of the shaded surface. A reference point on the surface is chosen and cylindrical coordinate system is used to describe the azimuth angle and the height angle for an object in the surrounding. The surrounding is surveyed and expressed in cylindrical coordinate system. The different structures can be described using polygons. The result from the survey can be displayed alongside the sun orbit diagram to determine when shading is likely to occur. But only helps to determine the time and duration of shading. The method continues to determine a shading factor for the direct and diffused irradiance. For the direct irradiance the methodology was to determine if the sun’s position falls inside the polygon or outside. If it falls inside shading factor of 1 is used assuming the object in question is opaque. If it falls outside the polygon, no shading exists and shading factor equals zero. A polygon point containment test is used to determine if the sun position falls

inside or outside. How the shading factor for the diffused irradiance element is calculated is beyond the scope of this report and can be found in the paper [16]

D.D.Nguyen, B.Lehman and Sagar Kamarthi in their work used artificial neural network to predict the maximum power output of an array under shadowing condition. This work is again for shadowing caused due to nearby stationary objects. A shading function is defined that express the relationship between the power output of the array and environmental factor such as irradiation level, solar azimuth and elevation angle, ambient temperature. In their method, the shading function is determined using neural network. Measurement data of the power output and ambient temperature for a particular time was done on a solar PV array with shaded condition during certain time in a day. The irradiance level is also measured. The solar position defined by two angles is calculated from the time, latitude and longitude of the area [17].

A study carried out in Wichita State University to see the effect of PV generator output dependency on sunlight [18]. The study was carried out to assess the effect of PV rapid change in generation on a partially cloudy day. Data measurement was taken on a one second interval at the corner and at the center of a 30 meter square area in Wichita. Based on the data, the movement of cloud shadow was studied. The study was carried out to determine how the utility reaction to rapid variation of generation caused by cloud shadowing.