STUDY, DESIGN AND PERFORMANCE ANALYSIS OF PHOTOVOLTAIC POWER GENERATION SYSTEM

A Thesis Submitted

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Approval Sheet

This thesis entitled Study, Design and Performance Analysis of Photovoltaic Power Generation System by Rabindra Nath Shaw is approved for the degree of Doctor of Philosophy.

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis, entitled "Study, Design and Performance Analysis of Photovoltaic Power Generation System" in fulfillment of the requirements for the award of the degree of Doctor of Philosophy in Faculty and submitted in Galgotias University, Greater Noida is an authentic record of my own work carried out during a period from September 2017underthesupervisionofDr. Pratima Walde.

The matter embodied in this thesis has not been submitted by me for the award of any other degree of this or any other University/Institute.

(Rabindra Nath Shaw)

This is to certify that the above statement made by the candidate is correct to the best of our knowledge.

(**Dr. Pratima Walde**)
Supervisor

The Ph.D. Viva-Voiceexaminationof**Rabindra Nath Shaw**has been held on___________.

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ABSTRACT

Recently, the electrical power industry has shifted its focus towards the Renewable energy system. This shift is done in order to mitigate the problem of ever-increasing power demand as well as to reduce the carbon emission to safeguard the environment from the adverse effects of burning of fossil fuels. Renewable energy is a form of energy that is naturally obtained from the environment and from sources that can be replenished naturally. The renewable energy sources are cleaner source of energy and they do not dissipate heat to the environment that is responsible for global warming. Solar and wind energy are the most promising available renewable energy sources which have continuously attracted the attention of researchers. Residential solar energy systems correspond to an investment in the future of the world, conserving non-renewable energy sources and protecting the environment. The technology in the solar power industry is constantly advancing.

The increasing penetration of the renewable energy sources into the grid is fruitful for the utilities from the sustainable point of view and it provides economic benefit for long-term operation. The reliable and secure energy supply has become the utmost important thing for the modern society and this has led to the concerns to be raised towards increasing renewable energy penetration with its intermittent nature. The utility companies may be concerned about the implications of variable solar generation on the power quality, its impact on the low-tension (LT) distribution grid. Therefore, there are lot of challenges and issues in integrating distributed energy sources like Photovoltaic (PV) systems.

The grid integrated system has some responsibility to maintain a reliable grid supply with respect to harmonics, flicker, and DC injection as they are connected to a power system network. Hence due to the power quality problems power converters are required for interface with the grid. Solar photovoltaic (PV) needs power electronic converters like DC to DC and DC to AC in order to make interconnection.

Apart from the several benefits offered by the solar energy, the solar PV system suffers from two these two main challenges:

(i) The energy conversion efficiency of a commercial PV system is not more than 16% or 17%, especially when the irradiation level is less than standard test condition (STC).

(ii) The power generated from the PV system continuously varies with the variation in the atmospheric condition. Moreover, the characteristic of the PV array is non-linear, and thus, the current and voltage vary with the irradiation and temperature.

In order to tackle these challenges the maximum power point on the P-V curve, with the unique characteristic is tracked continuously for harnessing the maximum solar energy. At this point, the whole PV system (array, converter, inverter, etc…) operates at its maximum efficiency and tries to obtain maximum generated power. Thus the most important part of harnessing the solar energy is to track the maximum

power point of the solar PV system. To achieve maximum efficiency, it is necessary to locate the system at MPP.

Other environmental factors which effect the output of any PV system are (i) shadowing, (ii) dust and dirt, (iii) snow, bird droppings etc. out of these shadowing is one the biggest concern that decreases about half of the efficiency of the PV panels according to the place where the solar panels is mounted. Hence some mechanism is needed in respect to increase the output of solar panel and maximize the more amount of solar energy get it converted into the electrical energy.

Researchers have drawn lots of interest on the problem of partial shading and its mitigation as impact of partial shading condition affects the performance and reliability of photovoltaic system. The safe operational temperature limit of PV cells is about 85˚C, but because of partial shading condition, it reaches up to 150˚C which exceeds the safe operational limit. This high temperature causes hot spotting or local over heating which can damage PV modules. Hotspot (local over heating) is the most commonly occurred phenomenon which limits the operation life of PV cells. To produce the desired photon current and terminal voltage, series and parallel connection is used between PV cells.

The photon current flowing through each series connected PV cells has to be equal for better performance of PV module. But this is not possible during partial shading condition, in such situation shaded cell get reverse biased and act as a load. Large number of researchers drawn interest on impact of partial shading and its mitigation techniques. To avoid the reverse breakdown of PV cells due to partial shading condition, a diode is connected across the shaded PV cells to carry the reverse bias current. By diverting the reverse bias current, creation of hotspot on the PV cells can be avoided.

These mitigation techniques are very worthwhile to enhance the performance of PV system but cause additional cost, more power consumption and reduce the reliability of the PV system. The efficiency of a photovoltaic system is very low and depends upon various parameters like irradiance; temperature levels etc. In addition to that, a shadow upon the solar panel affect extensively on the efficiency of the Photo Voltaic system. Output of PV arrays is decrease due to partial shading condition. Modules of the photo voltaic array receive unbalance solar irradiation because of partial condition, so the PV arrays exhibit number of different peaks in I-V and P-V curve. During partial shadow condition efficiency of the PV array gets tremendously affected. This Ph.D. work presents the detailed steady state modeling of the solar PV system and its integration to the GRID for future operations and avoiding the problem of partial shading.

In this thesis, an extensive literature review of photovoltaic system for various aspects has been done. A good understanding of MPPT and different PV array design for different condition is very much required for installation of PV system in partial shading region. Various MPPT algorithms and various PV system topologies for partial shading condition have investigated here. However, none of these MPPT techniques may be called the best, because, the choice of MPPT depends upon the application, weather condition, accuracy, reliability and convergence time, of the system. The same theory applies on the different topologies also. The configuration of PV cell connection is totally depends on the environment, weather condition, shading effect and reliability of the system. This survey has helped the candidate in further research in this area which would be beneficial for producing efficient, clean and sustainable solar energy to the mankind.

This Thesis firstly studied on the performances of PV module/cell in a 4array is affected due to shadow cast upon it. Output power of the PV arrays gets reduced because the solar irradiation received by the PV array during the partial shading condition is different as received during no shading condition. A new model for configuration of Photo voltaic array has been presented in this work and its performance has been studied. The performance analyses for other classical configurations like SP, BL, TCT,HC, BL-HC, BL-TCT, HC-TCT and SP-TCT have also studied. The shade dispersion effect on PV array with various configurations is also investigated. Different partial shading patterns are applied to photo voltaic module to assess the performance of different PV array configuration. Simulation results show the efficacy of proposed Su-Do-Ku configuration for photovoltaic array. Results clearly show that, the proposed Su-Do-Ku configuration has enhanced the output power and performances and is better than the other configurations with puzzle shade dispersion and different partial shading conditions.

In addition to the above work a new model for Photo Voltaic array configuration has been developed, and its efficiency has been studied. Here it proposes a new PV system design to enhance PV system performance under partial shade conditions. This design uses different PV modules rearrangement techniques. In the presence of different shading patterns, the performance analyses of the PV array (9x4) with the proposed configuration and some other configurations have been performed. Performance analyzes have been carried out for different configurations and the obtained voltage, current, power have been considered as output parameters. The shade dispersion effect on PV array with various configurations has also examined. Simulation results show the effectiveness of NS-PVF for the photovoltaic array in 9x4 configuration. Results evidently demonstrate that shading cases on these topologies results in a rise in the non-linear effect and in many cases causing multiple maxima. NS-PVF has shown better performance for all kinds of shading cases.

Further this Thesis presents the novel approach for the maximum power extraction from the solar PV panels efficiently by using the IOT system, the proposed technique ensures the global power optimization for photovoltaic generators irrespective of the irradiance conditions. Individual MPPTs have been implemented and comparative analysis studied for with and without IOT systems and the results depicted that the overall efficiency of the photovoltaic energy production system is increased. Thus a reliable, high quality and more efficient power can be provided to the consumer by the PV grid.

In this thesis, the effect of change in load and irradiance on photovoltaic integrated power system network has investigated. The power system network considered here is IEEE 14 bus system. The simulation is done on MATLAB platform by studying the variation in the three parameters, i.e., Voltage, Power and THD (Total Harmonic Distortion). The results indicates that how power quality of the power system is affected by the irradiance on Photovoltaic cell. The study is performed considering the other environmental factors such as wind velocity, ambient temperature and humidity have a negligible effect on the photovoltaic module. In a steady-state controlled environment, the simulation results depicts that the output voltage, current and its power decrease with time as the irradiance on the photovoltaic panel decreases.

The present Thesis work is step forward to develop better technique for improvement of PV System. Therefore, the presented research carried out is expected to be very useful tool to the researchers working in this area and also to all the industries excelled in generating an efficient, clean and sustainable energy to the mankind.

Keywords: PVsystem, MPPT, Partial Shading, GRID integration, PV array topology, IOT.

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Greater Noida (Rabindra Nath Shaw)

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List of publications from the thesis

(Journal)

1. R. N. Shaw, Pratima Walde and Ankush Ghosh, "Review And Analysis of Photovoltaic Arrays With Different Configuration System In Partial Shadowing Condition", International Journal of Advanced Science and Technology, Vol. 29, No. 9s, (2020), pp. 2945-2956. (**Scopus Indexed)**
2. R. N. Shaw, Pratima Walde and Ankush Ghosh, "Enhancement of Power and Performance of 9x4 PV Arrays by a novel arrangement with shade dispersion", Test Engineering and Management, ISSN: 0193 - 4120 Page No. 13136 – 13146, 2020. (**Scopus Indexed)**
3. R. N. Shaw, Pratima Walde and Ankush Ghosh,"Effects of Solar Irradiance on Load Sharing of Integrated Photovoltaic System with IEEE Standard Bus Network", International Journal of Engineering and Advanced Technology,Volume9 Issue-1, October 2019. (**Scopus Indexed)**
4. R. N. Shaw, Pratima Walde and Ankush Ghosh,"A New Model to Enhance the Power and Performances of 4x4 PV Arrays with Puzzle Shade Dispersion", International Journal of Innovative Technology and Exploring Engineering , Volume-8 Issue-12. (**Scopus Indexed)**

(International Conference)

5. R. N. Shaw, Pratima Walde and Ankush Ghosh, "IOT Based MPPT for Performance Improvement of Solar PV Arrays Operating Under Partial Shade Dispersion", 2020 IEEE 9th Power India International Conference (PIICON) held at DeenbandhuChhotu Ram University of Science and Technology, SONEPAT. India on FEB 28 - March 1 2020. (**Scopus Indexed)**

List of presentation in International Conference:

1. R. N. Shaw, Pratima Walde and Ankush Ghosh, "IOT Based MPPT for Performance Improvement of Solar PV Arrays Operating Under Partial Shade Dispersion", 2020 IEEE 9th Power India International Conference (PIICON) held at DeenbandhuChhotu Ram University of Science and Technology, SONEPAT. India on FEB 28 - March 1 2020

List of Abbreviations and Symbols Used

Abbreviations	Description
MPP	Maximum power point
MPPT	MAXIMUM POWER POINT TRACKING
RESS	RENEWABLE ENERGY SOURCES
PV	PHOTOVOLTAIC
STCS	STANDARD TEST CONDITIONS
PSCS	PARTIAL SHADING CONDITIONS
GP	GLOBAL PEAK
LP	LOCAL PEAK
SP	SERIES PARALLEL
TCT	TOTAL CROSS TIED
BL	BRIDGE LINKED
P&O	PERTURB & OBSERVE
Impp	PANEL CURRENT AT mpp
Vmpp	PANEL VOLTAGE AT mpp
Vpv	PANEL VOLTAGE
Vb	BATTERY VOLTAGE
Vdc	DC LINK VOLTAGE
Ipv	PANEL CURRENT
Ib	BATTERY CURRENT
iL	INDUCTOR CURRENT
Cp	POLARIZATION CAPACITOR
Vcb	ELECTROMOTIVE FORCE (IN VOLTS)
Iph	PHOTON GENERATED CURRENT
Id	CURRENT THROUGH DIODE
P	POWER
KW	Killo Watt
mW	milli Watt
η	EFFICIENCY

Chapter-1

Introduction & Organization of the Thesis

1.1 Introduction

1.2 Organization of the Thesis

1.1 Introduction

Recently, the electrical power industry has shifted its focus towards the Renewable energy system [1.1-1.5]. This shift is done in order to mitigate the problem of ever-increasing power demand as well as to reduce the carbon emission to safeguard the environment from the adverse effects of burning of fossil fuels. Renewable energy is a form of energy that is naturally obtained from the environment and from sources that can be replenished naturally. The renewable energy sources are cleaner source of energy and they do not dissipate heat to the environment that is responsible for global warming. Wind and solar energy are the most promising available renewable energy sources which have continuously attracted the attention of researchers. Residential solar energy systems correspond to an investment in the future of the world, conserving non-renewable energy sources and protecting the environment. The technology in the solar power industry is constantly advancing [1.6-1.10].

The increasing power injection by the renewable energy sources into the grid is fruitful for the utilities from the sustainable point of view and it provides economic benefit for long-term operation [1.11-1.12]. The reliable and secure energy supply has become the utmost important thing for the modern society and this has led to the concerns to be raised towards increasing renewable energy penetration with its intermittent nature. The utility companies may be concerned about the affect of variable solar generation on the overall quality of power, its impact on the low-tension (LT) distribution grid. Therefore, there are lot of challenges and issues in integrating distributed energy sources like Photovoltaic (PV) systems [1.13-1.20].

The grid integrated system has some responsibility to maintain a reliable grid supply with respect to harmonics [1.21-1.23], flicker [1.24-1.27], and DC injection [1.28-1.30] as they are connected to a power system network. Hence due to the power quality problems power converters are required for interface with grid. Only the power electronic converters like DC to DC and DC to AC are required by the solar PV panel for interconnection. The major power quality issues with increased renewable integration are given in Table 1.1.

Table- 1.1: Power Quality Problems and their Effects[1.31]

S. No.	Cause	Effect
1.	Harmonics	• Frequency disturbance • Waveform distortion
2.	Low Power Factor	• Equipment damage is caused by low power factor • Increases in Energy bills
3.	Transients in Power System	• Produces distortion like impulse and notches • Long and Short duration event
4.	Electro Magnetic Interferences	• Interference between electric and magnetic field High frequency phenomenon
5.	Power Frequency Disturbances	• Low frequency phenomenon • Produces voltage sags and swells

Among the various power qualities related problems Sl. No. 1 and 5 are applicable in case of power electronic converter used in PV system. Apart from the converter many power electronic devices are used to maintain to voltage level of the system and those are also contributor of harmonics.

For any solar PV system, photo voltaic (PV) cell is the fundamental unit which converts solar energy into electrical energy. Consequently, lot of innovations took place in the Photo Voltaic cell which can potentially increase the effectiveness of solar panels and of the solar power systems. PV panels utilizethe solar energy available in the nature to convert it into electrical energy. PV cells works on the principle of photoelectric phenomenon [1.32-1.40]. Operating and maintenance costs for Photo voltaic system are marginal, practically insignificant, compared with expenditures of other sustainable power source frameworks. PV panels have no rotating parts, with the exception of sun-following mechanical bases; therefore PV systems have less breakage.

Apart from the several benefits offered by the solar energy, the solar PV system suffers from two these two main challenges:

(i) ThePV system converts energy ataefficiency which is not more than 16% or 17%, especially when the irradiation level is less than standard test condition (STC) [1.41-1.45].

(ii) The generated power from the PV system continuously varies with the change in the atmospheric condition. Moreover, the characteristic of the PV array is non-linear, and thus, the current and voltage vary with the irradiation and temperature [1.46-1.48].

In order to tackle these challenges the maximum power point [1.49-1.50], with the unique characteristic is tracked continuously for harnessing the maximum solar energy. At this point, the whole PV system including converter, panel, inverter, etc, operates at its peak efficiency and tries to obtain maximum generated power. Thus, the most important part of harnessing the solar energy is tracking the MPP (maximum power point) of the solar PV system. To achieve maximum efficiency, it is necessary to locate the system at MPP.

Other environmental factors which effect the output of any solar system are (i) shadowing, (ii) dust and dirt, (iii) snow, bird droppings etc. out of these shadowing is one the biggest concern that decreases about half of the efficiency of the PV panels according to the place where the solar panels is mounted. Hence some mechanism system is needed in respect to increase the output of solar panel (PV) and maximize more and more amount of solar energy and get it converted into the electrical energy.

Researchers have drawn lots of interest on the problem of shading conditions and mitigation of its impact,as partial shading condition affects the performance and reliability of photovoltaic system. The safe operational temperature limit of PV cells is about 85˚C, but because of partial shading condition[1.51-1.57]., it reaches up to 150˚C which exceeds the safe operational limitThis high temperature causes hot spotting or local over heating which can damage PV modules. Hotspot (local over heating) is the most commonly occurred phenomenon which limits the operation life of PV cells. To produce the desired photon current and terminal voltage, series and parallel connection is used between PV cells[1.58-1.60].

The photon current flowing through each series connected PV cells has to be equal for better performance of PV module. But this is not possible during partial shading condition, in such situation shaded cell act as a load after getting reverse biased. Large number of researchers drawn interest on partial shading impact on the efficiency of PV array and techniquesto mitigate its effects [1.61-1.65]. The reverse breakdown of PV cells due to partial shading condition is avoided by connecting a diode across the PV cells under shading to carry the reverse bias current. By diverting the reverse bias current, creation of hotspot on the PV cells can be avoided[1.66-1.70].

These mitigation techniques are very worthwhile to enhance the performance of PV system but cause additional cost, more power consumption and PV system's reliability is also reduced. The efficiency of a photovoltaic system is very low and depends upon various parameters like irradiance; temperature levels etc. In addition to that, a shadow upon the solar panel affect extensively on the efficiency of the Photo Voltaic system[1.71-1.75]. Output of PV arrays is decrease due to partial shading condition. Modules of the photo voltaic array receive unbalance solar irradiation because of partial condition, so the PV arrays exhibit number of peaks and plateaus in power-voltage (P-V) and current-voltage (I-V) curve. During partial shadow condition efficiency of the PV array gets tremendously affected.

1.2 Organization of the Thesis

This Ph.D. thesis presents the detailed steady state modeling of the solar PV system and its integration to the GRID for future operations and avoiding the problem of partial shading. The major contribution of the thesis lies in its effectiveness in modeling the PV module by using the converters and developing the efficient techniques to reduce the effect of partial shading on the performance PV system. The major contributions of the thesis can be outlined as follows:

- New model for configuration (Su-Do-Ku) for PV system of Photo voltaic array has been presented for enhancing the efficiency of the PV system under the partial shading condition.
- Performance analysis for different configuration under various shade patterns have been studied and presented.
- Detailed comparative studies have also been done to show the superiority of the proposed configuration with different existing configurations.

- Proposed and implemented an IOT based MPPT techniques to get better efficiency and more power from the PV Solar module.
- An efficient simulation model of the IEEE 14 bus system with generators and loads have been developed.
- Grid and PV power output is plotted with the variation of irradiance and for a fixed load connected in the distribution system.
- The Load sharing of overall PV integrated System as well as of standalone PV system separately has also been studied.

1.3 Thesis Outline

Following this conceptual introduction regarding the GRID integration of renewable energy systems, PV systems and various challenges of integrating the PV system to the GRID, this thesis is divided into the following chapters, including individual brief introductions:

Chapter 2 gives the brief literature survey of the problem for better understanding of the problem and the research gaps have been identified at the end of the chapter which laid the foundation for the proposed work.

Chapter 3this chapter presents new models for configuration of Photo voltaic array and their performance has been studied. The real challenge lies in enhancing the efficiency of the PV system with partial shading condition. In this chapter a configuration is proposed to extract maximum power globally in order to evaluate the shedding effect. During the Partial shading condition the power generated by the PV system gets reduced because the solar irradiation received by the array of PV panel during the partial shading condition is different as received during no shading condition.

Chapter 4this chapter introduced a new model for Photo Voltaic array configuration, and its efficiency has been studied. This chapter proposes a new PV system design to enhance PV system performance under partial shading conditions. This design uses different PV modules rearrangement techniques. With the different shading patterns taken as input, the performance analyses of the PV array (9x4) with the proposed configuration and some other configurations have been performed.Detailed comparative studies have been performed to show the superiority of the novel configuration proposed with the different existing configurations.

Chapter 5 In this chapter, a new approach for maximum power extraction from the photovoltaic (PV) panels efficiently is presented using IOT system to ensure global power optimization, irrespective of the irradiance conditions, for the photovoltaic (PV) generators. Individual MPPTs have been implemented and comparative analysis studied for with and without IOT systems and the results depicted.

Chapter 6 introduces the PV array and presents the PV integrated power system for better understanding. It focuses mainly of developing the IEEE 14 bus consisting of 14 numbers of buses, 5 numbers of generators, and 11 numbers of loads. The effect of variation of irradiance on Grid and PV power output with fixed load connected to system is studied and presented in this chapter.

Chapter 7 presents the overall conclusion of the thesis and provides some information regarding the future research possibilities.

Chapter 2

Basic Theory of PV System and Survey of Literature with Comparative analysis

2.1 Introduction

2.2 Basic Theory of PV System

2.3 Survey of Literature

2.4 Comparative analysis of the PV cell arrangements review

2.1 Introduction

The demand for cleaner and greener energy is increasing day by day since every Government is imposing restriction over pollution due to fossil fuel. Solar energy is the most popular choice as green energy resources [2.1-2.3]. Researchers as well as industries are putting a lot of effort to make this energy resource better day by day. Compare to other energy resources solar is far better in respect of reliability, safety, low maintenance cost and low investment cost [2.4-2.7]. However, there are still some issues to be addressed in near future to make this more productive and low cost so that every citizen can use this energy source [2.8-2.10]. Solar works on sunlight which is free providing by the nature. The energy in sunlight absorb in solar panel which is called Photovoltaic cell or PV cell and then converted into electrical energy and send to grid or store in the battery for future use. However, the efficiency of the PV cell is reduced when a shadow fall upon the solar panel. It may be total shadow or partial shadow condition. In partial shadow condition the PV cell can generate energy but it is not the maximum value of its rating. In partial shadingcondition the temperature of the PV cell increases upto 150˚C, whereas the operating temperature of the PV cell is 85˚C [2.11]. Therefore, it can lead to overheating of a specific zone called hotspot and can damage the PV cell in that area. The operating life of a PV panel is also affected due to this hotspot phenomenon [2.12]. There are various ways to mitigate this hotspot on partial shading condition problem [2.13-2.15]. A lot of researchers are going on this to solve the issue. Researchers are trying to rearrange the PV module arrangement to minimize the problem. In a PV module, the cells are organized in series and parallel connections. The photocurrent passing through each series connection must be equal to balance the PV cell and thus efficiency is maximized. However, in parallel shadingcondition a disbalance of photocurrent happens due to shadow on some portion of a PV panel. A lot of researchers are working on this to find the solution to this problem. Diodes are connected in reverse bias condition in shaded PV cell and, therefore, reverse bias current is decreased and hotspot condition can be avoided. But power consumption increases due to this and also it needs additional cost. The PV module gets unbalance irradiance in partial shadingcondition. There are various reasons to be blamed for partial shadow. Some of the factors like shadow of building, factories, chimneys, billboards, lampposts, tree, bridge, airplanes, clouds etc. even shadow of leaves and dust are to be blamed for partial shedding.

The PV cell arrangement has a major role on contributing efficiency [2.16]. Therefore, different arrangement of PV cell can be utilized to decrease the partial shadingeffect and increase the efficiency. In this paper, we have reviewed the literature of different arrangements of PV solar systems used to addressed the partial shadingcondition and maximize the efficiency.

Table 2.1 Standard Test Condition described in PV data sheet

Irradiance	1000 W/m^2
Cell Temperature	25°C
Spectrum Air Mass	1.5

2.2 Basic Theory of PV System

A photovoltaic cell function is modeled into an equivalent circuit [2.17]. From the equivalent circuit mathematical equations are formed with a set of parameters. Then with a specific methodology the electrical response or the electrical power output of the PV cell is calculated. PV installation characteristics parameters like properties of PV module, interconnections schemes, operating condition and irradiance are used as input for this calculation. Whereas, the output for this model depends on user choice of global or local MPP or I-V characteristics curve. A typical equivalent circuit diagram of a PV cell is shown in the Fig.2.1, where, I_{ph} is the photocurrent source, D is the photodiode, R_s is the series resistance.

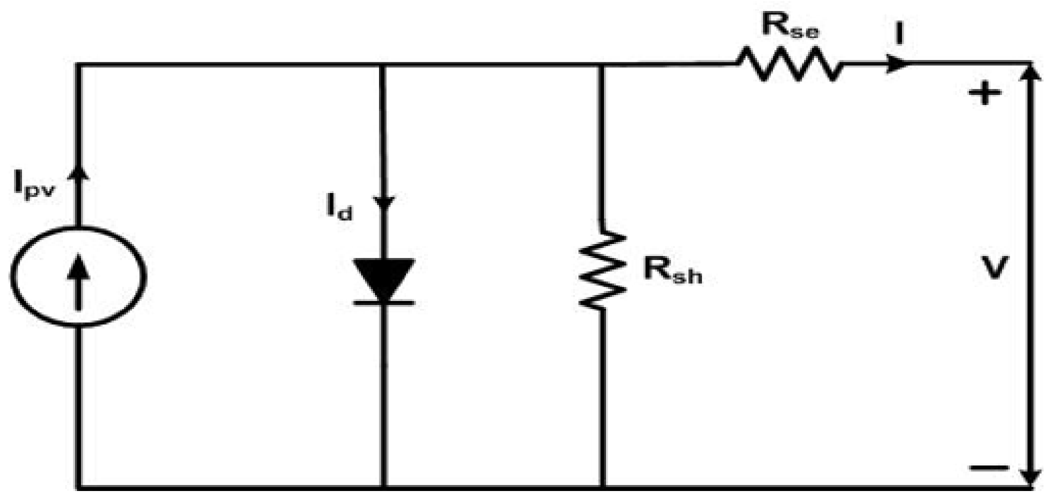


Fig. 2.1 Equivalent circuit of single diode solar cell

Total radiation incident on an inclined PVpanel can be given as follows [2.17]:

$$I_T = I_b R_b + I_d R_d + (I_b + I_d) Rd \qquad (2.1)$$

Where, I_d stands for diffuse radiation and direct $I_b$stands for normal radiation.R_r and R_d are the tilt factor for reflected radiation and diffuse radiation respectively.

2.2.1 PV Modeling under partial shadingcondition

The impact of partial shading on PV module is shown in fig 2.2, to overcome the performance, the arrangement of PV modules is changed from conventional to proposed.

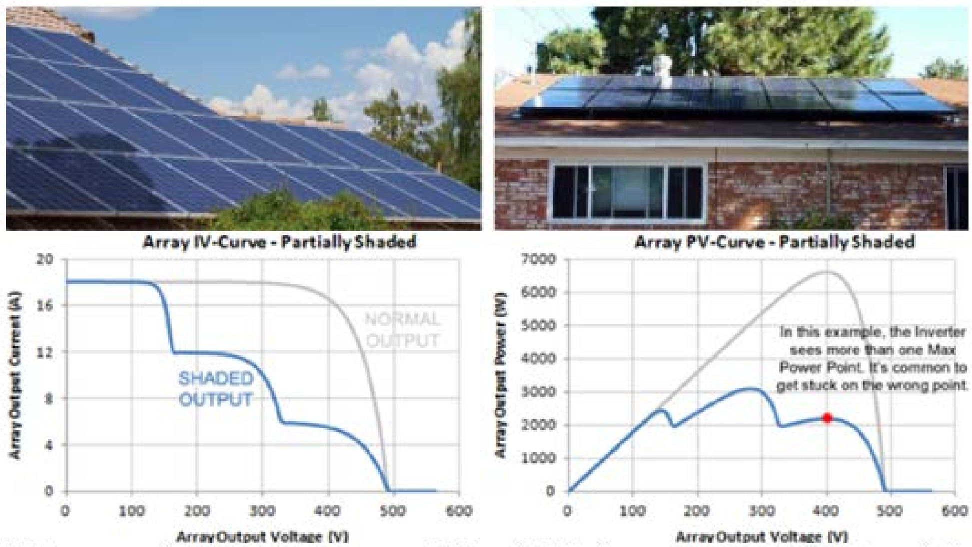


Fig. 2.2 Impact of Partial shading on I-V and P-V characteristics of PV module

2.2.2 MPPT algorithms

The output curve of a PV cell is nonlinear by nature because of various parameters are associated to it like, temperature, humidity, tilt angle, irradiance etc. however, irradiance is the most significant factor and with uniform irradiance an unique point called maximum power point can be found in the I-V curve of the PV system [2.18] as depicted in the fig.2.3. However, this maximum power point cannot be predicted since a number of parameters associated with it. But we can calculate with the mathematical equation known as maximum power point technique (MPPT), the maximum power point. Researchers have developed a huge number of algorithms over the years to precisely calculate the MPP (maximum power point).

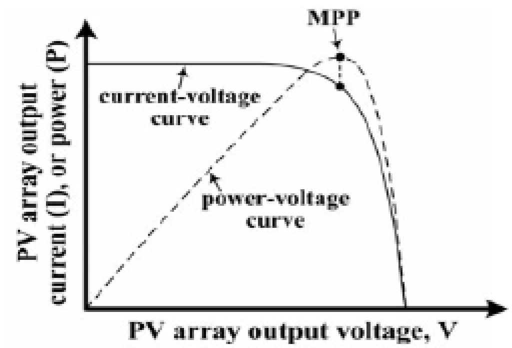


Fig. 2.3 MPP in the I-V/P-V characteristics of a PV array

2.2.3 Connection topology

Connecting the PV cells to form a module is needed so that the module can send the output to storage or load. Generally, the PV cells are connected serially to form a PV module [2.38]. However, arranging them in different pattern is important to resolve the issue of partial shading. Parallel connections are the summation of all current. Therefore, parallel connection [2.39] provides more output than series connection. But, when the current increase, the losses also increase. Therefore, serial-parallel (SP) [2.40] connection is the solution to that problem. It is the most common and popular connection in the field of PV array system. Another type of connection called Total-cross-tied (TCT) [2.41] configurations where PV cells are first tied parallel with a string to make the voltages one and the same and then currents are added up. It reduces the overall result of mismatch. A different type of connection topology called Bridge-link (BL)[2.42] topology formed to avoid the cable losses happens in TCT topology. And when both of these TCT and BL topology combined a new type of topology formed called the Honey-Comb (HC) topology [2.43]. Out of these various configurations, TCT and SP are the most common and reliable configurations [2.44].

2.3 Survey of Literature

2.3.1 Review and analysis of previous research on MPPT algorithms

It has been observed that, I-V characteristic in the PV systems is affected by temperature while the PV output current is affected by irradiation.Curve-fitting method, of I-V characteristics in the PV systems proposed by Phang et al. in 1984 [19], though it was very difficult to implement. A third order polynomial to be calculated as

$$P = aV^3 + bV^2 + cV + d \tag{2.2}$$

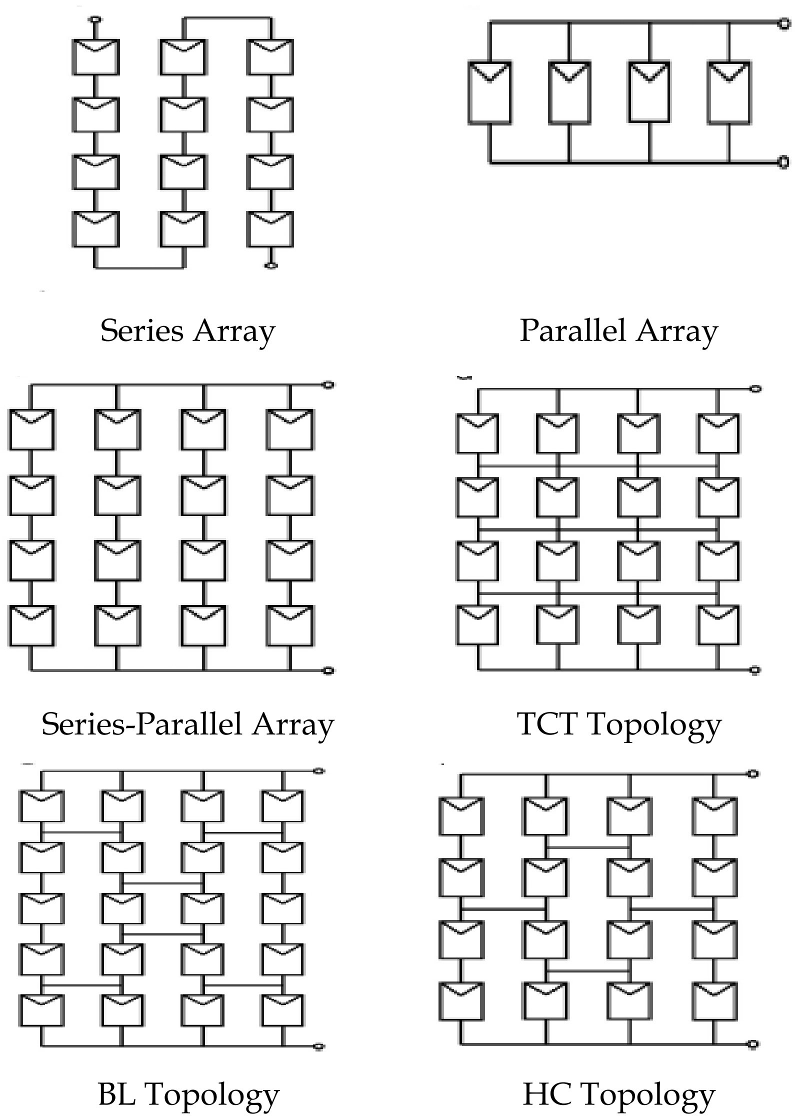


Fig.2.4Various PV array topologies

Where, the sampling of PV voltage and power in intervals is done in order to determine the coefficients a,b,c,d. However, a new model on this method proposed by M.A. Hamdy in 1994 [2.20].

Look-up table method proposed by Ibrahim, et al. in 1999 with a table contents of value for different climatic condition. But it is applicable for a specific condition and it needs a large memory to store the data [2.21].
Open-circuit voltage photovoltaic generator method proposed by P. Chetty in 1986 [2.22] based on the equation:

$$k_1 = \frac{V_{MPP}}{V_{OC}} \cong Constant < 1 \quad (2.3)$$

Where, K_1 is the proportionality constant depends on fill factor and the fabrication process. This is a simple and low-cost model. But, because of open circuit the real power cannot be calculated.
Similarly, short-circuit photovoltaic generator method proposed by S.M. Alghuwainem in 1994 [2.23] based on the following equation

$$k_2 = \frac{I_{MPP}}{I_{SC}} \cong Constant < 1 \quad (2.4)$$

But calculating K_2 is difficult here. The advantage and disadvantages are similar like previous one.
Differentiation method is proposed by L.T.W. Bavaro in 1988 [24] with following differential equation.

$$\frac{dP_{PV}}{dt} = V_{PV}, \frac{dI_{PV}}{dt} + I_{PV}\frac{dV_{PV}}{dt} = 0 \tag{2.5}$$

Where, I_{PV} and V_{PV} are the present array current and voltage. But real time output cannot be possible since it needs a lot to equations to solve.Another method available in the literature called Feedback voltage (current) method proposed by H.D. Maheshappa et. al in 1998[2.25] for the simple battery less supply.

However, the most common method used by most of the researchers are Perturbation and observe (P&O) method [2.26,2.30]. In this method MPP is come out with iterative method of calculation and the operating point of PV generator is perturbed to encounter the change in direction. It is an easy and simple method. However, sudden increase of irradiance makes this method faulty which is a disadvantage of this algorithm [2.31].

In recent years with the advancement of computer software, software simulated tools are used to calculate MPP. Fuzzy logic controllers (FLCs) and neural network methods are started at early years [2.32-2.37]. The computer simulated methods are much more accurate, controlled and robust.

2.3.2Review and analysis of previous research on Connection topology

Shading effect is the biggest setback for increasing efficiency of a PV solar system. To avoid shading effect in 1981 Arnett and Gonzales have tried with bypass diode [2.45]. The reverse bias breakdown model developed and explained by Spirito and Albergamo in 1982 [2.46]. In 1991 Bhattacharya and Neogi [2.47] have done optimization to avoid the formation of hotspot. The hotspot formation and efficiency reduction has been explained successfully by kovach in1995 [2.48]. In 1998 Laukamp et al. [2.49] developed cast shaded and simulated the result. At that time the researchers concluded that bypass diode is essential to reduce the shading effect. However, it was creating problem for architectures. To solve this problem in 1997 Meyer et al. [2.50] proposed cell integrated converter though it was not commercially used. However, in 1996 Quaschning and Hanitsch [2.51] successfully calculated the photocurrent under partial shading condition, while now a days we are the simulation tools to calculate that. In 2001 Zehner [2.52], presented a market survey with a large number of tools available in the market at that time. Versluis and

Jongen [2.53] also tried to minimize the shadingeffect by optimizing spacing between the rows of a PV module. An extensive study on partial shadingcondition and its effect studied by De-Blas et al. in 2002 [2.54]. The different type of cell arrangement first proposed by Kaushika and Gautam in 2003 [2.55]. However, various new types of configurations like SP, TCT, and BL for 9x4, 6x6, 2x6, 6x2, 3x4, 4x3 are found in the literature Karatepe et al. in2007 [2.56]. In 2011 and 2013, El-Dein et al. [2.57] investigated a 6x4 size of PV cell with various PV arrangements. In 2014 Lun et al. [2.58] worked with various conditions of shedding. Rani et al. in 2013 [2.59] started working with 9x9 PV cell configuration. To minimize the power loss due to partial shadingwith different configuration of SP, TCT etc. array configuration, various authors have tried found in the literature in 2015 Vijayalekshmy et al. [2.60] and in 2016 Pareek and Dahiya [2.61]. A new type of arrangement called, Su-Do-Ku arrangement is proposed by Potnuru et al. in 2015 [2.62]. Yadav et al. [2.63,2.64] in 2016 and 2017 analyzed TCT, SP-TCT, Su-Do-Ku with New System NS-I, NS-II for different array size 4x4, 4x5. They have also analyzed some more new structure like Magic Square (MS), BL-HC, RBL-HC, BL-TCT, RBL-TCT etc. In 2008 Nguyen and Lehman [2.65] reconfigured various SP, TCT array with series and parallel connections by using an electrical switch matrix.

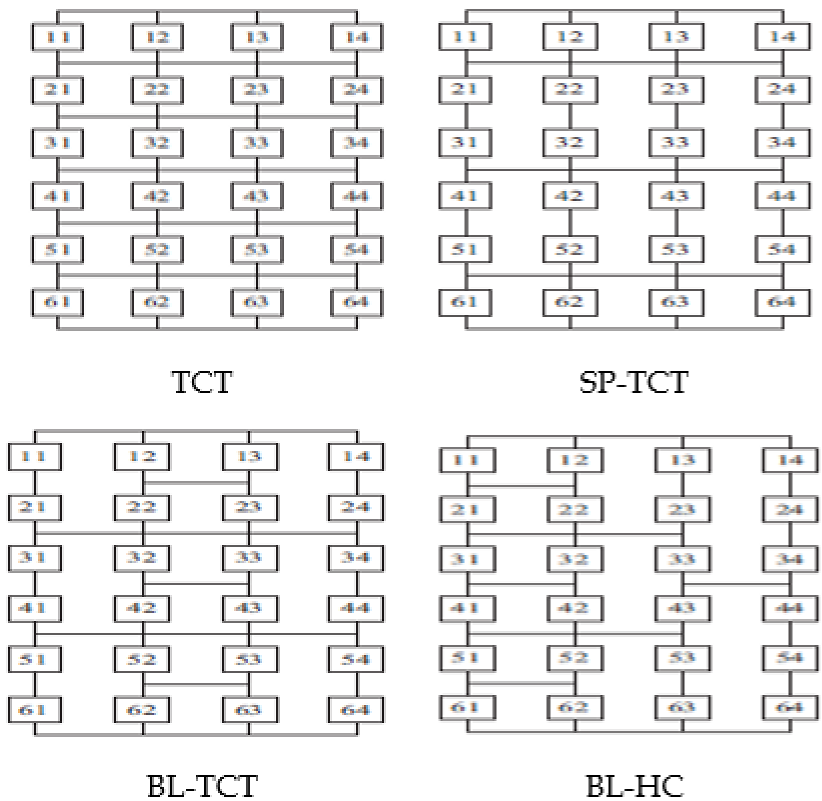


Fig. 2.5. Hybrid configuration PV array topologies

2.4 Comparative analysis of the PV cell arrangements review

The arrangements of PV cell in a PV system are directly related to efficiency, accuracy and reliability, where they are strongly varied with various reviewed literatures. Therefore, a comparative analysis is needed to compare them with each other. In the various types of arrangements shown here, the output currents depend on the irradiance [2.66], i.e.

$$I = \left(\frac{G}{G_{STC}}\right) \times I_m \tag{2.6}$$

Where, current produced by the PV cell at STC irradiance of 1000W/m2 is denoted as I_m. On the other hand, from the KVL the voltage may calculated as [2.66], and the voltage present in the nth row of PV array is V_{mn}.

$$V = \sum_{n=1}^{4} V_{mn} \tag{2.7}$$

Due to partial shading condition the fill factor also varies. The fill factor increases or decrease with the increment of shaded region. The fill factor can be calculated as [2.66]

$$FF = \frac{V_{mpp} \times I_{mpp}}{V_{oc} \times I_{sc}} \tag{2.8}$$

The mismatch of power losses can be calculated with the difference between the maximum power of PV array without power losses and Global maximum point with power losses [2.66].

To analyze we are considering a simple 4x4 array size configuration as shown in the Fig. 2.6 [67].

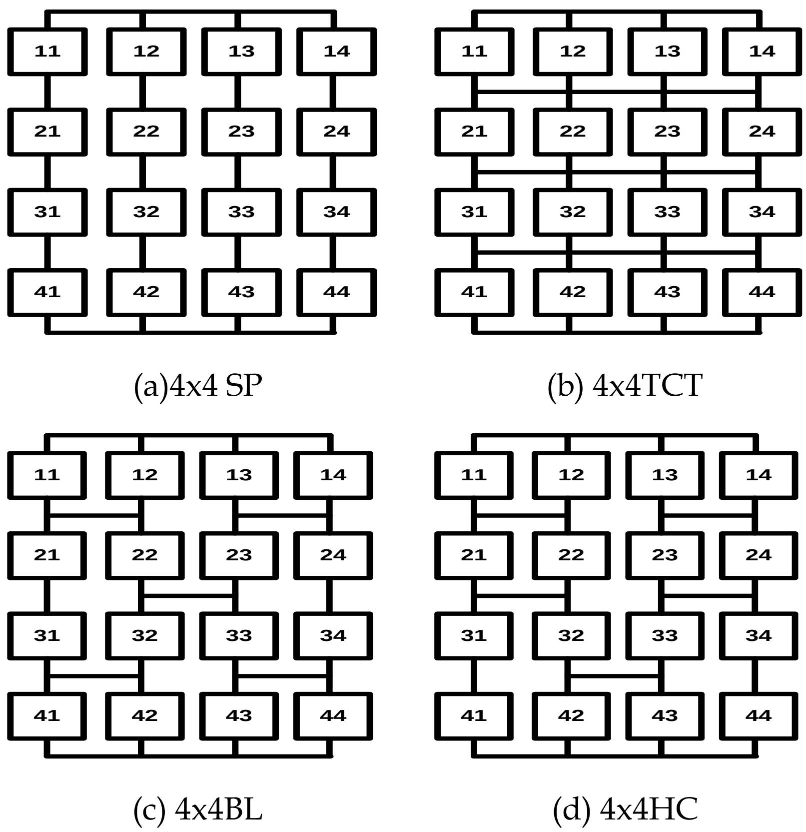
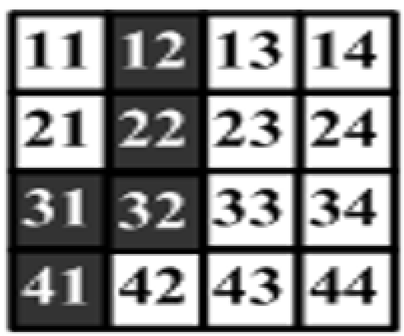


Fig.2.6Classical Solar PV array interconnection topologies

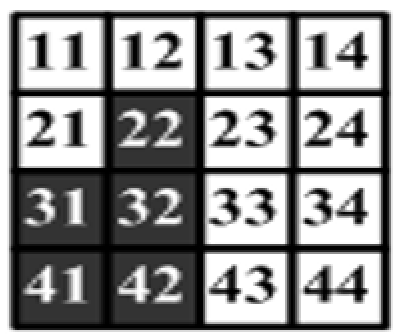
To analyze these simple 4x4 array we have to consider different shading pattern. Let us considering two different shading patterns with irradiation levelsof 1000W/m^{2}for STC and 350W/m^{2}under shaded condition [2.68] as shown in the Fig. 2.7 and Fig. 2.8.

case-a (I)

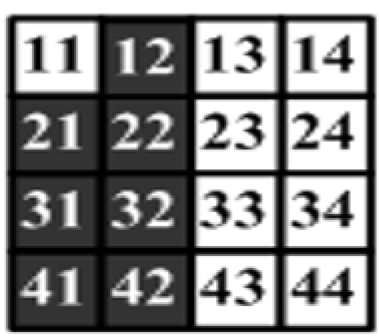
case-a (II)



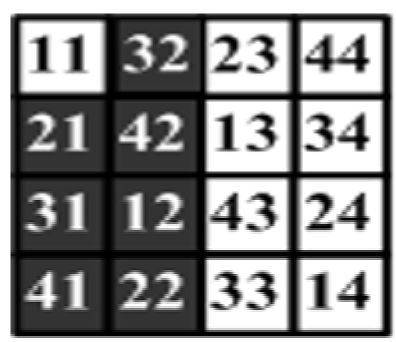
case-b (I)



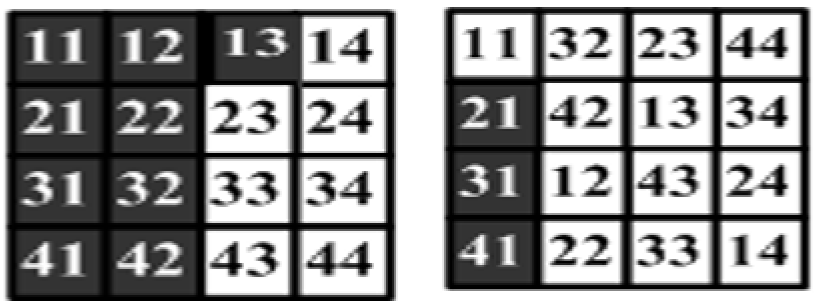
case-b (II)a



case-c (I)



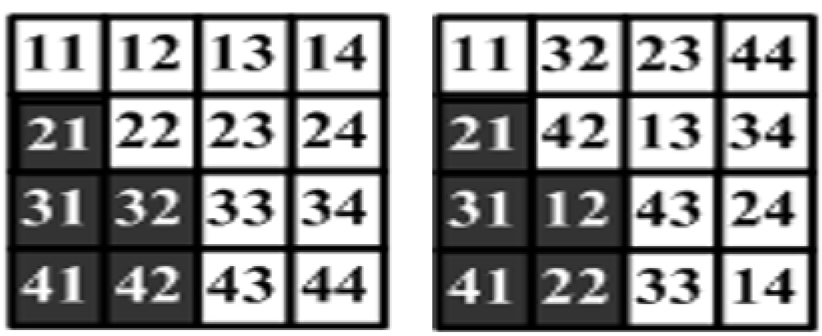
case-c (II)a



case-d (I) case-d (II)a

Fig. 2.7 Pattern-1: shading cases from all types of configurations

case-a (I) case-a (II)



case-b (I) case-b (II)a

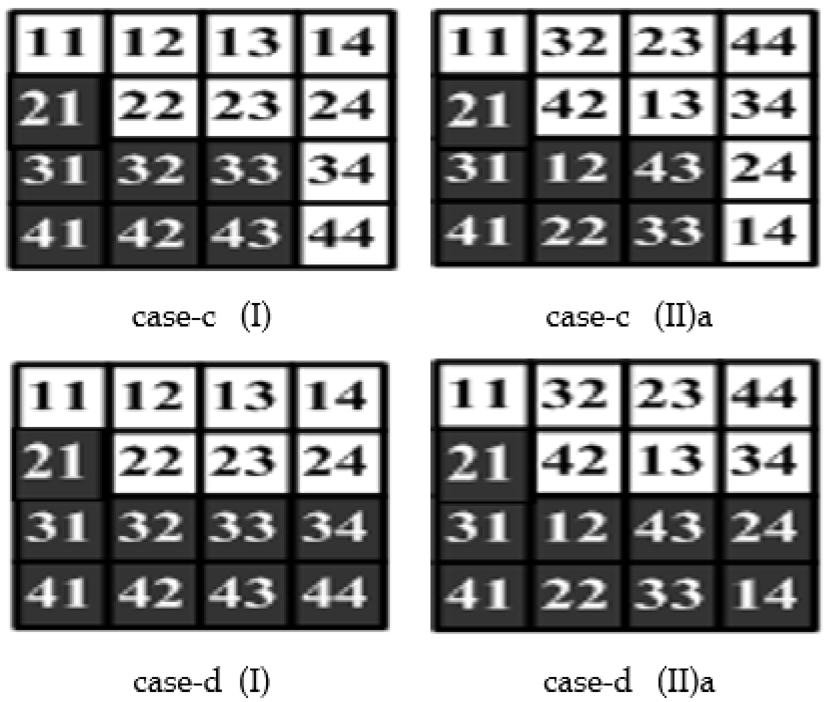


Fig. 2.8 Pattern-2: shading cases from all types of configurations

To analyze the pattern, we have to set the parameter value with STC (standard test conditions) as given in Table 2.2.

Table 2.2Photo voltaic module parameters at STC (1000W/m² and 25⁰C)

Parameters	Values
PV power	170 W
Short circuit current	5.2 A
Open circuit voltage	44.2 V
Voltage at MPP	35.8 V
Current at MPP	4.75 A
No. of cell	72

The result can be studied with MATLAB Simulink for all the configurations. After analyzing the performance of all these configurations, the results are tabulated in the table-2.3for pattern 1 and in table-2.4 for pattern 2.

Table 2.3Pattern-1 simulation results in terms of Power (Watt) and Voltage for different configurations

Topologies	Case-1a		Case-1b		case-1c		Case-1d	
	P	V	P	V	P	V	P	V
SP	2041	104.5	1781	138.3	1731	130	1620	131.1
TCT	1972	140	1854	139.8	1761	131.2	1620	130.5

BL	2001	100.3	1831	134	1730	130.2	1671	130.5
HC	1951	100.1	1771	131.3	1730	130.3	1672	130.5

From the table 2.3 the output power can be seen for different configurations of PV array system, the MPP is 1781,1854,1831,1771 for the configurations HC, BL, SP, and TCT respectively.

Table 2.4Pattern-2 simulation results in terms of Power (Watt) and Voltage for different configurations

Topologies	Case-1a		Case-1b		case-1c		Case-1d	
	P	V	P	V	P	V	P	V
SP	2190	131.4	1780	131.3	1370	131.4	1263	66.13
TCT	2271	131.3	1854	132.3	1411	132.3	1263	66.13
BL	2210	131.2	1830	134	1386	132.1	1262	66.13
HC	2225	131.1	1772	131.1	1402	131.2	1262	66.13

The power (in Watt) produced by different PV array for pattern-2 is given in table-2.4 as; the MPP is 2190, 2271, 2210, 2225 for the configurations HC, BL, SP, and TCT respectively.

Chapter- 3

Study on a new PVArray configuration to enhance the power and performances of 4x4 PVArrays with puzzle shade dispersion

3.1 Introduction

3.2 Modeling of 4x4 PV Arrays Integrated Power System

3.3 Simulation Results and Discussions

3.1 Introduction

Renewable energy is a form of energy that is naturally obtained from the environment and from sources that can be replenished naturally. The concern for the day by day reduction of natural occurring fossil fuels and depletion in environmental conditions with increased pollution due to burning of fossils has compelled the tremendous growth in the research carried out in the area of exploring RES for supplementing the increased energy demand. Solar and wind energy is the most promising RES for power distribution. The renewable energy sources are cleaner source of energy and they do not dissipate heat to the environment that is responsible for global warming. Residential solar energy systems correspond to an investment in the future of the world, conserving non-renewable energy sources and protecting the environment. Renewables are the fastest growing source of new electricity generation.

Technology in the solar power industry is constantly advancing. Researchers are trying to improve the technology which will intensify in the future. Photo Voltaic (PV) cell is the fundamental unit which convert solar energy into electrical energy. Consequently, innovations in Photo Voltaic cell can potentially increase the effectiveness of solar panels of the solar power systems. PV panels utilized solar energy which is available in abundance in the nature without any cost. Photoelectric phenomenon is basic operating principle for PV cell. Operating and maintenance costs for Photo voltaic system are marginal, practically insignificant, compared with expenditures of other sustainable power source frameworks. PV panels have no rotating parts, with the exception of sun-following mechanical bases; therefore PV systems have less breakage. Researchers have drawn lots of interest on the problem of mitigating the partial shading conditions, as it affects the efficiency and reliability of photovoltaic system, and thus effects its overall performance. The safe operational temperature limit of PV cells is about 85˚C, but because of partial shading condition, it reaches to 150˚C exceeding the safe operational limit. This high temperature causes hot spotting or local over heating which can damage PV modules. Hotspot (local over heating) is the most commonly occurred phenomenon which limits the operation life of PV cells. To produce the desired photon current and terminal voltage, series and parallel connection is used between PV cells. The photon current flowing through each series connected PV cells has to be equal for better performance of PV module. But this is not possible during partial shading condition, in such situation shaded cell start acting as load after getting reverse biased. Large number of researchers drawn interest on the issue of partial shading and techniques to mitigate its effects.

The reverse breakdown of PV cells is avoided during partial shading condition by connecting a diode across the shaded PV cells to carry the reverse bias current. By diverting the reverse bias current, creation of hotspot on the PV cells can be avoided. These mitigation techniques are very worthwhile to enhance the performance of PV system but cause additional cost, more power consumption and decrease the reliability of the PV system. The efficiency of a photovoltaic system is fluctuating, depends upon various parameters like irradiance; temperature levels etc. In addition to that, a shadow upon the solar panel affect extensively on the efficiency of the Photo Voltaic system. Modules of the photo voltaic array receive unbalance solar irradiation because of partial condition, so the PV arrays exhibit number of different peak in the I-V and P-V curve. Shading may happen upon solar panel due to cloud, tree, buildings; even snow or dust may create partial shading. In our work here, we are trying to increase the efficiency of solar PV system for partial shading condition by a novel configuration of PV array design. In a PV array, the different modules are unified to enhance the output power of the array using different interconnection schemes. PV array has very low conversion efficiency, so it is very difficult to improve the efficiency of PV arrays under the shading condition. To deal with this issue of PV system different configuration have been developed and analyzed with PV system. The researchers have proposed various PV array design configuration to restrict the effect of partial shading like, Series-parallel(SP), Total cross tied (TCT), Honey- comb(HC), Bridge-link(BL), for different shading pattern [1] etc. Various types of connections are studied which increase electrical power received from the PV array with diverse of shading patterns. PV module is the interconnection of many PV cells. Different connections are possible for PV cells but normally 36 cells are serially connected. The series/parallel connection of PV cells is depends upon voltage/current rating of PV module. The PV cells should have identical electrical properties. But because of different level of solar irradiation, mismatch of losses occurs.

In this work a new model for configuration of Photo voltaic array has been presented and their performance has been studied. The real challenge lies in efficiency improvement of the PV system with partial shading condition. We need to track local and global maximum power points (MPP) to evaluate the shading effect. During the Partial shade condition the power generated by the PV system gets reduced because the solar irradiation received by the PV panel array during the partial shading condition is different as received during no shading condition.

It is required to keep monitoring the solar power plants performance, so the system performance can be analyzed and hence we can calculate the efficiency of the solar PV modules based on solar radiation level and some environmental factors. So, with the help of all this data, we can analyze and study the system performance. Several changes can be made in designing the solar PV cells by using the study and analysis of the power plant if needed.

In this work a new configuration (Su-Do-Ku) for PV system is designed for improving the overall efficiency and thus performance of PV system during light shading conditions. This configuration utilizes various rearrangement techniques of PV modules i.e., puzzle pattern. The performance analysis of PV array (4x4) with proposed configuration and some other configurations have been done in the presence of different shading pattern. Detailed comparative studies have also been done for different configurations to show the superiority of proposed configuration. Photo voltaic module with different configuration is modeled using the MATLAB/Simulink software.

Section 2 deals with modeling of PV cell. Different configurations used for the PV array to deal with partial shading condition are introduced in Section 3. A new configuration for photo voltaic array is introduced in Section 4. PV array with different configuration is analyzed in Section 5.

3.2 Modeling of 4X4 PV Integrated Power System

A photo voltaic module is made up of small cells that work on the principle of energy conservation and transfer of light energy to electrical energy. This cell acts as the basic module of the PV array. This cell is essentially a normal p-n junction diode made using highly doped silicon wafer and works on the principle of conservation and transfer of energy from light to electricity, individual cell can generate electricity and these cells can be combined to increase the generated power of photovoltaic system. Hence, large numbers of cells are joined together using different combinations and methods to increase the generated power and make the PV module of the desired size and capacity. The PV gadget used has a rated capability of two hundred kW working at 250 V. The power a PVpanel generates depends upon the quantity of sun radiation incident on its floor and temperature. Both temperatureand solar irradiancerange according tothe vicinity of the sun in the sky. Hence, the seasonality which affects the solar radiation directly has great impact on the electricity generation capability of the PV module. Total radiation incident on an inclined PVpanel can be given as follows [3.1]:

$$I_T=I_bR_b+I_dR_d+(I_b+I_d)R_d \quad (3.1)$$

Where, I_d stands for diffuse radiation and direct $I_b$stands for normal radiation.R_r and R_d are the tilt factor for reflected radiation and diffuse radiation respectively.

Fig. 1 represents the electrical equivalent circuit of a PV cell, where a diode and one resistor connected with a current source as,

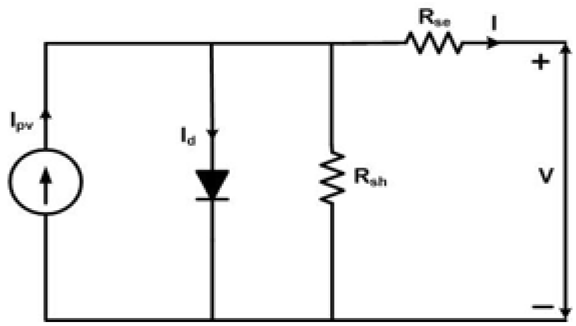


Fig. 3.1 Equivalent circuit of single diode solar cell

In ideal condition the losses occurring in the PV array are considered to be zero, but in practical condition achieving zero losses is not possible. As shown in Fig. 3.1, a series and parallel resistor is connected in the equivalent circuit of PV cell to represent the internal losses of it [3.1]. For a PV cell working in the ideal condition the value of this series resistance is zero and parallel resistance is infinite. The efficiency reduction of the PV cell is represented by power dissipation across series resistor. The current passing through the parallel connected diode across the current source in Fig. 3.1 can be given by Shockley diode equation [3.2].

$I_s$is the reverse saturation current,

I_d is the diode current,

K = Boltzmann's constant,

Q = elementary charge,

N = Ideality factor.

Mathematically, Solar PV cell voltage (V_C) depends on current (I_{ph}) and solar irradiation, is expressed as,

$$V_C = \frac{AkT_C}{e} \ln\left(\frac{I_{ph} + I_o - I_c}{I_o}\right) - R_s I_c \quad (3.2)$$

The operating temperature $T_x$is governed by ambient temperature (T_a) and solar irradiation level.To measure the effect of irradiation level on the photo current and voltage, two correction factors C_{TV} and $C_{TI}$are needed, as given by Eq. (3.3) [3],

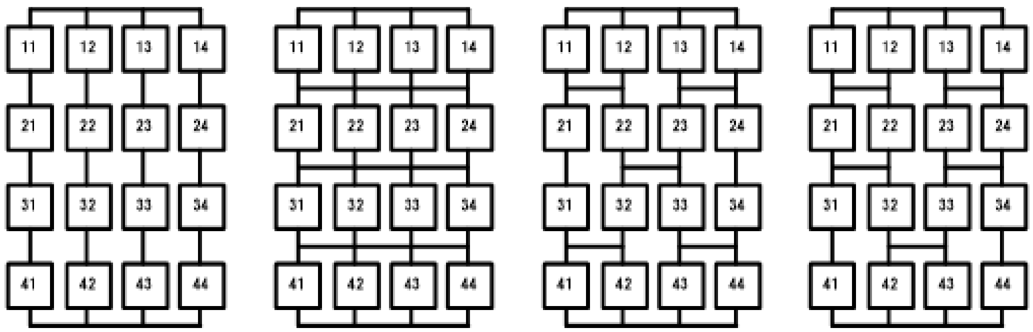
$$C_{TV} = 1 + \beta(T_a - T_x) \quad \& \quad C_{TI} = 1 + \frac{\gamma T}{S_C}(T_x - T_a) \quad (3.3)$$

Where, represents new irradiation level and represents reference solar irradiation. The magnitude of the PV cell voltage and photo current, can be written as Eq. (3.4),

$$C_{SV} = 1 + \beta_T \alpha_S (S_x - S_c) \quad \& \quad C_{SI} = 1 + \frac{1}{S_C}(S_x - S_C) \quad (3.4)$$

3.2.1 Different Configurations of the PV Array

In the PV array row and column of modules are connected inserially and parallel manner respectively. Here we are analyzing the performance of four different configurations SP, BL, HC and TCT.



(a)4x4 SP (b) 4x4TCT (c) 4x4BL (d) 4x4HC

Fig. 3.2. Solar PV array interconnection topologies

Fig. 3.2 depicted four different configurations of PV array interconnection topologies where row modules and column modules are connected in parallel and series respectively. Performances of these configurations can be studied.

The current generated by PV modules can be written as Eq. (3.6).

$$I = \left(\frac{G}{G_{STC}}\right) \times I_m \quad (3.6)$$

Where, I_m is the generated module current. The Array voltage can be expressed as,

$$V = \sum_{n=1}^{4} V_{mn} \quad (3.7)$$

Where, V_{mn} is the n^{th} row voltage of photo voltaic array.

Fill-Factor of a solar cell can be calculated from the P-V curves. It variesin partial shading conditions and expressed as,

$$FF = GMPP/V_{OC} \times I_{SC} \quad (3.8)$$

Where, GMPP is global maximum power points and LMPP is local maximum power points [5-7] under partial shaded conditions. In the scenario when the multiple Maximum Power Points (MPPs) are considered that conventional tracking techniques do not give the desired results for tracking the GMPP [8].

PV array power losses occurring due to partial shading conditions can be expressed as [3.9],

Power loss = (Maximum power of PV array without PS – GMPP with PS) (3.9)

3.2.2 Proposed 4x4 PV Array Configurations

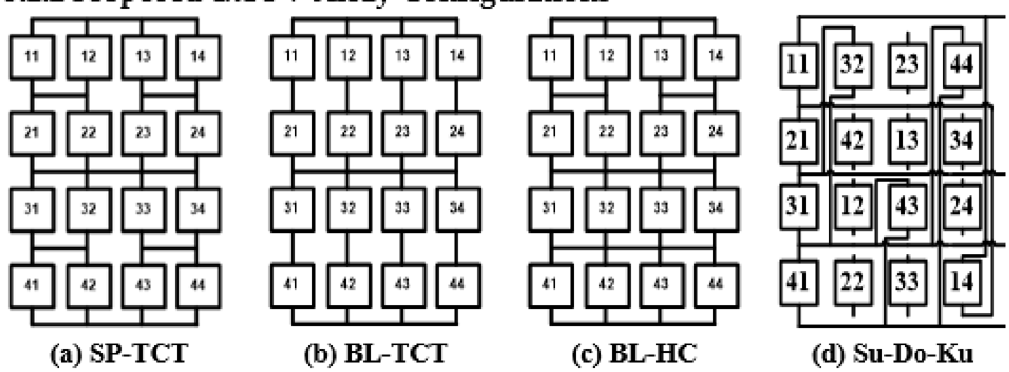
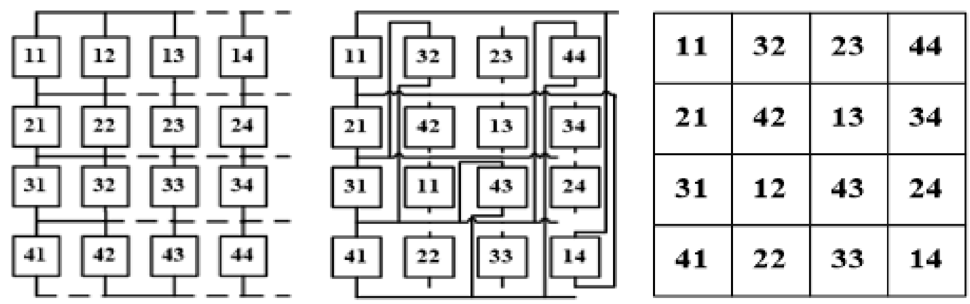


Fig. 3.3 Proposed 4x4 PV Array configurations

3.2.3 Arrangements of Su-Do-Ku Configured 4x4 PV Array

The proposed novel Su-Do-Ku configuration for PV array, is a logical based configuration, combinatorial number-placement puzzle [10]. The whole Grid (puzzle areas), is divided into columns (vertical lines) and rows (horizontal lines) consisting of the individual Su-Do-Ku squares. An easier 4x4 puzzle size, will have only four possibilities to think and it is shown in Fig.3.4 with the TCT topology arrangement as,



(a) TCT arrangement (b) Su-Do-Ku pattern (c)Su-Do-Ku arrangement

Fig. 3.4 Su-Do-Ku configuration for PV Array

In the proposed model of Su-Do-Ku configuration is depicted in fig.3.4, where first digit represents the row position and second digit denotes the position. Here in first row, third column panel 23 has shifted to the new position (first row third column) but the electrical connection of the panel remains same. In the same way, the new position for panel 44 is first row and fourth column but the electrical connection of the panel remains same. Therefore, the position of the panels is change without disturbing the electrical connection of panel. Since the electrical configurations of the array does not change with position of panel, the voltage & current equations remains the same for all used configuration e.g. SP,TCT, BL [4].

3.2.4 Study of 4x4 PV Array Shading Patterns

Three different shading patterns are deliberated to ascertain the impacts of shading on PV array. All individual patterns have four cases a, b, c and d except pattern-3 having only two cases. In all the patterns, two irradiation levels ($350W/m^2$ and $1000W/m^2$) are taken for performance investigation on pattern-1, pattern-2 and pattern-3 as depicted in fig.3.5a, 3.5b and 3.5c respectively.

The values of different parameters of available PV module (for commercial use) at standard test condition (STC) are given in Table 3.1;

Table 3.1. Specifications of photo voltaic module at STC ($1000W/m^2$ and 25^0C)

Parameters	Values
PV power	170 W
Short circuit current	5.2 A
Open circuit voltage	44.2 V
Voltage at MPP	35.8 V
Current at MPP	4.75 A
No. of cell	72

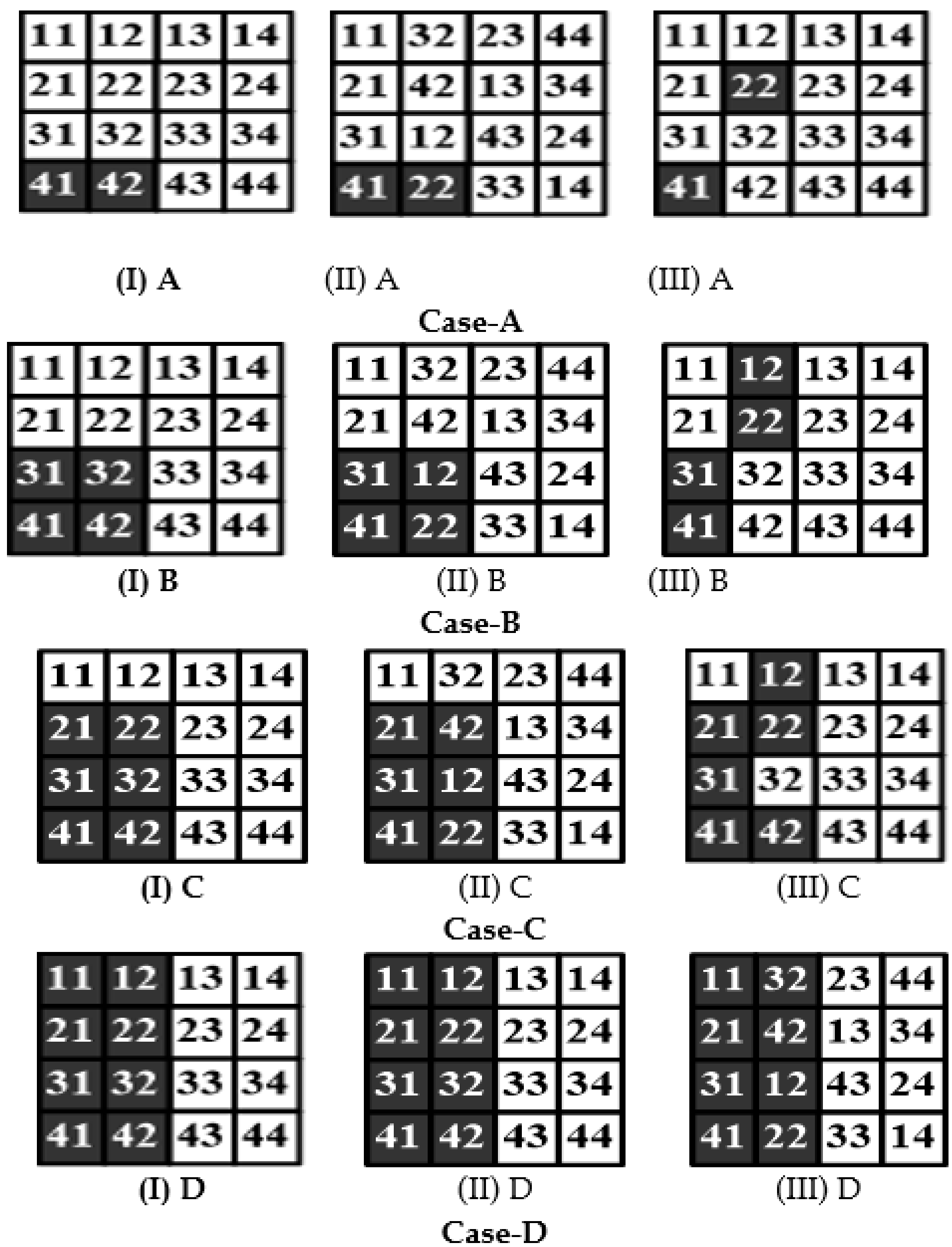


Fig.3.5a Proposed shading cases from all types of configurations Pattern1

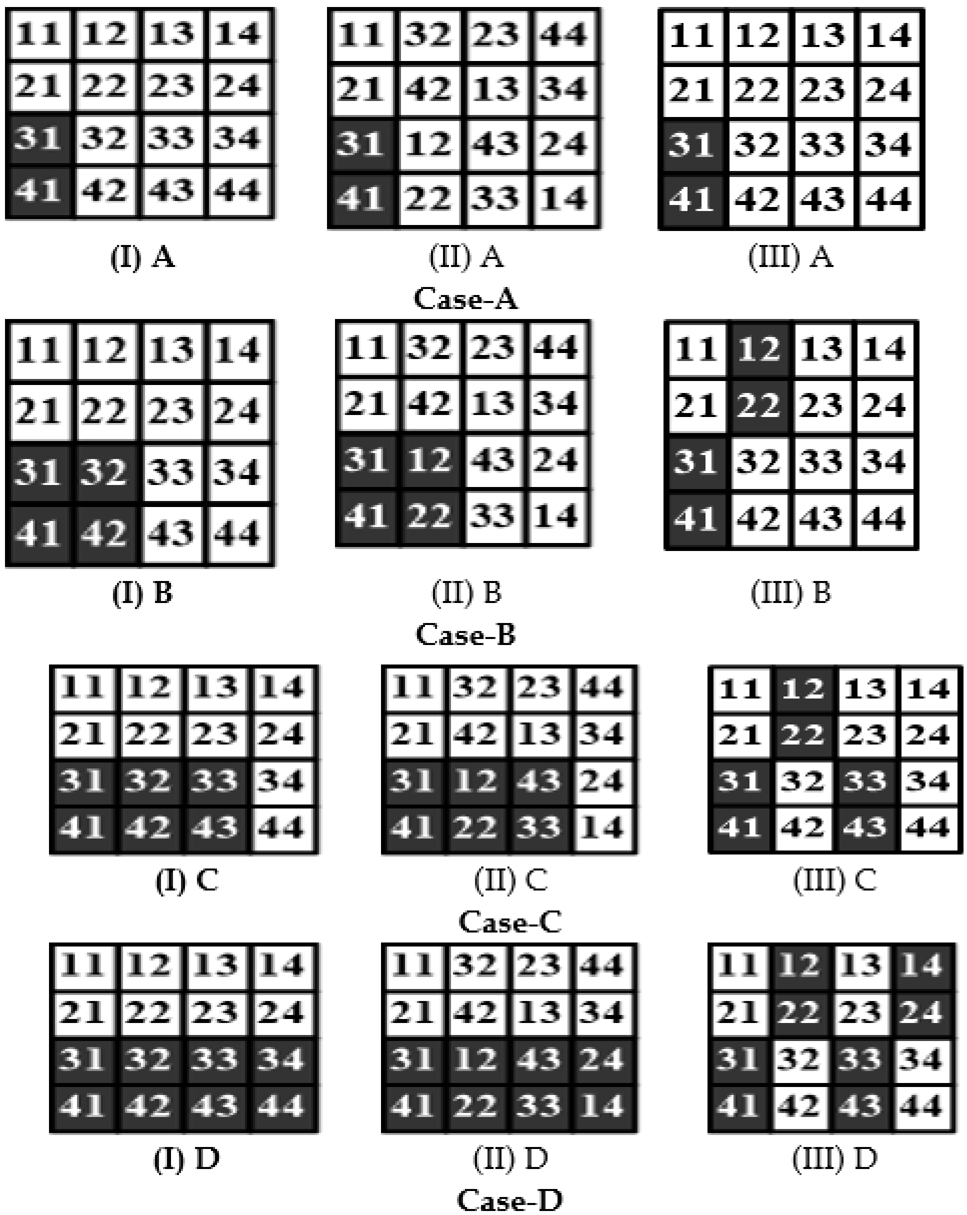


Fig.3.5b Proposed shading cases from all types of configurations

Pattern-2:

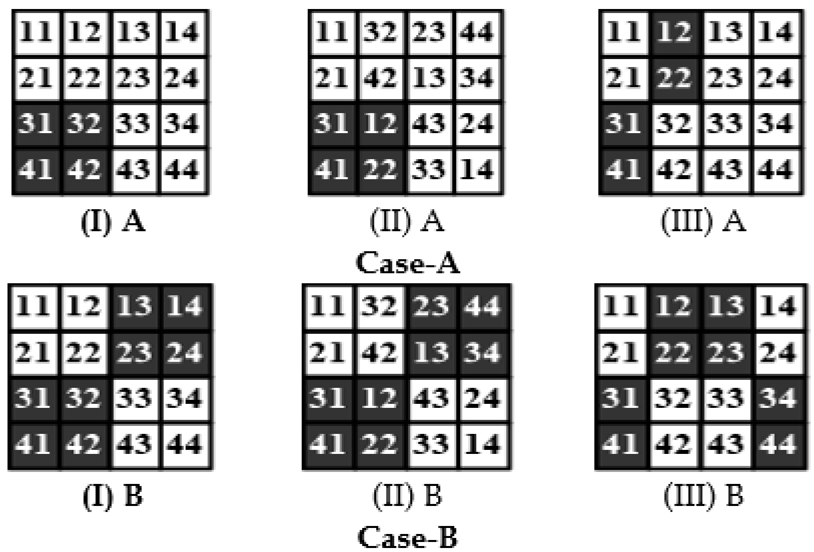


Fig 3.5c Proposed shading cases from all types of configurations Pattern-3:

3.3 Simulation, Results and Discussion

MATLAB/Simulink is used for simulation study of all configurations namely SS, SP, TCT performance analysis of PV panel with different configuration. Performance analysis for different configuration under various shade patterns have been shown in results in figure as well as tabular form.

3.3.1 Effects on MPP ofpattern-1 and shade dispersion

The PV modules with same solar irradiation of 1000W/m^{2}falling on their surface are used in the 1st, 2nd and 3rd row. But in row no. 4, there are 2 modules which receives solar irradiation of 1000W/m2 and the other 2 modules receiving solar irradiation of 350W/m2. Therefore, for 4x4 TCT PV, the array current can be calculated by case-5a shading pattern-1 as;First, second and third row-generated currents are

$$I_{R1} = 4 \times \left(\frac{G}{G_{STC}}\right) I_m = 4 \times \left(\frac{1000}{1000}\right) I_m = I_{R2} = I_{R3} = 4I_m \quad (3.10)$$

Fourth row generated current are

$$I_{R4} = 2I_m + \left(\frac{350}{1000} + \frac{350}{1000}\right) I_m = 2.7I_m \quad (3.11)$$

Similarly, the current generated by the shading pattern-1 case-b, c and d can be calculated as follows;

Case 5b:

$$I_{R1} = I_{R2} = 4I_m \text{ and } I_{R3} = I_{R4} = 2.7I_m \quad (3.12)$$

Case 5c:

$$I_{R1} = 4I_m \text{ and } I_{R2} = I_{R3} = I_{R4} = 2.7I_m \quad (3.13)$$

Case 5d:

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = 2.7I_m \quad (3.14)$$

To prove the efficacy of the proposed novel approach (i.e., So-Do-Ku configuration)of the PV array, the modules are arranged according to Su-Do-Ku puzzle model, the realignment of the array is again exposed to the shading pattern-1 as input [Fig. (5a)-(5c)] for all shading cases, the current in each row is represented as

First and third row-generated currents are

$$I_{R1} = 4 \times \left(\frac{G}{G_{STC}}\right) I_m = 4 \times \left(\frac{1000}{1000}\right) I_m = I_{R3} = 4 \quad (3.15)$$

Second and fourth row generated current are

$$I_{R2} = 3I_m + \left(\frac{350}{1000}\right) I_m = I_{R4} = 3.35I_m \quad (3.16)$$

Similarly the generated current on shading pattern-1 case-b,c and d can be calculated as;

Case 5b: $I_{R1} = I_{R2} = I_{R3} = I_{R4} = 3.35I_m$ (3.17)

Case 5c:
$I_{R1} = I_{R3} = 3.35I_m$ and $I_{R2} = I_{R4} = 2.7I_m$ (3.18)

Case 5d: $I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} = 2.7I_m$ (3.19)

The array currents for Su-Do-Ku and TCT patterns, respective power and voltages are tabulated in Table II, which clearly shows the before and after the arrangement of modules according to Su-Do-Ku puzzle configuration, the location of GP. This increases the generated power of the photo voltaic array. PV Array characteristics are plotted in Fig. 6(5a-5d) with the respect of shading pattern-1which shows the power has improved.

Table 3.2: Locations of GMPP on Su-Do-Ku and TCT configuration in shading pattern-1

TCT configuration			Su-Do-Ku configuration		
I-Case-a			***III-Case-a***		
I_R*	V	P	I_R*	V	P
I_{R4}= 2.7Im	4V_m	10.8V_mI_m	I_{R4}= 3.35Im	4 V_m	13.4 V_mI_m
I_{R3}= 4Im	3 V_m	12 V_mI_m	I_{R3}= 4Im	3 V_m	12 V_mI_m
I_{R2}= 4Im	2 V_m	8 V_mI_m	I_{R2}= 3.35Im	2 V_m	6.7 V_mI_m
I_{R1}= 4Im	V_m	4 V_mI_m	I_{R1}= 4Im	V_m	4 V_mI_m
I-Case-b			***III-Case-b***		
I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 3.35Im	4 V_m	13.4 V_mI_m
I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m
I_{R2}= 4Im	2 V_m	8 V_mI_m	I_{R2}= 3.35Im	2 V_m	6.7 V_mI_m
I_{R1}= 4Im	V_m	4 V_mI_m	I_{R1}= 3.35Im	V_m	3.35 V_mI_m
I-Case-c			***III-Case-c***		
I_{R4}=2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m
I_{R3}=2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m
I_{R2}=2.7Im	2 V_m	5.4 V_mI_m	I_{R2}= 2.7Im	2 V_m	5.4 V_mI_m
I_{R1}=4Im	V_m	4 V_mI_m	I_{R1}= 3.35Im	V_m	3.35 V_mI_m
I-Case-d			***III-Case-d***		
I_{R4}=2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m
I_{R3}=2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m
I_{R2}=2.7Im	2 V_m	5.4 V_mI_m	I_{R2}= 2.7Im	2 V_m	5.4 V_mI_m
I_{R1}=2.7Im	V_m	2.7 V_mI_m	I_{R1}=2.7Im	V_m	2.7 V_mI_m

3.3.2 Effects of pattern-2 and shade dispersion on MPP

Currents, voltages and the PV array power output are noted in Table III for Su-Do-Ku and TCT configuration which shows the power generation is increased and the PV Array characteristics plotted in Fig. 3.6(a-d) with the respect of shading pattern-2.

Table 3.3: Locations of GMPP on Su-Do-Ku and TCT configuration in shading pattern-2

TCT configuration			**Su-Do-Ku configuration**		
I-Case-a			***III-Case-a***		
I_R*	V	P	I_R*	V	P
I_{R4}= 3.35Im	4V_m	13.4V_mI_m	I_{R4}= 3.35Im	4V_m	13.4V_mI_m
I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m	I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m
I_{R2}= 4 Im	2 V_m	8 V_mI_m	I_{R2}= 4 Im	2 V_m	8 V_mI_m
I_{R1}= 4 Im	V_m	4 V_mI_m	I_{R1}= 4 Im	V_m	4 V_mI_m
I-Case-b			***III-Case-b***		
I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 3.35Im	4 V_m	13.4 V_mI_m
I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m
I_{R2}= 4Im	2 V_m	8 V_mI_m	I_{R2}= 3.35Im	2 V_m	6.7 V_mI_m
I_{R1}= 4Im	V_m	4 V_mI_m	I_{R1}= 3.35Im	V_m	3.35 V_mI_m
I-Case-c			***III-Case-c***		
I_{R4}= 2.05Im	4 V_m	8.2 V_mI_m	I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m
I_{R3}= 2.05Im	3 V_m	6.15 V_mI_m	I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m
I_{R2}= 4Im	2 V_m	8 V_mI_m	I_{R2}= 3.35Im	2 V_m	6.7 V_mI_m
I_{R1}= 4Im	V_m	4 V_mI_m	I_{R1}= 3.35Im	V_m	3.35 V_mI_m
I-Case-d			***III-Case-d***		
I_{R4}= 1.4Im	4 V_m	5.6 V_mI_m	I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m
I_{R3}= 1.4Im	3 V_m	4.2 V_mI_m	I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m
I_{R2}= 4Im	2 V_m	8V_mI_m	I_{R2}= 2.7Im	2 V_m	5.4 V_mI_m
I_{R1}= 4Im	V_m	4V_mI_m	I_{R1}= 2.7Im	V_m	2.7 V_mI_m

3.3.3 Effects of shading pattern-3 and shade dispersion on MPP

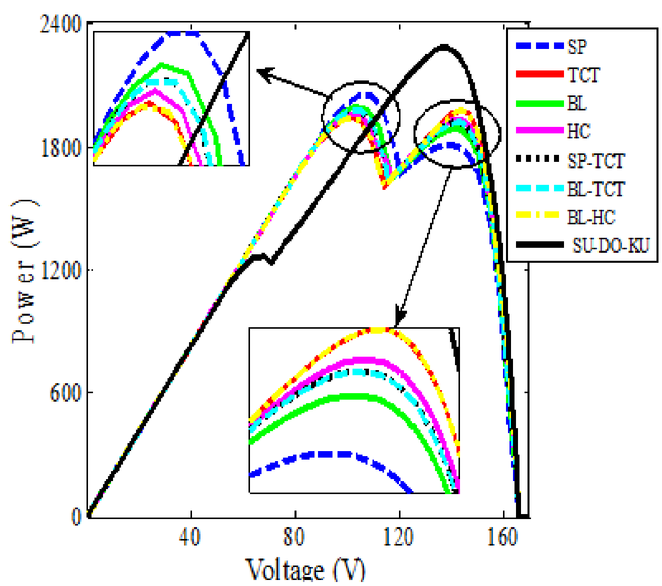
PV array currents, voltages and power for the TCT and Su-Do-Ku configuration are noted in Table IV which shows the location of GP is according to Su-Do-Ku puzzle pattern. The power outputby the array is increased and the PV Array characteristics plotted in Fig. 3.7(casea-b) with the respect of shading pattern-3.

Table 3.4: Locations of GMPP on Su-Do-Ku and TCT configuration in shading pattern-3

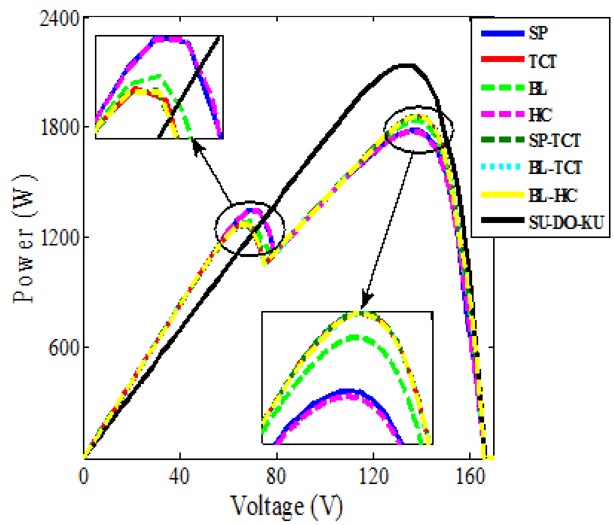
TCT configuration			**Su-Do-Ku configuration**		
I-Case-a			***III-Case-a***		
I_R*	V	P	I_R*	V	P
I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 3.35Im	4 V_m	13.4 V_mI_m
I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 3.35Im	3 V_m	10.05 V_mI_m
I_{R2}= 4Im	2 V_m	8 V_mI_m	I_{R2}= 3.35Im	2 V_m	6.7 V_mI_m
I_{R1}= 4Im	V_m	4 V_mI_m	I_{R1}= 3.35Im	V_m	3.35 V_mI_m
I-Case-b			***III-Case-b***		
I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m	I_{R4}= 2.7Im	4 V_m	10.8 V_mI_m
I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m	I_{R3}= 2.7Im	3 V_m	8.1 V_mI_m
I_{R2}= 2.7Im	2 V_m	5.4 V_mI_m	I_{R2}= 2.7Im	2 V_m	5.4 V_mI_m
I_{R1}= 2.7Im	V_m	2.7V_mI_m	I_{R1}= 2.7Im	V_m	2.7V_mI_m

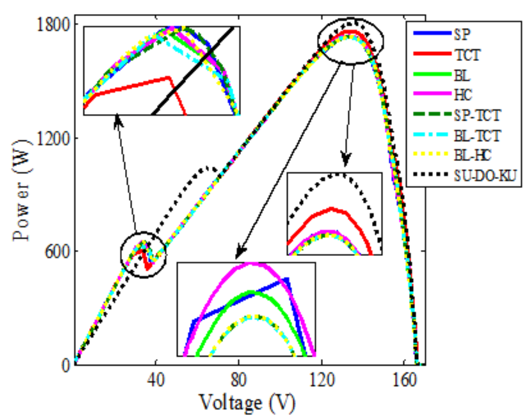
3.3.4 P-V characteristics of 4x4 PV array with shading pattern-1

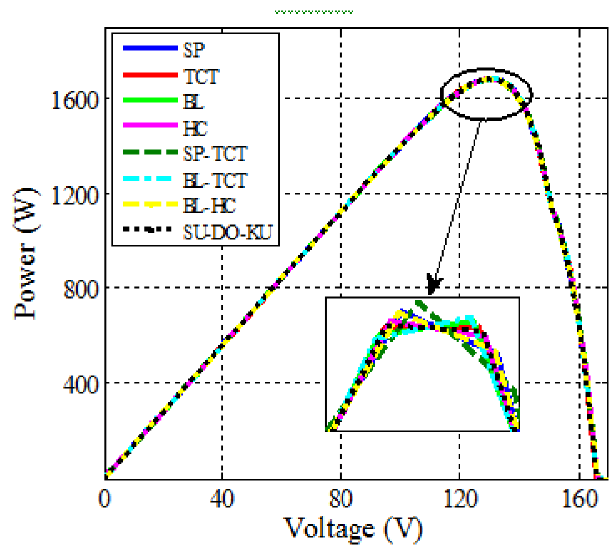
The given results depict effectiveness and superiority of the PV array (4x4) with Su-Do-Ku arrangement, simulation result also suggests that the configuration produces more power than the other available configurations. The P-V characteristics of PV array for shading pattern '1' are given in Fig.3.6 (case a-d). In this case 'a' shading, the P-V curve with two different MPPs can be observed. Here, local MPP is very close to the global MPP. Here, shading effect is observed on the power output in Fig.3.6 (case a).The power at global MPP is obtained as 1961 W, 1976 W and 2047 W, 2000 W, 1975 W, 1977 W, 1994 W and 2279 W for HC, TCT, SP,BL Hybrid BL-TCT, SP-TCT, H-6 and Su-Do-Ku topology respectively. In the case 'b' local MPP is at a distance from the global MPP is shown in Fig. 3.6(case b).



case-a


2400
1800
1200
600
0
40
80
120
160
Power (W)
Voltage (V)
SP
TCT
BL
HC
SP-TCT
BL-TCT
BL-HC
SU-DO-KU
case-b


1800
1200
600
0
40
80
120
160
Power (W)
Voltage (V)
SP
TCT
BL
HC
SP-TCT
BL-TCT
BL-HC
SU-DO-KU
case-c



case-d

Fig.3.6. Effect of shading cases (a-d) on P-V characteristics for all 4x4 PV array configurations

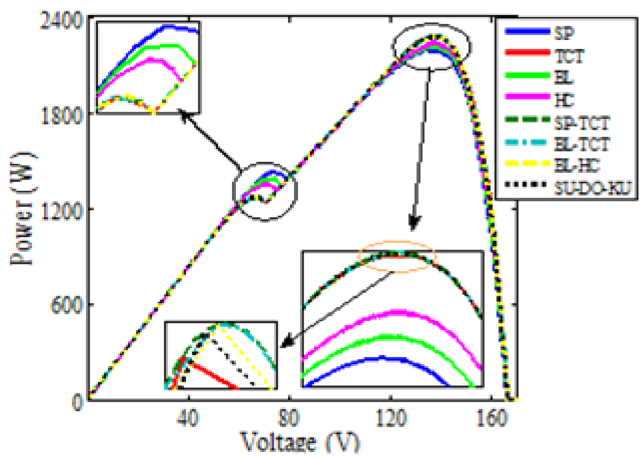
Table 3.5: Pattern-1simulation results in terms of Power (Watt) and Voltage for different configurations

Topologies	3.6 Case-a		3.6 Case-b		3.6 Case-c		3.7 Case-d	
	P	V	P	V	P	V	P	V
SP	2047	108.5	1784	136.3	1735	132	1680	131.5
TCT	1976	144	1860	138.3	1765	134.2	1680	131.5
BL	2000	103.3	1835	138	1734	132.2	1679	131.5
HC	1961	102.3	1778	136.3	1736	132.3	1679	131.5
SP-TCT	1977	104.8	1860	138.3	1732	132.1	1681	131.5
BL-TCT	1975	102.1	1860	138.3	1732	132.1	1680	131.5
BL-HC	1975	103.1	1860	138	1732	132.2	1680	131.5
SU-DO-KU	2279	137.3	2139	133	1806	135.1	1680	131.5
BEST TOPOLOGY	SU-DO-KU						ALL	

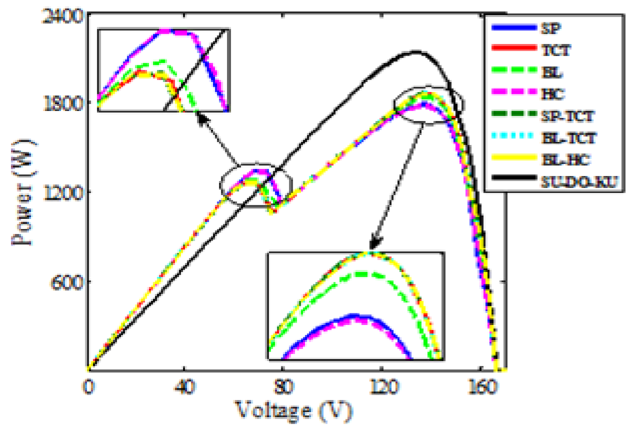
The power produced by different PV arrays using global MPP is 1784 W, 1860 W, 1835 W, 1778W, 1860W, 1860W, 1840W and 2139W for the SP, TCT, BL, HC, Hybrid BL-TCT,SP-TCT, BL-HC and the proposed topology (So-Do-Ku) respectively. The projected different configurations of the 4x4 PV array compares the power output and voltages at different locations of the GMPP as shown in the Table 3.5. similarly, for the shading case studies 'c' and case 'd' the PV characteristics are shown in Fig. 3.6(case c) and Fig. 3.6(case d) respectively. The shading effect caused due to partial shading conditions can be seen to decrease from case 'a' to case 'd' and it reaches zero for the case 'd' for all the considered topologies, i.e., TCT, SP, HC,BL, Hybrid BL-TCT, BL-HC, SP-TCT and Su-Do-Ku considered in the proposed work. The power at global maximum power point for these two cases are noticed as 1735 W, 1765 W, 1736 W, 1734W, 1732W, 1732W, 1732W and 1806W for case 'c' and 1680 W, 1680 W, 1679 W, 1679W, 1681W, 1680W, 1680W and 1680W for case 'd' respectively.

3.3.5 P-V characteristics of 4x4 PV array with shading pattern-2

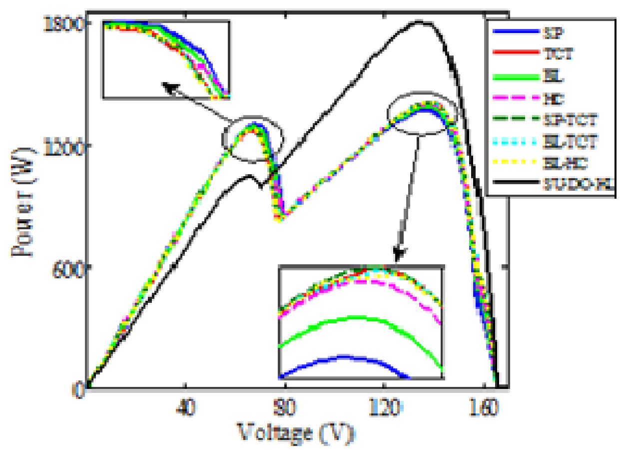
Fig.3.7 (case a-d) shows the P-V characteristics of array for shading pattern '2'. In the case 'a' shading, two maximum power points global and local are seen on the P-V curve which are very close to each other. As shown in Fig.3.7 (case a), shading effect is quite significant on the output power.



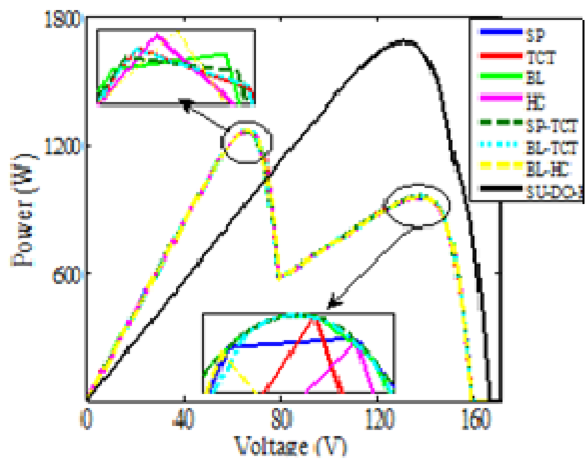
Case-a


2400
1800
1200
600
Power (W)
0
40
80
120
160
Voltage (V)
SP
TCT
BL
HC
SP-TCT
BL-TCT
BL-HC
SU-DO-KU

Case-b


1800
1200
600
0
Power (W)
40
80
120
160
Voltage (V)
SP
TCT
BL
HC
SP-TCT
BL-TCT
BL-HC

Case-c



Case-d

Fig. 3.7 Effect of shading cases (a-d) on P-V characteristics for all 4x4 PV array configurations

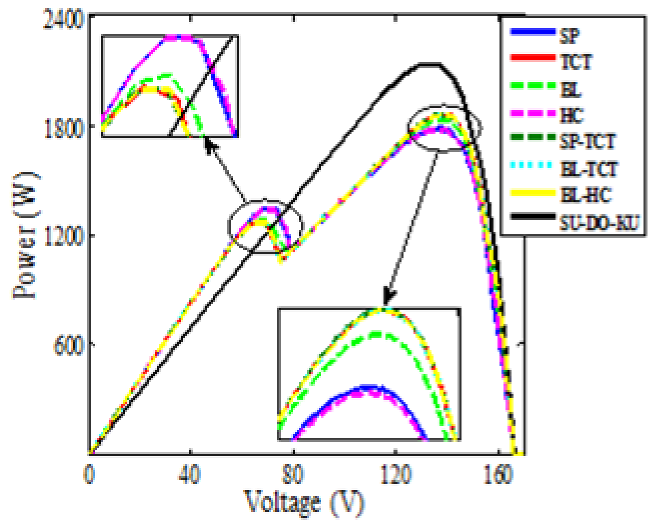
The power produced by different PV arrays using global MPP is 2232 W, 2279 W and 2213 W, 2197W, 2279 W, 2279W, 2279 W and 2279 W for HC, TCT, BL, SP, Hybrid BL-TCT, SP-TCT, BL-HC and Su-Do-Ku topologies respectively. The power output and voltages of 4x4 PV array for different configuration used here are given in Table 3.6 with reference to the different locations of GMPP. These results depicts that the 4x4 PV array with proposed Su-Do-Ku arrangement is giving more output power as compared to other classical configurations. Fig. 3.7 (case b) shows P-V characteristics for shading case ‘b. It is notice from the Fig. 3.7 (case b) that MPP at local point is far from the MPP at global point and results of shade condition on the power curve is not so enhanced as in case ‘a’. The observed output power at global MPP is 1784 W,1860 W, 1835 W, 1778W, 1860W, 1840W, 1860W and 2139W for the SP, TCT, BL, HC, Hybrid SP-TCT, BL-HC, BL-TCT and Su-Do-Ku topology. Fig.3.7 (case c) and Fig.3.7 (case d) shows the P-V curve for shading case 'c' and 'd' respectively. The result of shading is reducing from case 'a' to case 'd' and it is nullified for the case 'd' for all the considered TCT, SP, BL, HC, BL-TCT, SP-TCT, BL-HC and Su-Do-Ku topology. The generated power at MPP (global) for these cases are seen as 1390 W, 1414 W, 1371 W, 1408W, 1414W, 1414W, 1412W and 1806W for case 'c' and 1268W, 1269W, 1267W, 1267W, 1267W, 1273W, 1269W and 1682W for case 'd' respectively.

Table 3.6: pattern-2 simulation results in terms of Power (Watt) and Voltage (V) for various configurations

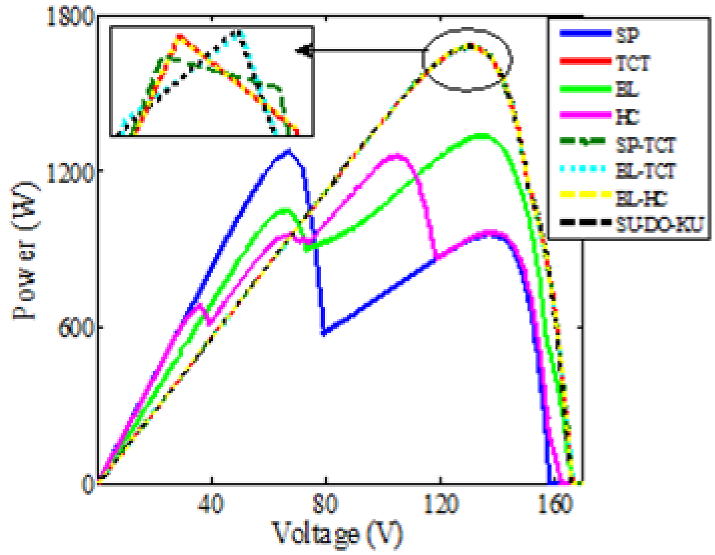
Topologies	3.5b Case-a		3.5b Case-b		3.5b Case-c		3.5b Case-d	
	P	V	P	V	P	V	P	V
SP	2197	136.4	1784	136.3	1371	137.4	1268	66.63
TCT	2279	137.3	1860	138.3	1414	138.7	1269	66.63
BL	2213	137.2	1835	138	1390	138.1	1267	66.63
HC	2232	137.1	1778	136.3	1408	137.8	1267	66.63
SP-TCT	2279	137.3	1860	138.3	1414	138.7	1267	66.63
BL-TCT	2279	137.1	1860	138.3	1414	138.7	1267	66.63
BL-HC	2279	137.2	1860	138	1412	138.1	1273	66.63
SU-DO-KU	2279	137.3	2139	133	1806	135.1	1682	131.5
BEST TOPOLOGY	SU-DO-KU		SU-DO-KU		SU-DO-KU		SU-DO-KU	

3.3.6 P-V characteristics of 4x4 PV array with shading pattern-3

Fig. 3.8 shows the P-V characteristics of PV array with different configurations (SP, TCT, HC, BL, BL-HC, SP-TCT, BL-TCT and Su-Do-Ku) for case 'a' and 'b' with shading pattern '3'.



Case-a



Case-b

Fig.3.8 Effect of shading cases on P-V characteristics for all different configurations

For the shading 3.5 C case 'a' similar to the pattern-2 3.5 B case 'b', so we discuss the only shading 3.5 C case 'b'. As shown in results two MPP local and global are seen on the P-V curve, which are very close to each other. The effect of shading is quite significant on the power output, which is to be seen in Fig. The power at global MPP is obtained as 1335 W, 1681 W, 1274 W, 1257W, 1681 W, 1679W, 1681 W and 1681 W for BL, TCT, SP, HC, Hybrid BL-TCT,SP-TCT, BL-HC and Su-Do-Ku topology respectively. Output power and voltages of photo voltaic array with different configurations techniques are compared with respect to the global maximum power point, given in Table 3.7.

Table 3.7: pattern-3 simulation results: Power (Watt) and Voltage (V) for different configurations

Topologies	3.5c Case-a		3.5c Case-b	
	P	V	P	V
SP	1784	136.3	1274	67.07
TCT	1860	138.3	1681	131.5
BL	1835	138	1335	134.1
HC	1778	136.3	1257	105
SP-TCT	1860	138.3	1679	131.5
BL-TCT	1860	138.3	1681	131.5
BL-HC	1860	138	1681	135.9
SU-DO-KU	2139	133	1681	131.5
BEST TOPOLOGY	SU-DO-KU		SU-DO-KU	

Here in this work, in Su-Do-Ku configuration the voltage, current, power have been calculated. The performance analyses for other classical configurations like SP, BL, TCT,HC, BL-HC, BL-TCT, BL-HC and SP-TCT have also done. The obtained voltage, current, power has been considered performance parameters for considered PV array with different classical and proposed configuration. The shade dispersion effect on PV array with various configurations is also investigated. Different partial shading patterns are applied to photo voltaic module to assess the performance of different PV array configuration. Simulation results confirm the efficacy of proposed Su-Do-Ku configuration for photovoltaic array. Results clearly show that, the proposed novel configuration of Su-Do-Ku has enhanced the output power and performances and is better than the other configurations with puzzle shade dispersion and different partial shading conditions.

Chapter-4

Study on a newPVArray configuration to enhance the power and performances of 9x4 PVArrays with shade dispersion

4.1 Introduction

Declination of fossil fuels with ever increasing environmental pollution is a real concern of today's time. This has compelled the tremendous growth of Renewable Energy Sources (RES) research to balance the growing demand for energy. Solar is one of the most attractive renewable energy sources for power distribution. Solar energy is a cleaner source of energy and does not responsible for any pollution as well as global warming. For this reason, solar energy systems are correspond to future investment for conserving of non-renewable energy sources and environmental protection [4.1-4.10]. Scientists are busy on improving the Photo Voltaic (PV) cell technology which is the fundamental block for converting solar energy into electrical energy. PV cell operates based on the principle of photoelectric phenomenon. Compared to other sustainable power sources it is more reliable, safe, low cost and required minimal maintenance. However, there are some issues with PV cell. Since the PV cell works on sun light, shading is a real concern for PV cell. Efficiency of a solar panel is highly affected by shading. Even partial shading affects a solar panel's efficiency. Because in partial shading condition the operational temperature increases. It can reach upto 150˚C, where as the safe operating temperature of a PV cells is approximately 85 ° C. This over heating phenomenon creates local over heating (hotspot) which is the most frequently occurred phenomenon and can seriously damages the PV cell. This is a most frequent phenomenon occurred in solar panel which limits the operation life of PV cells. Moreover, partial shading also affects the efficiency of the PV modules. To mitigate the partial shading problem a large number of researchers are working on distinct arrangement of the PV modules. The photon current flowing through each series connected PV cells must be equal so as to improve the efficiency of a PV array, which is not the case in partial shading condition. Since, in partial shading condition the shaded cell is in reverse biased condition which behaves as a resistance. To avoid this situation, diodes are connected across shaded PV cells in order to carry the current of reverse bias. Hence, the reverse bias current, and formation of hotspot on the PV cells can be avoided. However, power consumption increases in this case. A shadow upon the solar panel also affects the various parameters like irradiance; temperature levels etc. In partial shadow condition solar panel receive unbalance solar irradiation [4.11-4.20]. Hence, the PV arrays depict numerous peaks in P-V and I-V curve due to bypass circuit activation.Partial shadow effect can be minimized by a new configuration of PV array design. Various configuration of PV array design is available in the literature like, Total cross tied (TCT), Honey-comb (HC),Bridge-link (BL),Series-parallel (SP), for different shading pattern etc [4.21-4.30]. A PV module is configured with a number of interconnected PV cell. Usually, 36 cells are serially connected. The connection of PV cells depends on the PV module voltage (series) / current (parallel) rating. The electrical properties of the PV cells should be same.

This paper introduced a new model for Photo Voltaic array configuration, and its efficiency has been studied. To improve the efficiency of the partially shaded PV system is the real challenge. Local and global maximum power points (MPPs) should be monitored to determine the shading effect. Due to the different solar irradiation obtained by the PV array during the partial shading condition as received during no shading period, the power generated by the PV system is reduced during the partial shading. Due to its simplicity and cost-effectiveness, the commonly used traditional incremental conductance and perturb & observe MPP tracking (MPPT) has a significant implementation [4.31-4.41].

Solar PV modules performance is based on the level of solar radiation and certain environmental factors.

This chapter proposes a new PV system design to enhance PV system performance under the partial shadingcondition. This design uses different PV modules rearrangement techniques. In the presence of different shading patterns, the performance analyses of the PV array (9x4) with the proposed configuration and some other configurations have been performed. Detailed comparative studies have also been done show the superiority of the proposed configuration with different configurations. The MATLAB / Simulink software is used to model photo voltaic module with different configurations [4.42-4.49].

The remaining chapter is structured in the following manner. Section 2 addresses PV cell modeling. Section 3 describes different configurations used for the PV array to manage partial shading condition. Section 4 introduces a new configuration for the photovoltaic array. Section 5 analyzes the PV array for different configurations. Section 6 provides a conclusion.

4.2 MATHEMATICALMODELING OF PHOTO VOLTAIC CELL

Solar photovoltaic cell working is basedon the principle of energy conservation and electrical energy transfer from heat and light energy. This is the PV array's fundamental building block.A single PV cell is a diode made from a highly doped silicon wafer p-n junction. A large number of p-n junction diodes are connected in various combinations and methods to increase the power generated and make the PV module the desired size and capacity. Power generation of a PV pane depends on sun radiation incident on its floor and temperature. Hence, the electricity generation varies with time to time as well as in seasons. Total radiation incident on an inclined PVpanel can be given as follows [4.50]:

$$I_T=I_bR_b+I_dR_d+(I_b+I_d)R_d \quad (4.1)$$

Where, $I_d$and $I_b$stands for diffuse radiation normal radiation respectively. $R_d$and R_r are the tilt factor for diffuseand reflected radiation respectively. Fig. 4.1 shows the PV cell's electrical equivalent circuit, where a diode and a resistor are connected with a current source as,

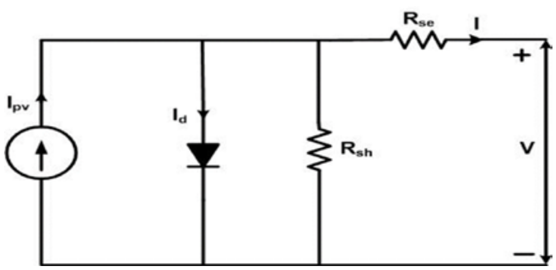


Fig. 4.1 Equivalent circuit of single diode solar cell

PV array is the interconnection of large number of PV cells [4.50]. As illustrated in Fig.4.1, a series and parallel resistors is connected to the PV cell equivalent circuit to reflect internal photovoltaic cell losses [4.50]. The value of this resistance is zero and infinite for a PV cell functioning in the ideal condition.The PV cell's reduction in efficiency is represented through power dissipation across the series and parallel resistor. The current passes through the diode connected across the current source as shown in Fig. 1, can be given by Shockley diode equation [4.50].

Mathematically, Solar PV cell voltage (V_C) depends on solar irradiation and current (I_{ph}), is expressed as,

$$V_C = \frac{AkT_C}{e}\ln\left(\frac{I_{ph}+I_o-I_c}{I_o}\right)-R_sI_c \qquad (4.2)$$

where, I$_d$ is the diode current,

I$_s$ is the reverse saturation current,

Q = elementary charge,

K = Boltzmann's constant,

N = Ideality factor.

The temperature coefficients for current (C_{TI}) and voltage (C_{TV}) for PV cell can be given by Eq. (3) [4.50],

$$C_{TV} = 1+\beta\left(T_a-T_x\right) \;\&\; C_{TI} = 1+\frac{\gamma_T}{S_C}\left(T_x-T_a\right) \qquad (4.3)$$

The operating temperature T_x depends on ambient temperature (T_a) and solar irradiation level. Two correction factors C_{SV} and C_{SI} are needed to calculate the effect of irradiation level (S_x) on the photo current and voltage, as given by Eq. (4.4),

$$C_{SV} = 1+\beta_T\alpha_S\left(S_x-S_c\right) \;\&\; C_{SI} = 1+\frac{1}{S_c}\left(S_x-S_c\right) \qquad (4.4)$$

Where, S_c represents reference solar irradiation and S_x represents new irradiation level. The magnitude of the PV cell voltage V_{cx} and photo current I_{phx}, can be given as Eq. (4.5),

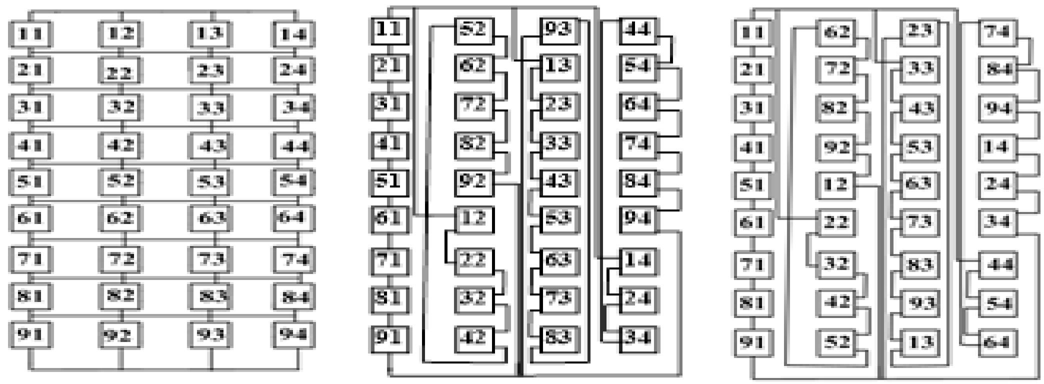
$$V_{cx} = C_{TV} C_{SV} V_C \ \& \ I_{phx} = C_{TI} C_{SI} I_{ph} \tag{4.5}$$

4.3 MODELLING OF PV ARRAY CONFIGURATION

The performance of the PV system is dependent on the irradiation, temperature, aging, particles of dust such as sand and ash etc. New topologies are explored and used to optimize efficiency.In the present study, different topologies of PV array, e.g. NS-1, NS-2 and TCT, are studied for the various shadeconditions and patterns to examine and improve the PV moduleefficiency. Therefore, in shading situation, the behavior of PV arrays is more important.

The performance of the array is degraded as an effect of shadings [4.51-4.59]. By changing the interconnection of the solar PV array, a way outfor this type of shading problem can be provided, so conventional topologies contain less interconnections compared to the TCT.

In this paper, with proposed topologies such as TCT, NS-1 and NS-2, the 9x4 PV array is simulated as shown in Fig. 4.2. The presented two topologies of the PV array are designed in the MATLAB / Simulink environment [4.60-4.66].



(a) TCT (b) NS-1 pattern (c) NS-2 pattern

Fig. 4.2 Solar PV array topologies.

The proposed configuration of the 9x4 model is shown in fig. 4.2, where the digits represent the position of the row and column respectively. Here, the panel position is changed without disturbing the panel's electrical connection.Since the array's electrical configurations do not change with the panel position, for all configurations, the voltage & current equations remain the same [4.50].

The current generated by PV modules can be given as Eq. (6).

$$I = \left(\frac{G}{G_{STC}}\right) \times I_m \tag{4.6}$$

Where, I_m is the generated module current. The Array voltage can be expressed as,

$$V = \sum_{n=1}^{4} V_{mn} \qquad (4.7)$$

Where, V_{mn} is the n^{th} row voltage of photo voltaic array.A solar cell's fill-factor can be determined from the P-V curves. It varies and describes partial shading conditions as,

$$FF = GMPP/Voc \times Isc \qquad (4.8)$$

Where, LMPP is local point of maximum power and GMPP is global point of maximum power under partial shaded conditions. In the scenario when the multiple Maximum Power Points (MPPs) are considered that conventional tracking techniques do not give the desired results for tracking the GMPP.

Power loss in the partially shaded PV array can be expressed as,

Power loss = (Maximum power of PV array without PS – GMPP with PS) (4.9)

4.4 ANALYSIS OF 9X4 PV ARRAY SHADING PATTERNS

In order to determine the effect of shading on the PV array, two separate shading patterns are considered. Pattern-1 has nine (a-i) cases, but pattern-2 has only four (a-d) cases. Two different levels of irradiation are taken for output analysis on pattern-1 and pattern-2 in all two models (350W / m2 and 1000W / m2) as shown in fig. 4.3.

Table 4.1 gives the values of different parameters of PV module (for commercial use) at standard test condition (STC).

Table 4.1. Parameters of photo voltaic module at STC (1000W/m^2 and 25^{0}C)

Parameters	Values
No. of cell	72
Open circuit voltage	44.2 V
Short circuit current	5.2 A
PV power	170 W
Current at MPP	4.75 A
Voltage at MPP	35.8 V

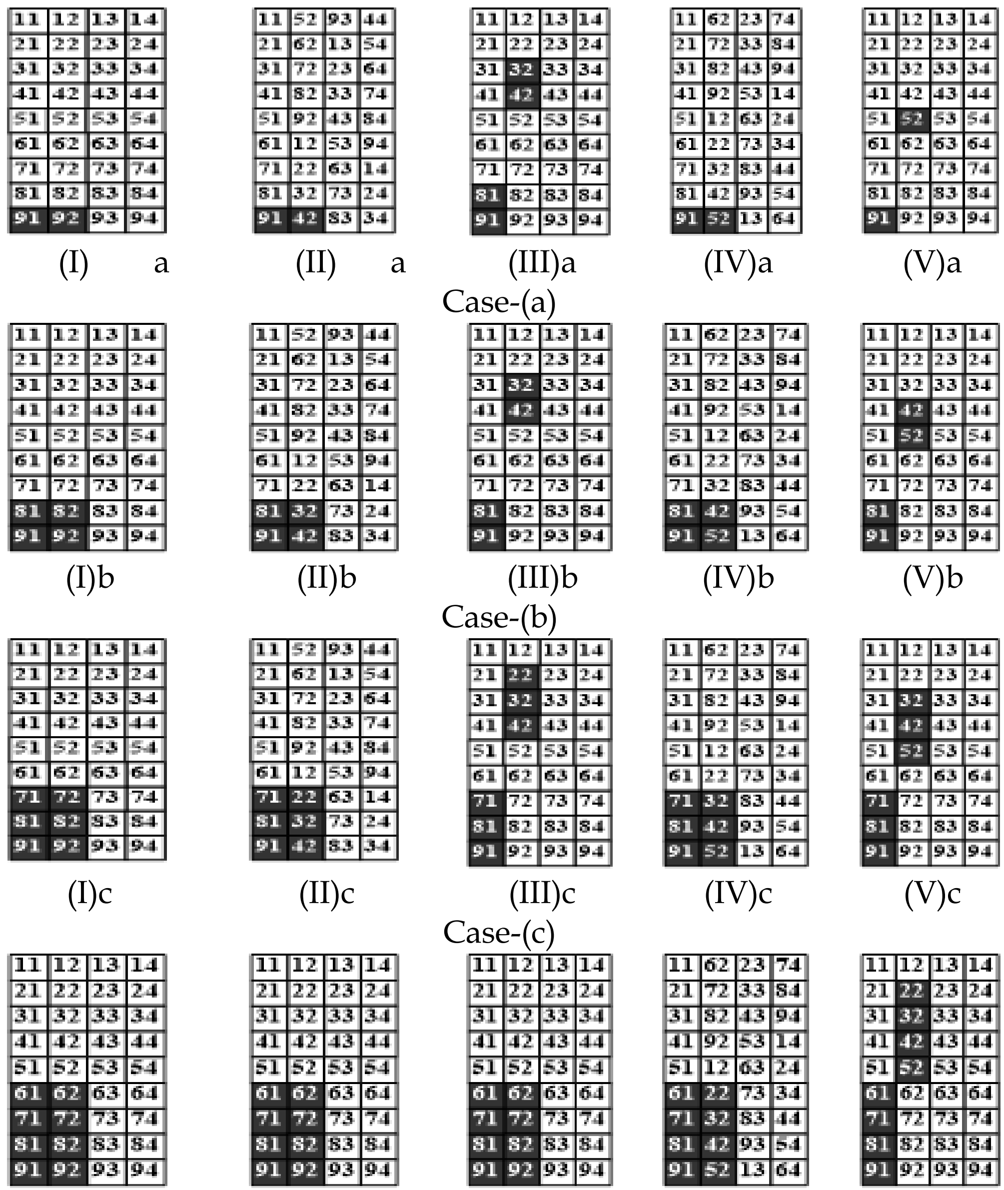
Arrangements method for NS-1 and NS-2 configurations are depicted in Table 4.2

Table 4.2. Arrangement of Digits by using Proposed NS-1 and NS-2 method for 9x4 PV Array

NS-1 Arrangement			
Column 1	**Column 2**	**Column3**	**Column4**
11	52	93	44
21	62	13	54
31	72	23	64
41	82	33	74
51	92	43	84
61	12	53	94
71	22	63	14
81	32	73	24
91	42	83	34

NS-2 Arrangement			
Column 1	**Column 2**	**Column 3**	**Column 4**
11	62	23	74
21	72	33	84
31	82	43	94
41	92	53	14
51	12	63	24
61	22	73	34
71	32	83	44
81	42	83	54
91	52	93	64

Shading cases for 9x4 PV array with all types of configuration is shown below.



(I) a (II) a (III)a (IV)a (V)a

Case-(a)

(I)b (II)b (III)b (IV)b (V)b

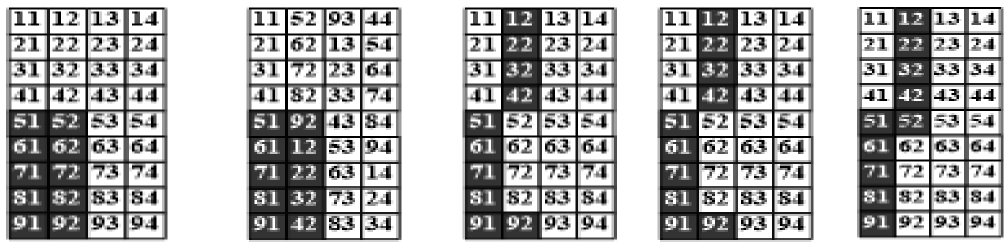
Case-(b)

(I)c (II)c (III)c (IV)c (V)c

Case-(c)

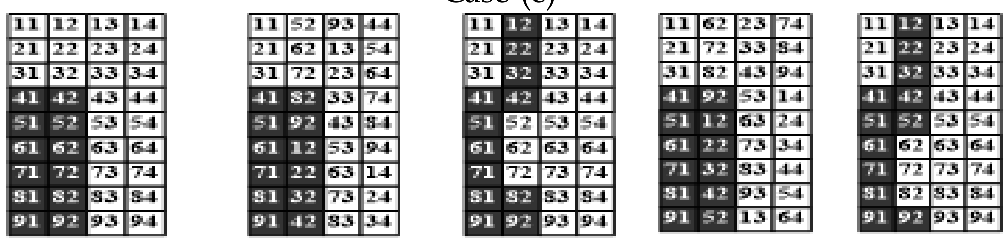
(I)d (II)d (III)d (IV)d (V)d

Case-(d)



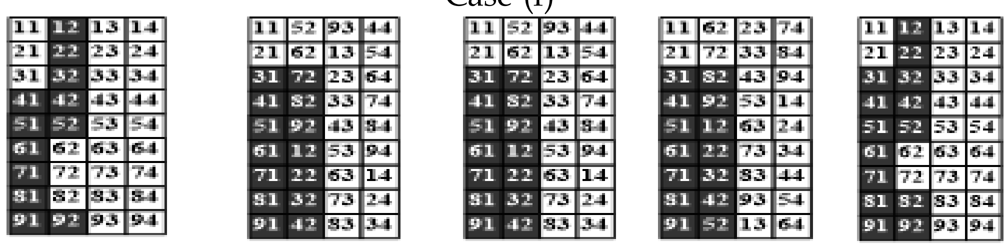
(I)e (II)e (III)e (IV)e (V)e

Case-(e)



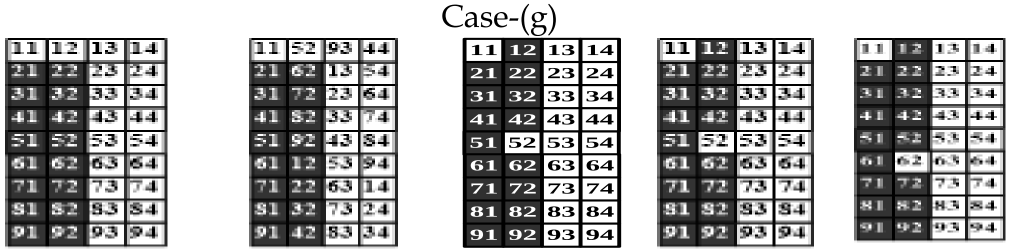
(I)f (II)f (III)f (IV)f (V)f

Case-(f)



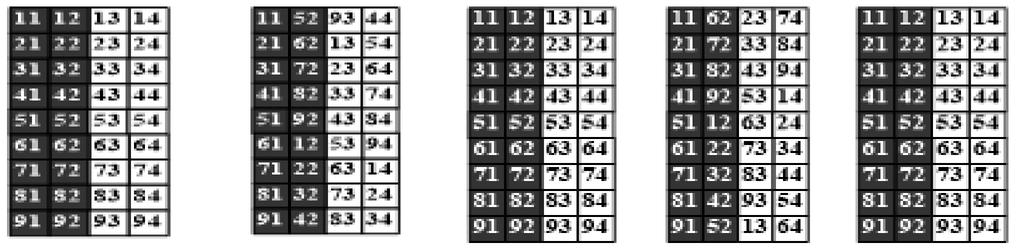
(I)g (II)g (III)g (IV)g (V)g

Case-(g)



(I)h (II)h (III)h (IV)h (V)h

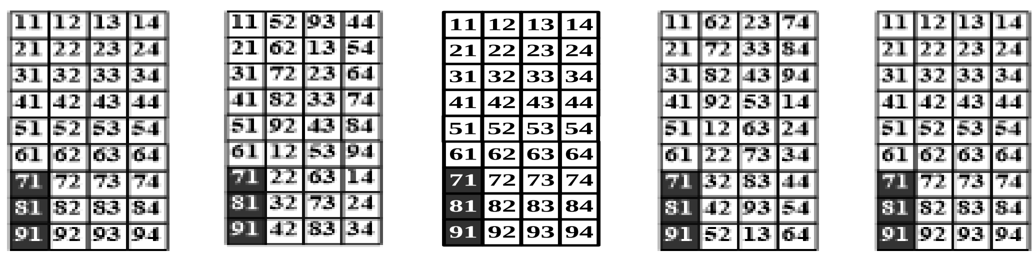
Case-(h)



(I)i (II)i (III)i (IV)i (V)i

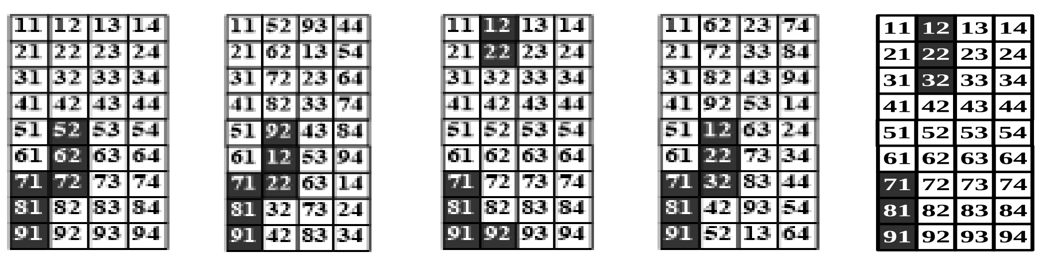
Case-(i)

Fig. 4.3 Proposed shading cases of Pattern-1 from all types of configurations



(I) a (II) a (III) a (IV)a (V) a

Case-(a)



(I) b (II) b (III) b (IV)b (V) b

Case-(b)

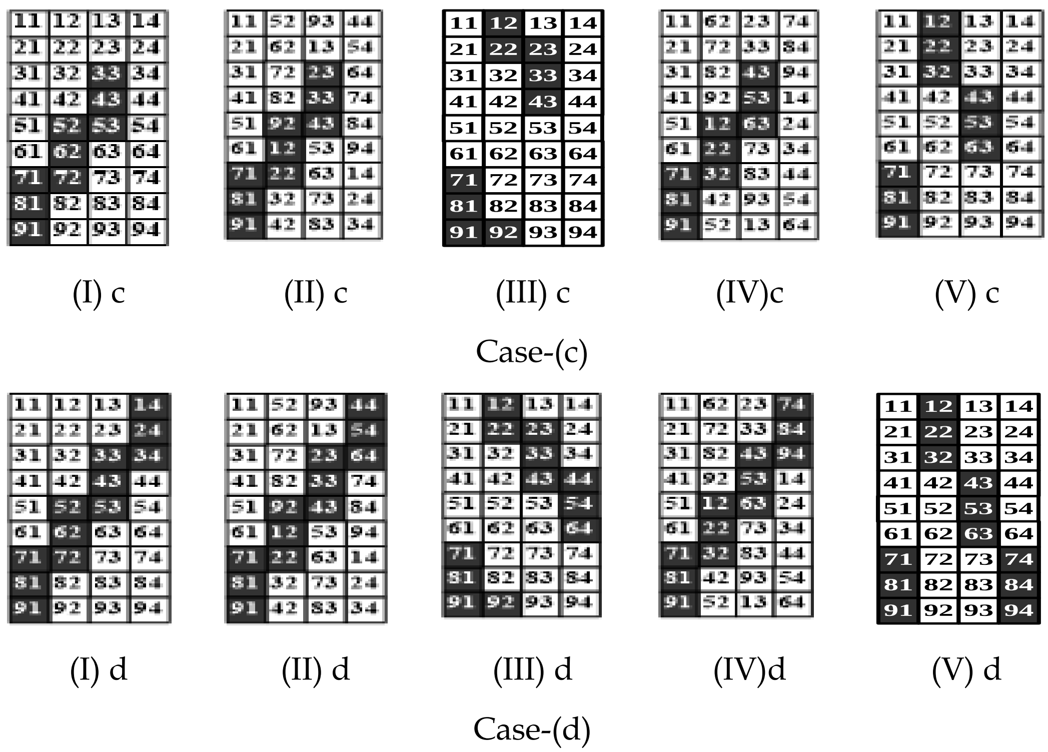


Fig. 4.4. Proposed shading cases from diagonal on all topologies and shade dispersion arrangement (pattern -2)

4.5 SIMULATION, RESULTS AND DISCUSSIONS

Simulation study and performance analysis of PV panel for three different configurations has been performed on the MATLAB/Simulink platform. The results shown in figure as well as tabular formfor different configuration under different shade patterns.The cases shown in Figure 4.4(a) for NS-1, NS-2 and TCT are examined. The shadow is in left side and how configuration of PV array is impacted by the shadow is described by Fig.4.5(a). It can be observed that there is a space between LMPP and GMPP. In terms of shading shifting the power of 3342 W is produced by both the configurations at real PPP. It is clearly observed from the figure that the shadow now shifted to PV array and its impact on P-V profiles is examined. As described in Figure 4 many LMPP's are generated due to shading.

4.5.1 Effects on MPP of Shading pattern-1 and shade dispersion

The PV modules falling on their surface with the same 1000W/m^2 solar irradiation are used in the 1-8th row,but in the 9th row two modules are receiving 1000W/m^2 solar irradiation and 350W/m^2 received by two other modules. Therefore, for 9x4 PV (TCT), for 4.3 case-(I)a shading pattern-1, the array current can be calculated by as;Generated currents forfirst, second and third row- are

$$\mathrm{I_{R1}} = 4 \times \left(\frac{\mathrm{G}}{\mathrm{G_{STC}}}\right) \mathrm{I_m} = 4 \times \left(\frac{1000}{1000}\right) \mathrm{I_m} = 4\mathrm{I_m} \quad (4.9)$$

$$\mathrm{I_{R1}} = \mathrm{I_{R2}} = \mathrm{I_{R3}} = \cdots = I_{R8} = 4\mathrm{I_m} \quad (4.10)$$

Fourth row generated current are

$$\mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{350}{1000} + \frac{350}{1000}\right) \mathrm{I_m} = 2.7\mathrm{I_m} \quad (4.11)$$

In case of 4.3 case-(III)a, the array current can be calculated by as; generated currents for row1 to row3 and row5 to row8 all the modules are exposed to 1000W/m^2 and in row 4 and row 9 one module is exposed to 350W/m^2 and rest three modules in each receives 1000W/m^2

$$I_{R1} = 4 \times \left(\frac{G}{G_{STC}}\right) I_m = 4 \times \left(\frac{1000}{1000}\right) I_m = 4I_m \quad (4.12)$$

Similarly, the following row current $I_{R1}, I_{R2}, I_{R3}, I_{R5}, I_{R6}, I_{R7}$ *and* I_{R8} have same magnitude value $4I_m$. the other two rows generated current is given by

$$I_{R9} = 3I_m + \left(\frac{350}{1000}\right) I_m = 3.35I_m = I_{R4} \quad (4.13)$$

Similarly, for shading pattern-1 case-b, c and d, the current generated can be calculated as follows;

4.3 Case (I)b:

$$I_{R1} = I_{R2} = \cdots = I_{R7} = 4I_m \text{ and } I_{R8} = I_{R9} = 2.7I_m \quad (4.14)$$

4.3 Case (I)c:

$$I_{R1} \text{to } I_{R6} = 4I_m \text{ and } I_{R7} = I_{R8} = I_{R9} = 2.7I_m \quad (4.15)$$

4.3 Case (I)d:

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} = 4I_m \quad (4.16)$$

$$I_{R6} = I_{R7} = I_{R8} = I_{R9} = 2.7I_m \quad (4.17)$$

4.3 Case (I)e:

$$I_{R1} = I_{R2} = I_{R3} = I_{R4} = 4I_m \quad (4.18)$$

$$\mathrm{I_{R5}} = \mathrm{I_{R5}} = \mathrm{I_{R7}} = \mathrm{I_{R8}} = \mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{3500}{1000} + \frac{3500}{1000}\right) = 2.7\mathrm{I_m} \tag{4.19}$$

4.3 Case (I)f:

$$\mathrm{I_{R1}} = \mathrm{I_{R2}} = \mathrm{I_{R3}} = 4\mathrm{I_m} \tag{4.20}$$

$$\mathrm{I_{R4}} = \cdots = \mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{3500}{1000} + \frac{3500}{1000}\right) = 2.7\mathrm{I_m} \tag{4.21}$$

4.3 Case (I)h:

$$\mathrm{I_{R1}} = \mathrm{I_{R2}} = 4\mathrm{I_m} \tag{4.22}$$

$$\mathrm{I_{R3}} = \cdots = \mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{3500}{1000} + \frac{3500}{1000}\right) = 2.7\mathrm{I_m} \tag{4.23}$$

4.3 Case (I)h:

$$\mathrm{I_{R1}} = 4\mathrm{I_m} \tag{4.24}$$

$$\mathrm{I_{R2}} = \cdots = \mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{3500}{1000} + \frac{3500}{1000}\right) = 2.7\mathrm{I_m} \tag{4.25}$$

4.3 Case (I)i:

$$\mathrm{I_{R1}} = \cdots = \mathrm{I_{R9}} = 2\mathrm{I_m} + \left(\frac{3500}{1000} + \frac{3500}{1000}\right) = 2.7\mathrm{I_m} \tag{4.26}$$

With the respect of shading pattern-1, PV array characteristics are plotted in Fig. 4.5(a-i) which shows the power has improved.

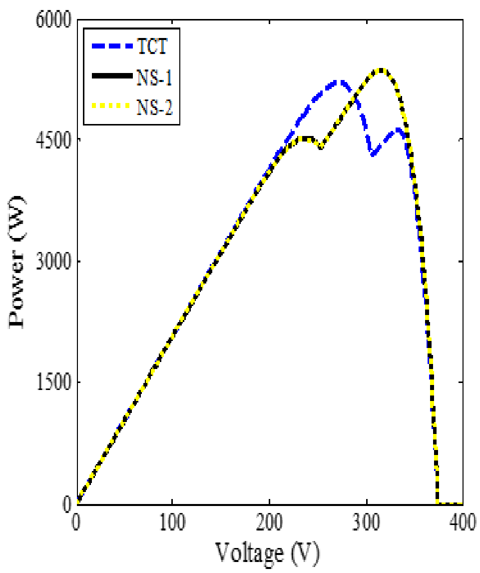


Fig. 4.5 'a' (for case- 4a)

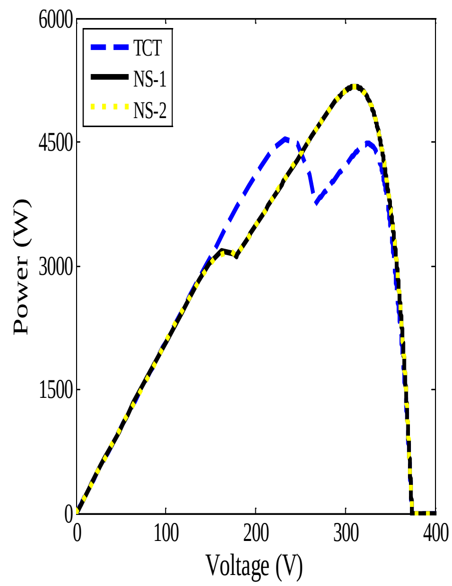


Fig. 4.5'b' (for case- 4b)

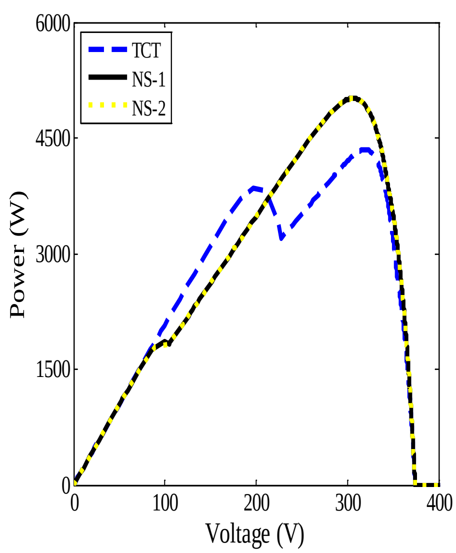


Fig. 4.5 'c' (for case- 4c)

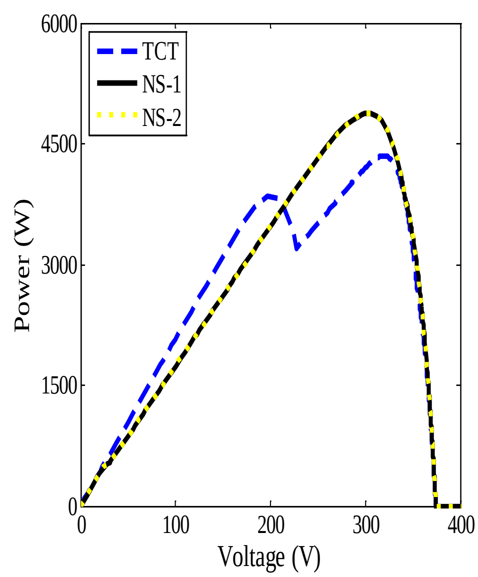


Fig. 4.5 'd' (for case- 4d)

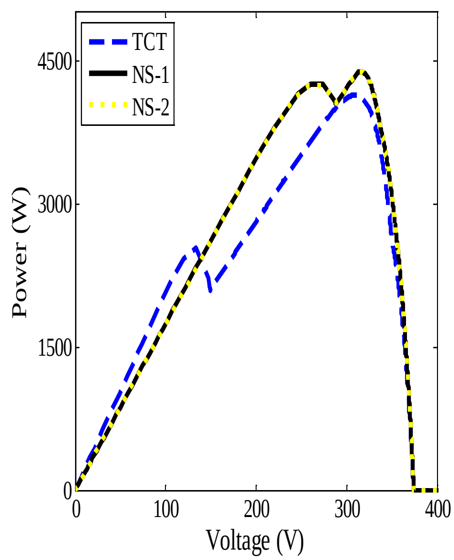


Fig. 4.5 'e' (for case- 4e)

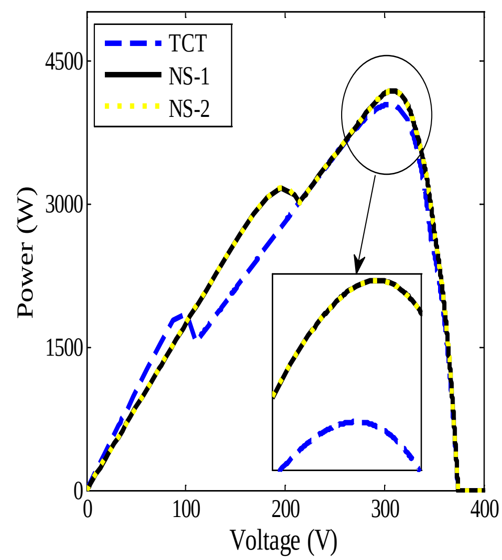


Fig. 4.5 'f' (for case- 4f)

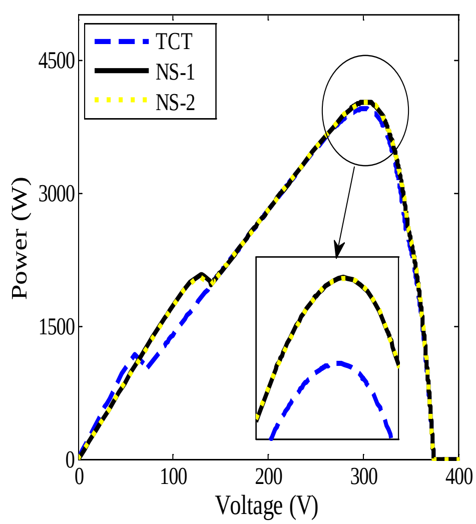


Fig. 4.5 'g' (for case- 4g)

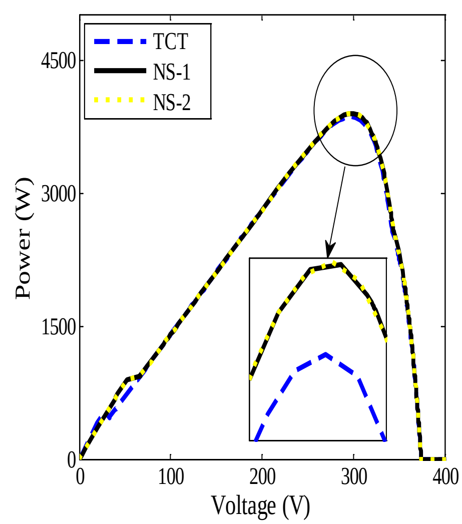


Fig. 4.5 'h' (for case- 4h)

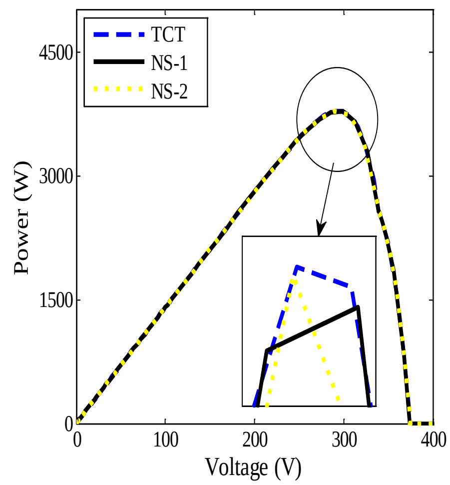


Fig. 4.5 'i' (for case- 4i)

Fig. 4.5 Effect of shading pattern-1 on PV characteristics of 9x4 PV array for TCT, NS-1 and NS-2 topologies

4.5.2 P-V characteristics of 9x4 PV array with shading pattern-2

PV array Power- Voltage characteristics under the partial shading pattern 2 results shown in fig 4.6(a-d). On the P-V curve, two different global and local power points are observed that are very similar to each other. As shown in Fig.4.6, the shading effect on the output power is very significant. In each case, NS2 and NS1 results are superior than TST.

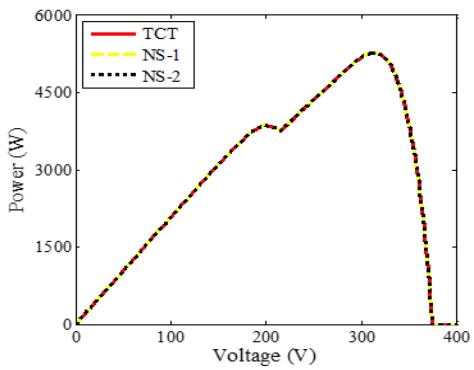


Fig. 4.6. ‘a’ (for case- 3a)

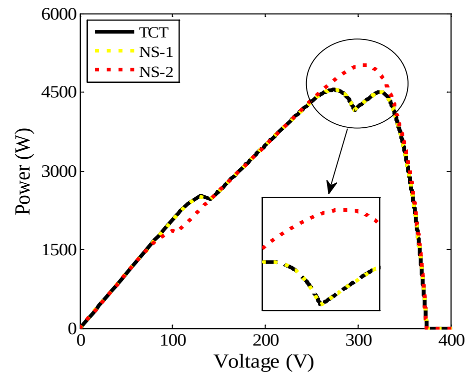


Fig. 4.6.‘b’ (for case- 3b)

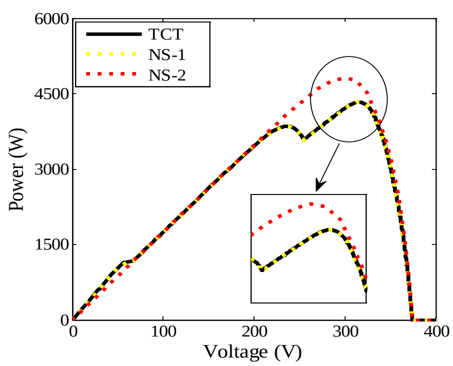


Fig. 4. 6. ‘c’ (for case- 3c)

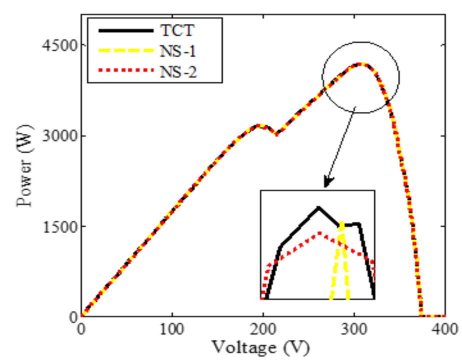


Figure 4.6.‘d’ (for case- 3d)

Fig. 4.6. Effect of shading pattern-2 on PV characteristics of 9x4 PV array for TCT, NS-1 and NS-2 topologies

4.5.3 P-V Effect of shading pattern-1 on power losses and fill factor for 9x4 PV array

The results showthe effectiveness and superiority of the PV array (9x4) with TCT arrangement, simulation result also shows that the configuration consumes more power losses than the other available arrangements. The P-V power loss graph given in Fig.4.7 (case a-i) depicts that power loss is high for TCT arrangement (case a-d). However, in the case 'e' to 'h' power loss is comparable with other arrangements. In case of 'i' power loss is equal for all configuration is shown in Fig. 4.7(case i).

Fill factor for 9x4 PV array of all three configurations are almost comparable. Fill factor of TCT is slightly lower in case of a-h. However, it is equal for all arrangements in case of 'i', as shown in fig 4.8.

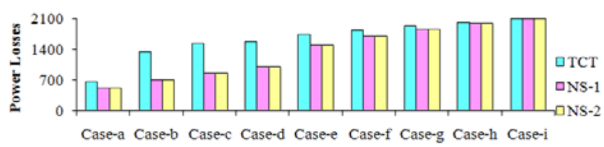


Fig. 4.7. Effect of shading pattern-1 on power losses for 9x4 PV array

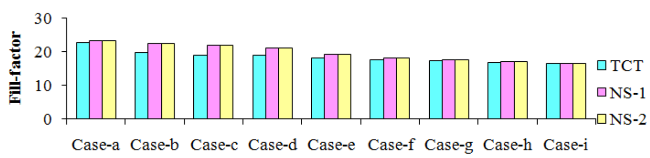


Fig. 4.8. Effect of shading pattern-1 on fill factor for 9x4 PV array

Table 4.3: Power at MPP for shading pattern-1 for 9x4 PV array

Shading patterns		NS-1 P (W)	NS-2 P (W)	TCT P (W)	Best Topology
Pattern-1	Case-a	5363	5205	5363	NS-1/NS-2
	Case-b	5170	4528	5170	NS-1/NS-2
	Case-c	5013	4352	5013	NS-1/NS-2
	Case-d	4876	4312	4876	NS-1/NS-2
	Case-e	4385	4134	4385	NS-1/NS-2
	Case-f	4182	4038	4182	NS-1/NS-2
	Case-g	4028	3948	3897	NS-1/NS-2
	Case-h	3897	3864	3897	NS-1/NS-2
	Case-i	3780	3780	3780	ALL

Table 4.4: Mismatch power losses for shading pattern-1 for 9x4 PV array

Shading patterns		NS-1 P (W)	NS-2 P (W)	TCT P (W)	Best Topology
Pattern-1	Case-a	507	665	507	NS-1/NS-2
	Case-b	700	1342	700	NS-1/NS-2
	Case-c	857	1518	857	NS-1/NS-2
	Case-d	994	1558	994	NS-1/NS-2
	Case-e	1485	1736	1485	NS-1/NS-2
	Case-f	1688	1832	1688	NS-1/NS-2
	Case-g	1842	1922	1842	NS-1/NS-2
	Case-h	1973	2006	1973	NS-1/NS-2
	Case-i	2090	2090	2090	ALL

Table 4.5: FF for shading pattern-1 for 9x4 PV array

Shading patterns		NS-1	NS-2	TCT	Best Topology
Pattern-1	Case-a	23.33	22.64	23.33	NS-1/NS-2
	Case-b	22.49	19.70	22.49	NS-1/NS-2
	Case-c	21.81	18.93	21.81	NS-1/NS-2
	Case-d	21.21	18.79	21.21	NS-1/NS-2
	Case-e	19.07	17.98	19.07	NS-1/NS-2
	Case-f	18.19	17.56	18.19	NS-1/NS-2
	Case-g	17.52	17.17	17.52	NS-1/NS-2
	Case-h	16.95	16.83	16.95	NS-1/NS-2
	Case-i	16.44	16.44	16.44	ALL

4.5.4 P-V Effect of shading pattern-2 on power losses and fill factor for 9x4 PV array

The results show the superiority and efficacy of the PV array (9x4) with TCT arrangement, simulation result also shows the configuration consumes more power than the other available arrangements. The P-V power loss graph given in Fig.4.7 depicts that power loss is low for NS-2 arrangement (case b,c) than other two arrangements. However, in the case ‘a’ to ‘d’ power loss s is almost equal for all configuration is shown in Fig. 4.7.

Fill factor for 9x4 PV array of all three configurations are almost comparable. In fact, Fill factor in case ‘a’ and ‘d’ equal for all arrangements as shown in fig 4.10.However, Fill factor of NS2 is higher in case of 'b' and 'c'.

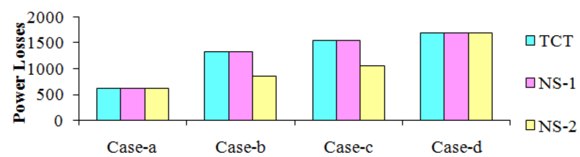


Fig. 4.9. Effect of shading pattern-2 on power losses for 9x4 PV array

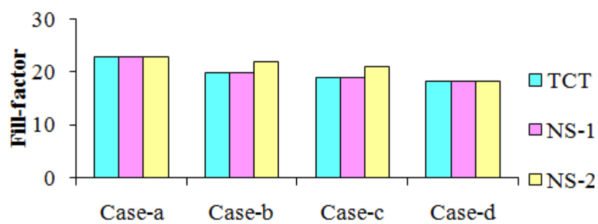


Fig. 4.10. Effect of shading pattern-2 on fill factor for 9x4 PV array

Table 4.6: Power at MPP for shading pattern-2 for 9x4 PV array

Shading patterns		NS-1 P (W)	NS-2 P (W)	TCT P (W)	Best Topology
Pattern-3	Case-a	5260	5260	5260	ALL
	Case-b	4545	5013	4545	NS-2
	Case-c	4332	4811	4332	NS-2
	Case-d	4182	4182	4182	ALL

Table 4.7. Mismatch power losses for shading pattern-2 for 9x4 PV array

Shading patterns		NS-1 P (W)	NS-2 P (W)	TCT P (W)	Best Topology
Pattern-3	Case-a	610	610	610	ALL
	Case-b	1325	1325	857	NS-2
	Case-c	1538	1538	1059	NS-2
	Case-d	1688	1688	1688	ALL

Table 4.8: Fill-Factor for shading pattern-2 for 9x4 PV array

Shading patterns		NS-1	NS-2	TCT	Best Topology
Pattern-3	Case-a	22.84	22.84	22.84	ALL
	Case-b	19.77	21.81	19.77	NS-2
	Case-c	18.84	20.93	18.84	NS-2
	Case-d	18.19	18.19	18.19	ALL

Chapter- 5

Study on IOT based MPPT for performance improvement of Solar PV arrays operating under partial shade dispersion

5.1 Introduction

Due to ever-increasing population, meeting the growing energy demand is one of the foremost challenges for today's world. The total energy consumption on the planet is increasing leaps and bound as compared from previous decades. The large pace of consumption of fossil fuels is inversely proportional to its life expectancy. As fossil fuel sources are limited, so there is a need of finding alternative to fulfil the load demand. During the past few decades renewable energy sources has emerged as an unconventional source to produce electricity all over the world. Especially solar PV (photovoltaic) technology received remarkable attention due to its non-polluting, high availability and high potential features [5.1-5.7]. However, the solar PV system suffers from two main challenges: low energy conversion efficiency which is not more than 16% or 17%, especially when the irradiation level is less than standard test condition (STC) and the generated power from the PV system continuously varies with the atmospheric condition. Moreover, the characteristic of the PV array is non-linear, and thus, the current and voltage vary with the irradiation and temperature. On the P-V and I-V curve, there is a point which is a unique characteristic and termed as the maximum power point. The whole PV system (array, converter, inverter, etc…) operates at its maximum efficiency and tries to obtain maximum generated power. Thus, the most important part of harnessing the solar energy is to get maximum power by continuously tracking the maximum power point of the solar PV system. To achieve maximum efficiency, it is necessary to locate the system at MPP [5.8-5.13]. Solar panel efficiency is also decreased by the various factors like shadowing, dust and dirt, snow, bird droppings etc. Shadowing is one the biggest concern that decreases about half of the efficiency of the PV panels according to the place where the solar panels is mounted. Hence some mechanism system is needed in respect to increase the output of solar panel (PV) and maximize more and more amount of solar energy and get it converted into the electrical energy. To maximize the power and to minimize tracking time of power a MPPT controller is connected between the load and PV panel [5.14-5.18]. This system is also prevent premature battery failure. For this reason, MPPT is the most practicable way to enhance the efficiency of the solar panel. However, utilizing solar energy from the sun is a very difficult task due to limited efficiency and high cost of solar cell. The various factors affecting the efficiency are temperature of the module, solar irradiance and the load impedance.

In this chapter, a novel technique for efficient extraction of maximum power from photovoltaic (PV) panels is presented using IOT system [5.19-5.25] to ensure global power optimization for photovoltaic (PV) generators regardless of the irradiance conditions. Individual MPPTs have been implemented and comparative analysis studied for with and without IOT systems and the results depicted.

5.2 MPPT Technique

As the weather condition always changes throughout the day, the generated power from the solar PV system also fluctuates according to the irradiation and temperature. Fig. 5.1 shows the I-V and P-V curves of a typical solar PV cell that depicts the MPPT's working principle [5.26-5.36]. Here, the constant load R1 is represented by a line with slope *I/R*1. By connecting the load R1 with the PV cell, the obtained operating point is P1 as shown in Fig. 5.1, even though the maximum power point is also available in PV array curve. If the MPPT controller is introduced with the PV system the MPP P2 can be obtained. Thus, the power converter adjusts the load with the PV array so that the operating point near to the maximum power point can be obtained and maximum output power can be extracted from the PV array. Also, the duty cycle (D) of the converter is adjusted till the time maximum power point is reached.

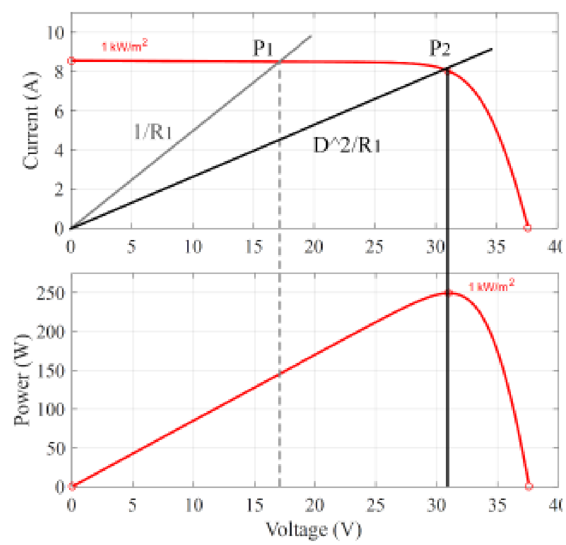


Fig. 5.1. I-V and P-V curve of a Solar cell, loadline and MPP

MPPT Solar System depicted in Fig. 5.2., in the presented system the PV generation systems an IOT based controller is interfaced between PV system and load. Constant charging voltage on batteries is continuously maintained by the charge controller. For getting maximum power from the photovoltaic solar panels' operation, IOT based method has been proposed.

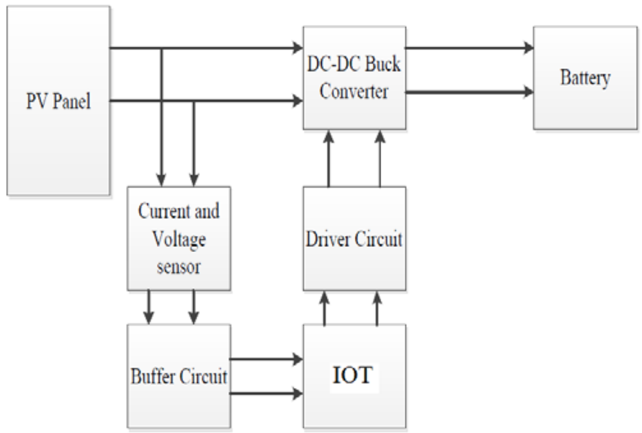


Fig. 5.2. Block Diagram of MPPT Solar System

5.3 IOT Based MPPT

The PV panels are placed on the top of the building or house to track the intensity of sun. The tradition is that the PV panels are fixed according to the latitude angle of the specific country. In few cases human's manually try to relocate the solar tracker module towards the direction of the sun based on the upcoming season. To obtain the most effective and maximized output the PV panels should be at 90 degree perpendicular to the sun or light emitting source [5.37]. As the sun rotates all through the day as well as all over the year, hence there is demand to make a solar panel tracking mechanism that controls the solar panel (PV) with the changing direction of sun. Solar tracking system which is used to trace the sun's movement has increased the efficiency of the solar panels between 30 to 60% as compared with fixed tracking systems [5.38]. Under the situations of shading and discharged batteries, IOT can be efficiently used for the extraction of maximum power by MPTT [5.38-5.46]. The main components in an IOT based MPPT configuration include solar panel, IOT controller system, a server, cloud, battery, and inverter. MPPT is calculated in the server and send the output to the PV module through controller via IOT cloud. With variation in sunlight intensity, load characteristic of PV system under consideration changes to keep the output power maximum by this method.

The maximum power is tracked by regulating the output voltage and sensing the output current and by increasing both the output current and output voltage simultaneously [5.47]. The maximum power is,

$$VMPP \approx KOC\,VOC \tag{5.1}$$

Where KOC is a proportional constant value and varies between 0.79 & 0.92 [5.48] and can be obtained by analyzing the solar PV system under various range of solar irradiation saved in the server. The method uses 76% of VOC as VREF (reference value) and tries to achieve MPP. The VOC is measured by the open circuit of the solar PV system at the load side for very less time. A series switch is placed in between the solar array and the converter to measure VOC. Finally, with the help of the above equation the VMPP is measured [5.49,5.50]. Fig. 5.3 shows the flowchart of the method.

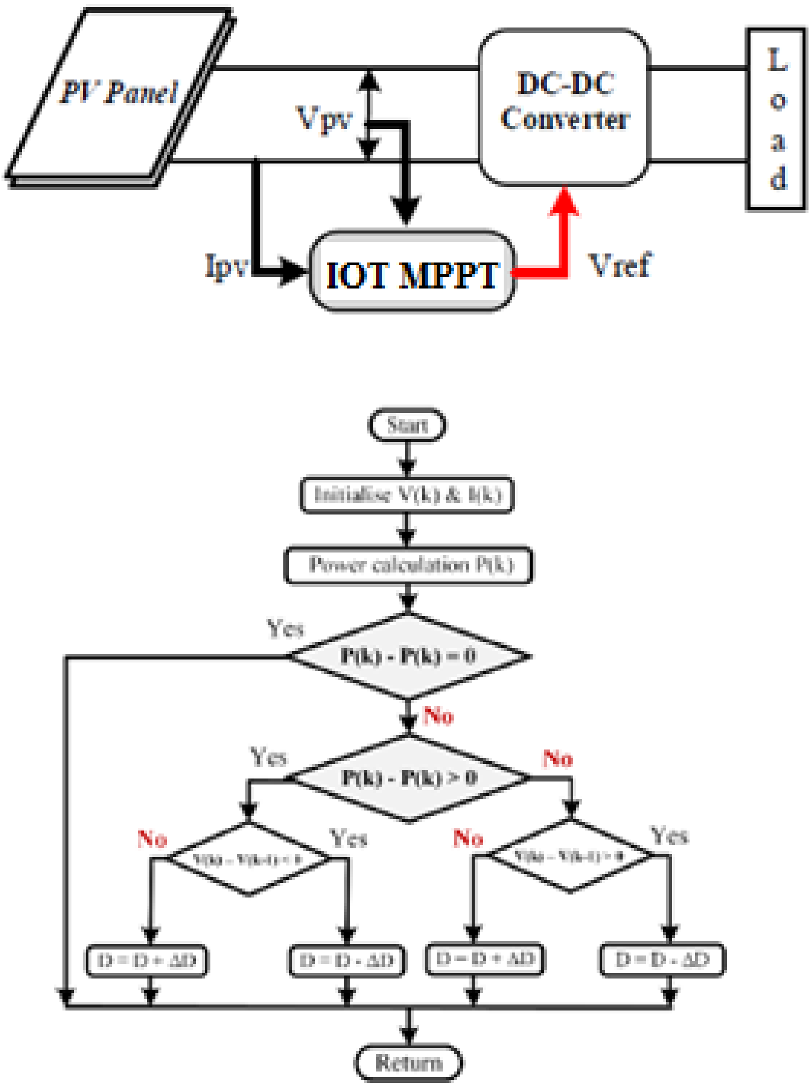


Fig. 5.3 Flowchart of IOT-MPPT

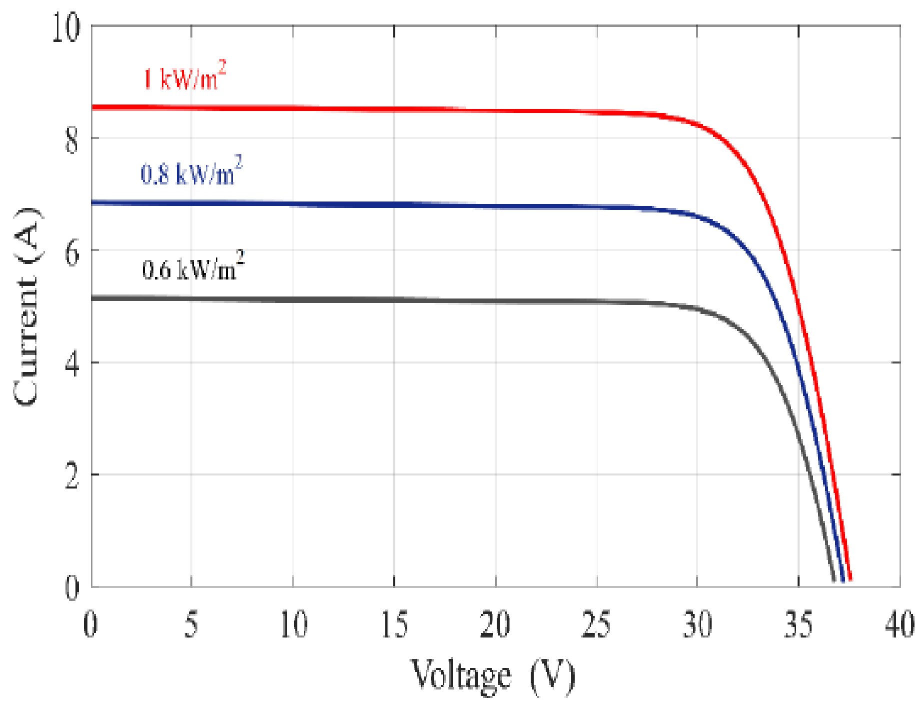


Fig.5. 4 I-V Characteristics of the PV array with varying irradiation

5.4 Results and Discussions

In the presented work IOT based MPPT techniques to get better efficiency and more power from the PV Solar module is proposed. Real-time data for with and without IOT is given in table 5.1.

Table 5.1 Real-time data for with and without IOT

Sr. No	Time in Hrs	Case1(Without IOT)			Case2(With IOT)		
		V(V)	I(A)	P(W)	V(V)	I(A)	P(W)
1	7:00 AM	10.80	0.70	7.56	14.80	0.90	13.32
2	8:00 AM	10.70	1.00	10.7	14.60	1.20	17.52
3	9:00 AM	11.10	1.20	13.32	14.70	1.30	19.11
4	10:00 AM	11.30	1.20	13.56	15.20	1.40	21.28
5	11:00 AM	11.40	1.22	13.908	15.70	1.50	23.55
6	12:00 PM	11.50	1.30	14.95	16.00	1.60	25.6
7	1:00 PM	12.00	1.35	16.2	16.30	1.70	27.71
8	2:00 PM	12.80	1.42	18.176	16.80	1.75	29.4
9	3:00 PM	12.20	1.36	16.592	16.20	1.71	27.702
10	4:00 PM	11.40	1.25	14.25	15.80	1.62	25.596

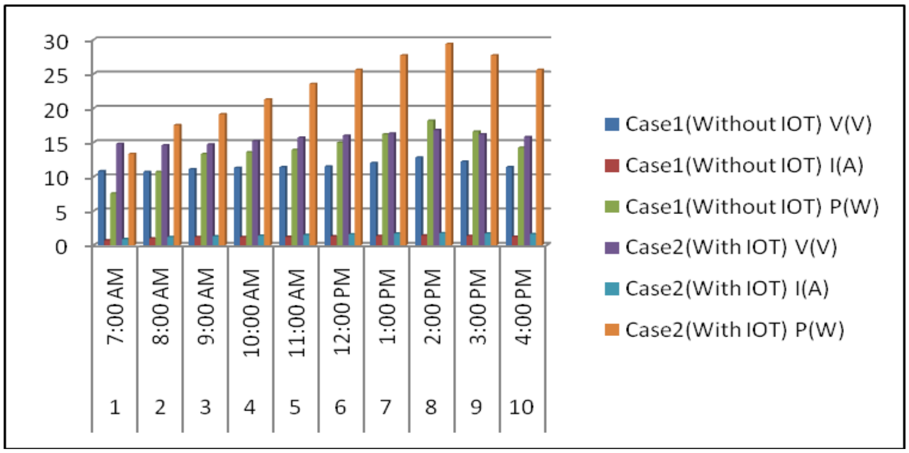


Fig. 5. 5 Real time data analysis of PV power, with and without IOT

Data analysis for 'with IOT' and 'without IOT' is depicted in the Fig. 5.5. From the figure it is clearly visible that the power has been increased after introducing the IOT based MPPT method. A comparison of various MPPT techniques with IOT based MPPT is given in table 5.2 and it describes performance of each.

Table -5.2 comparisons of different MPPT techniques based on selected parameters

MPPT Techniques	PV array Dependency	Analog or Digital	Convergence Speed	Implementation Complexity	Sensor parameters
P&O	No	Both	Varies	Low	Voltage Current
Incremental Conductance	No	Digital	Varies	Medium	Voltage Current
Open circuit voltage V_{OC}	Yes	Both	Medium	Low	Voltage
Short Circuit current I_{SC}	Yes	Both	Medium	Medium	Current
Temperature based	No	Digital	Medium	High	Voltage Irradiation Temperature
IOT based	Yes	Digital	Fast	Medium	Voltage Current Irradiation

Chapter-6

Effects of Solar Irradiance on Load Sharing of Integrated Photovoltaic System with IEEE Standard Bus Network

6.1 Introduction

Now days, the global energy sector is transiting towards the non-conventional energy system and sources, in order to mitigate the ever increasing power demand of the world and to protect the environment from the detrimental effects of burning of fossil fuels. It is well known that to get a clean as well as reliable power supply both the renewable and renewable energy system source should be work together and as a result the integration of Photovoltaic (PV) systems is increasing drastically [6.1-6.10].

However, utility companies are concerned about the consequences of flexible solar generation on the power quality, and its impact on the distribution grid. Therefore, there are lot of challenges and issues in integrating distributed energy sources like Photovoltaic (PV) systems [6.11-6.18].

The grid integrated system has some responsibility to maintain a reliable grid supply with respect to harmonics [6.19-6.25], flicker [6.26-6.33], and DC injection [6.34-6.41] as they are connected to a power system network. Hence due to the power quality problems power converters are required for interface with grid. Solar photovoltaic (PV) needs only power electronic converters like DC to DC and DC to AC for interconnection. There are three basic interfacing technologies for PV module [6.42-6.48]. Fig. 6.1 represents block diagram of grid integrated PV system.

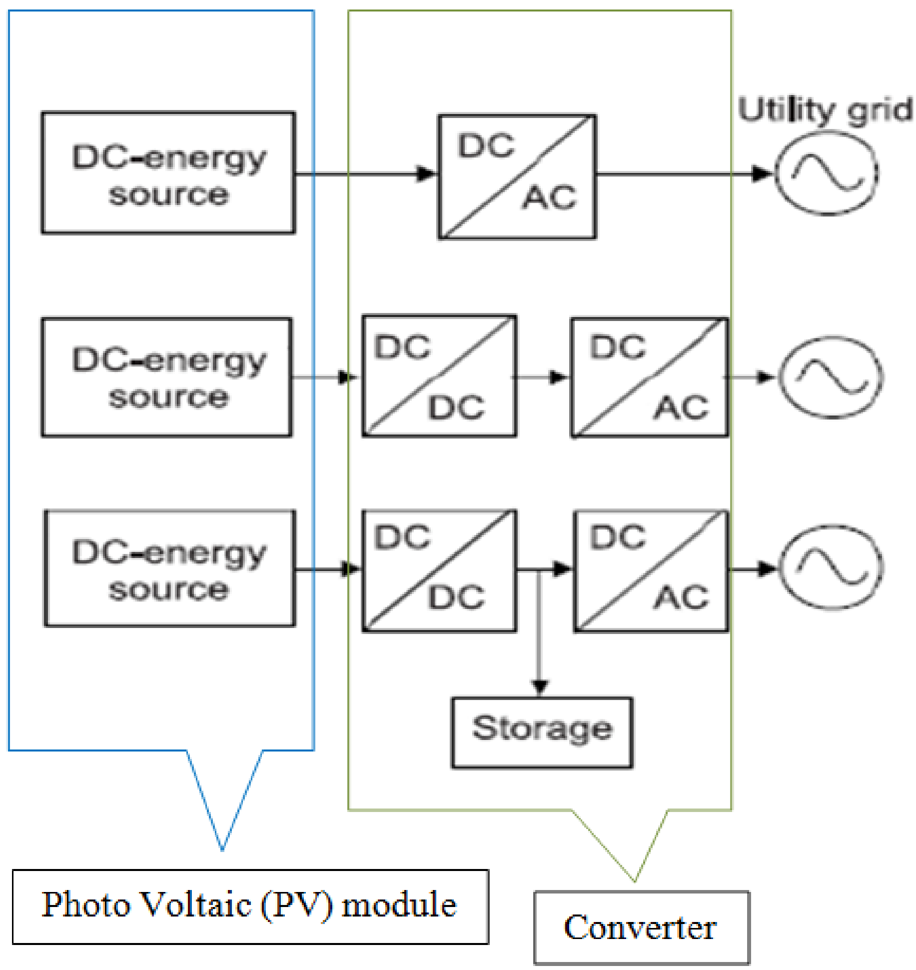


Fig. 6.1 Block Diagram of Grid Integrated PV System

6.2 Modeling of PV Integrated Power System

The photovoltaic current of the PV cell is

$$I_{ph} = [I_{sc} + K_i(T_c - T_r)].\frac{G}{G_r} \quad (6.1)$$

Here,

I_{ph}: Photovoltaic current of the PV cell

I_{sc}: Short circuit current

K_i: Temperature factor of short circuit current

T_c: PV cell temperature (in Kelvin)

T_r: Reference temperature

G: Solar radiation level under W/m^2

G_r: Reference solar radiation level (1000 W/m^2)

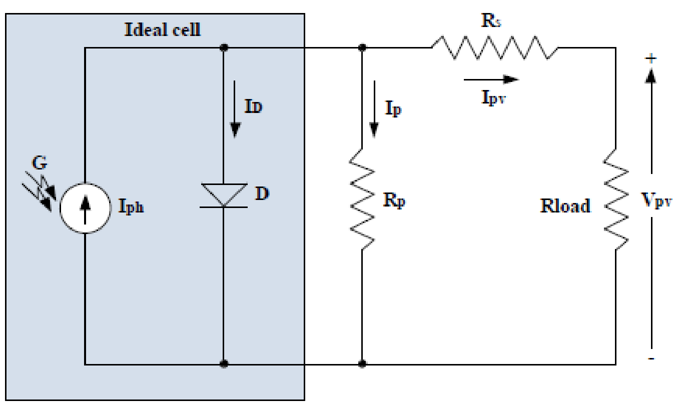


Fig. 6.2 represents equivalent circuit of an actual PV cell [6.49].

Diode current

$$I_D = I_o \cdot \left(e^{\frac{q \cdot V_d}{A \cdot k \cdot T_c}} - 1 \right) \tag{6.2}$$

q: Electric charge

k: Boltzman constant

A: Quality factor of diode

Current flowing through the parallel resistance

$$I_p = \frac{V_D}{R_p} = \frac{V_{pv} + I_{pv} \cdot R_s}{R_p} \tag{6.3}$$

PV Cell output current

$$I_{pv} = I_{ph} - \left[e^{\left(\frac{q \cdot \left(V_{pv} + I_{pv} \cdot R_s \right)}{A \cdot k \cdot T_c} \right)} - 1 \right] - \frac{V_{pv} + I_{pv} \cdot R_s}{R_p} \tag{6.4}$$

$$\left[I_{sc} + K_i \cdot \left(T_c - T_r \right) \right] \cdot \frac{G}{G_r} \tag{6.5}$$

$$= \left[e^{\left(\frac{q (V_{pv} + I_{pv} . R_s)}{A . k . T_c} \right)} - 1 \right] - \frac{V_{pv} + I_{pv} . R_s}{R_p} \tag{6.6}$$

From the equation 6.6 it is concluded that there is a non linear relationship between Photovoltaic current (I_{ph}) and Solar radiation (G) Photovoltaic current of the PV cell.

PV Cell output voltage is

$$V_{pv} = V_D - I_{pv} \cdot R_s \tag{6.7}$$

There is a voltage fluctuation at the output of the PV module due to irradiation, partial shading effect which makes the voltage flicker.

6.2.1 Power Quality Issues

The converter portion in Fig. 6.1 is designed with non-linear power electronics appliances, produced various power quality related problems as mentioned in table 6.1 when connected to grid.

Table- 6.1: Categories of Power Quality issues [6.50,6.51]

S. No.	Cause	Effect
1.	Harmonics	• Frequency disturbance • Waveform distortion
2.	Low Power Factor	• Equipment damage is caused by low power factor • Increases in Energy bills
3.	Transients in Power System	• Produces distortion like impulse and notches • Long and Short duration event
4.	Electro Magnetic Interferences	• Interference between electric and magnetic field High frequency phenomenon
5.	Power Frequency Disturbances	• Low frequency phenomenon • Produces voltage sags and swells

Among the various power qualities related problems Sl. No. 1 and 5 are applicable in case of power electronic converter used in PV system. Apart from the converter many power electronic devices are used to maintain to voltage level of the system and those are also contributor of harmonics.

The operation of Grid integrated PV module has been done in MATLAB platform. Fig. 6.3 represents the Simulink model of integrated PV module. The utility grid considered as IEEE 14 bus system.

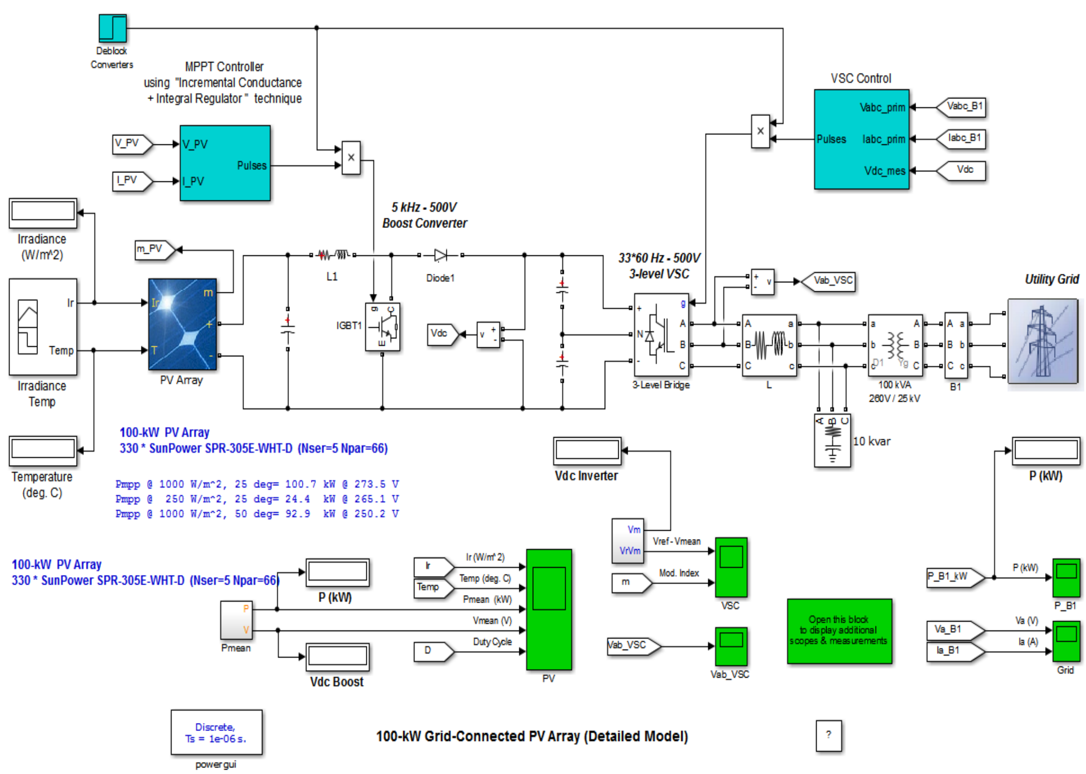


Fig 6.3. Integrated PV module

6.2.2 IEEE 14 Bus System

IEEE standard fourteen (14) bus system consists of fourteen (14) numbers of buses, five (5)numbers of generator sources, and eleven (11) number of electrical loads [Fig 6.4]. The PV model has sixty-six (66) strings with five (5)serially connected PV modules which are connected parallel. Each PV module has ninety-six (96) numbers of serially connected cells. The module has open circuit voltage (Voc) of 64.2 V and short-circuit current (Isc) of 5.96 A.

The PV module has Voltage (V) of 55 V and current (I) of 5.5 A at maximum power. The maximum power delivered by PV array is 100 kW at 1000 W/m^{2}sun irradiance, DC-DC boost converter at 5-kHz is used to increase the PV natural voltage from 275 V DC to 500 V DC. In order to get the required voltage for extracting maximum power output the duty cycle is automatically varied by MPPT controller. The 500 V DC link voltage is converted to 260 V AC by using 1980-Hz 3-level 3-phase VSC, which keeps unity power factor. The harmonics present in the system, which are produced due to use of VSC are filtered out by using 10-kvar capacitor bank. A three-phase coupling transformer of 100-kVA 260V/25kV is used forinter-connecting the converter to the bus 9 of IEEE 14 bus system [Fig 6.5].

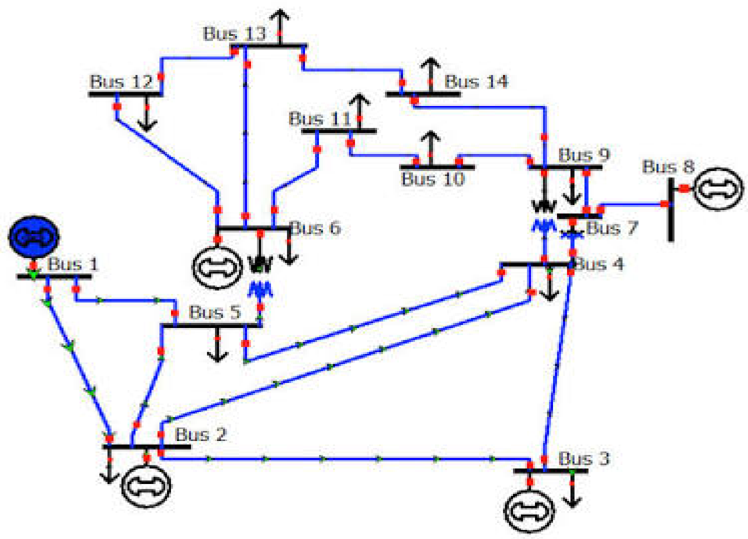


Fig 6.4. IEEE14 BUS system

6.3 Simulation Results and Discussions

For simulation, Grid and PV power output is plotted with the variation of irradiance in the distribution system for a fixed connected load. From equation 5 and 6 mathematically it has proven that variation in irradiance will affect the power generation of PV system.

For analysis we have selected that PV output power as 100 kW. The irradiance of 1000 W/m² is given as input to the PV array model initially. It is shown that that PV voltage under steady-state is 300V.

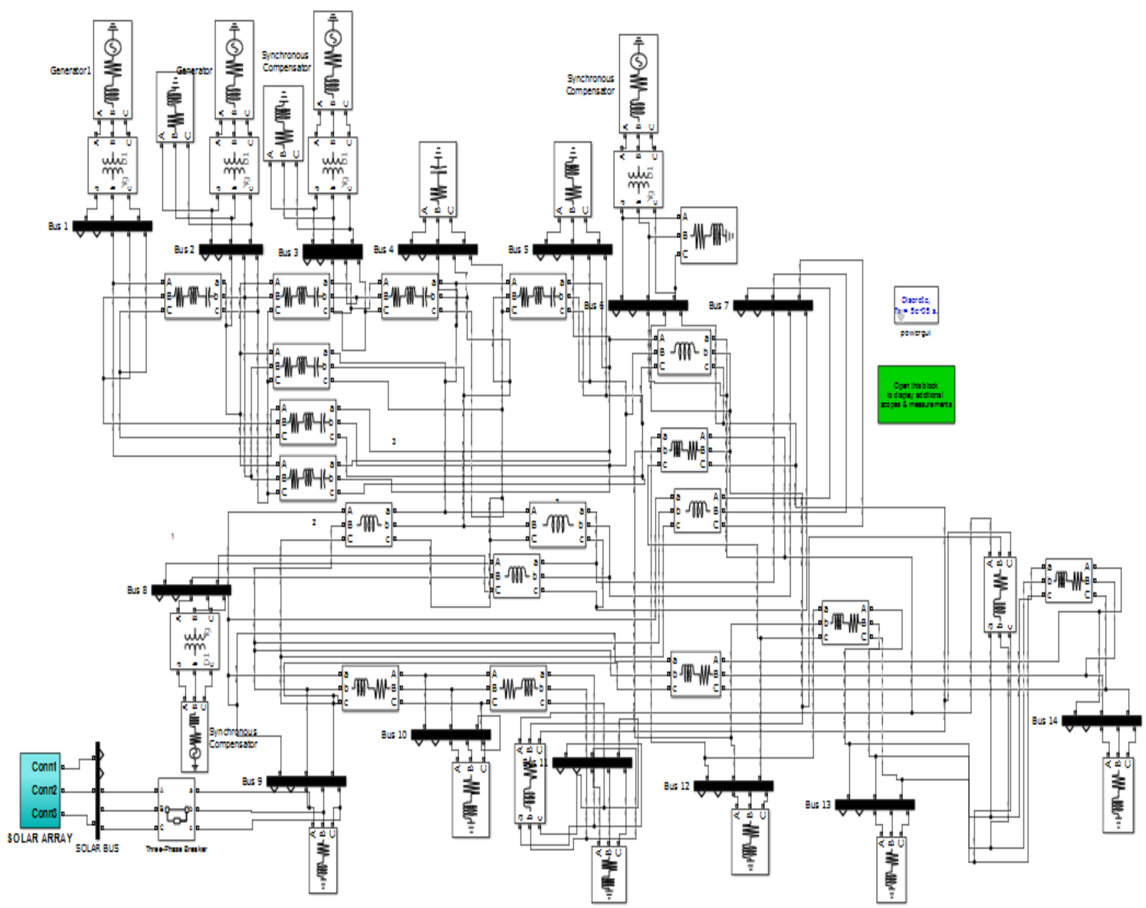
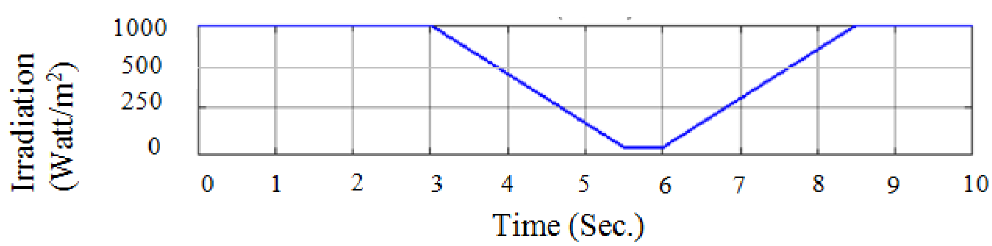


Fig 6.5. IEEE 14 bus system with Integrated PV Array

At t=3 sec, irradiance is varied from 1000 W/m² to 50 W/m².Less output power of PV will be generated for the low value of irradiance. Here the irradiance is changed from 1000 W/m^2 to 50 W/m^2 at time (t) = 3 sec.The output power from PV array is restricted to 25 kW, when irradiance reach at 50 W/m^2. Again, at t=6 sec, as the irradiance is changed from 50 W/m^2 to 1000 W/m^2, as a consequence the increase in PV power is observed and at t=8.5 sec it reaches to its rated maximum power.

Irradiance is kept steady at 50 W/m^2 from t=5.5 to t=6 sec and then further becomes normal to 1000 W/m2 at 8.5 sec. Presented study of the PV system is v=carried out by considering a load of 100 kW connected to the system.

The variations in various parameters with respect to time are represented graphically as in the fig.6.6.



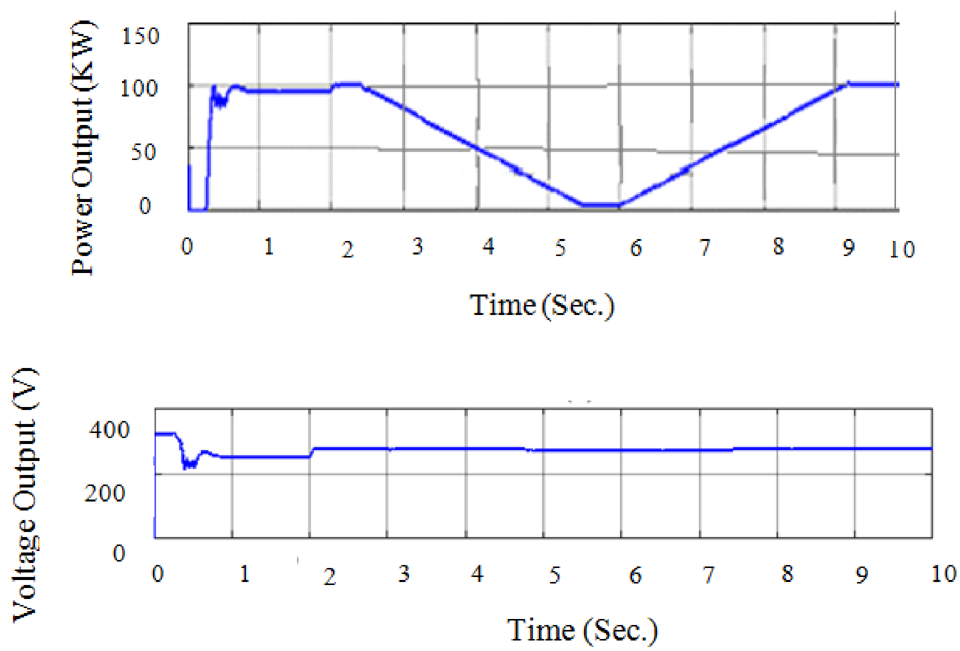


Fig. 6.6. Variation of Output of Grid integrated PV system with change in Irradiance with respect to time

During this period Load sharing overall PV integrated System as well as of PV system separately has also been studied and represented graphically in fig. 6.6 and 6.7.

In fig. 6.4, Load sharing overall PV integrated System as well as of PV system separately has also been plotted up to the steady state operation of PV System.

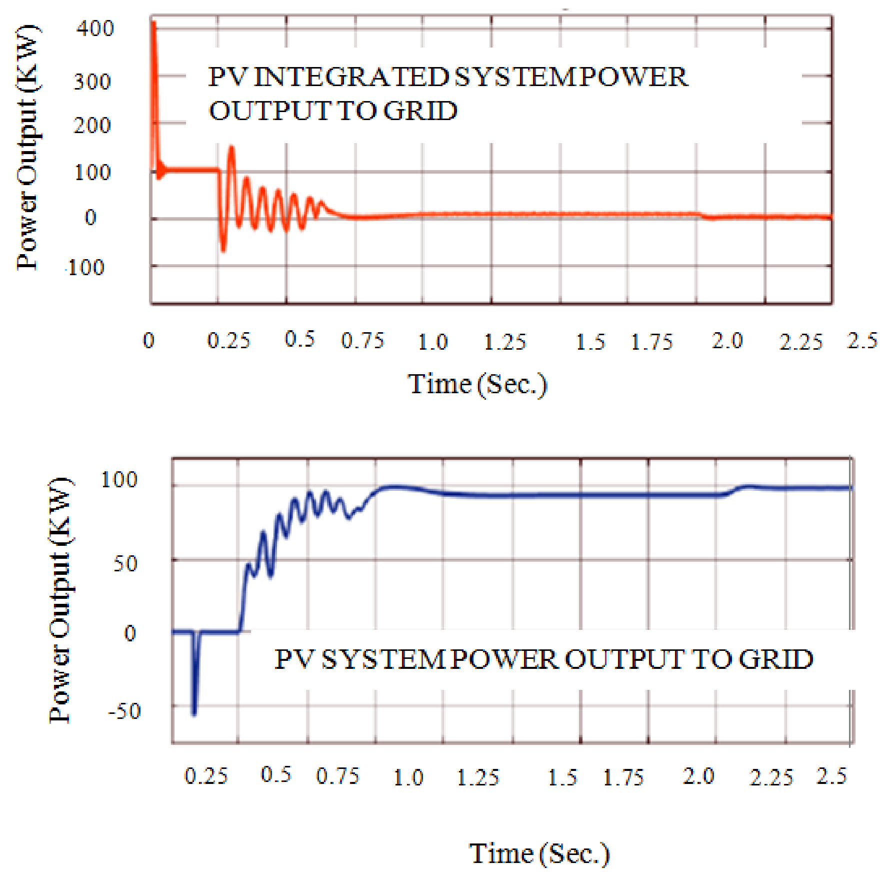


Fig. 6.7. Power Output of Grid integrated PV system and PV System separately with respect to time (up to the steady state period)

From the fig. 6.7, it is observed that during time (t) = 0 to 0.25 sec. the power output of PV integrated System is 100 kW and power output from PV system is 0 kW, hence it is concluded that during the initial period, the load is mainly shared by non-existing power system, in between t=0 and

0.25 sec. the power output from PV system becomes negative and this may be due to the inductance and capacitance present in converter of PV system. From t=0.25 sec. power system oscillation starts and PV system gradually comes into picture and nearly at t=0.78 sec. PV system takes the load over the entire 100 kW load from existing power system and the PV system operates at steady state condition.

From equation 6.6 it is observed that the solar irradiance has a large impact on PV output and typical V-I characteristics of a PV cell is presented in fig. 6.8.

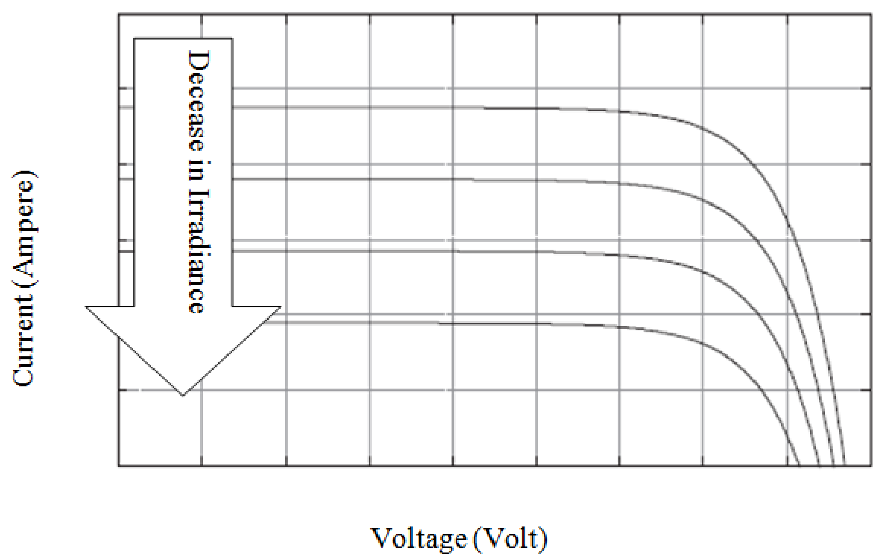


Fig. 6.8. Performance of PV system with varying irradiance and constant temperature

From the fig. 6.8 it is observed that effect of irradiance is a major concern because short circuit current, open circuit voltage is changed as a result the cells become reverse biased by other cells in PV module and thus exhibit higher resistance and non-uniform temperatures in the entire area of the solar cell. High power dissipation in a small area can cause breakdown in localized regions of the PV cell's p-n junction and can damage an entire module by creating hot spots. Variations and irradiance then a large circulating current will flow through it, which results in excessive heating and formation of hot spots; if used for a long period.
Now the load sharing overall PV integrated System (existing power system) as well as of PV system separately has been plotted studied and plotted in fig. 6.6. It is observed that any alteration in the present magnitude of the irradiance will impact the generated power of the PV system. If the irradiance level is lowered as compared to the current level the power output of the PV system will also gets reduced. Here the variation in the level of irradiance is done from 1000 W/m^2 to 500 W/m^2

At time (t) = 0.5sec, constant solar irradiance is given at 500 W/m^2 from t=0.6 to t=0.7sec and then at 0.8 sec the solar irradiance is brought to normal value of 1000 W/m^2. Assuming that the PV system is supplying the load of 100 kW. The maximum power generated by the PV system comes out to be 100 kW at 1000 W/m^2. However, at t=0.6 sec, power of 48 kW is getting generated by the PV system under 500 W/m^2 as compared to 100 kW at 1000 W/m^2.

This situation needs the Grid to supply remaining 52 kW to the load, i.e., the deficiency in load power. This is mainly fed from PV and is compensated by the grid power. It is observed that the power curve of the grid system increases proportionally with decrease of solar power.

From Fig. 6.8 it is observed that when at time t = 0 when the PV module just enter into grid it does cater load immediately but oscillate and reached to the final value of 100 kW and t = 0.5 sec and t = 0.8 sec. when irradiance changes the PV module does act instantaneously. This is due to the power electronic and other reactive components of the converter of the PV module. Partial shading of PV installations has a disproportionate impact on power sharing. In this simulation it is presumed that the load is invariant when the irradiance is varying. The non-linearity of power electronic converter also been studied with the change in irradiance. The output voltage, current and its power decrease with time as the irradiance on the photovoltaic panel decreases.

Chapter-7

Concluding Remarks

The present thesis contains the detailed investigations of the steady state modeling of the solar PV system and its integration to the GRID for future operations and evading the problem of partial shading. The key contribution of the thesis lies in its effectiveness, in modeling the PV array by using the distinct mathematical model and validating the efficient techniques to mitigate the effect of partial shading on the PV system. Further, the present thesis also provides the IOT based MPPT for performance improvement of Solar PV arrays operating under partial shade dispersion. The outcome of these studies is summed up here in this chapter. These results may provide essential information in the development of futuristic PV system.

The basic aspects of photovoltaic cell theory and formulae used in the present work for the calculations of photovoltaic system parameters were presented in chapter 2. The detailed literature review of photovoltaic system for various aspects has been done here. A good understanding of MPPT and different PV array design for different condition is very much required for installation of PV system in partial shading. Various MPPT algorithms and various PV system topologies for partial shading condition have investigated here. However, none of these MPP techniques may be called the best, because, the choice of MPPT depends upon the application, weather condition, accuracy, reliability and convergence time, of the system. The same theory applies on the different topologies also. The configuration of PV array connection is totally depends on the environment, weather condition, shading effect and reliability of the system. This survey has helped the candidate in further research in this area which would be beneficial for producing efficient, clean and sustainable solar energy to the mankind.

In chapter 3 the candidate studied on the performances of solar PV Array effected due to shadow acting upon it. Output power of the PV arrays gets reduced because the solar irradiation received by the PV array during the partial shading condition is different as received during no shading condition. A new model for configuration of Photo voltaic array has been presented in this work and its performance has been studied. The performance analyses for other classical configurations like SP, BL, TCT and HC along with combination of classical model like BL-HC, BL-TCT, BL-HC and SP-TCT have also studied. The shade dispersion effect on PV array with various configurations is also investigated. Diverse partial shading patterns are applied to photo voltaic module to assess the performance of different PV array configuration. Simulation results show the efficacy of proposed Su-Do-Ku configuration for photovoltaic array. Results clearly show that, the proposed Su-Do-Ku configuration has enhanced the output power and performances are better than the other configurations with puzzle shade dispersion and different partial shading conditions.

In chapter 4 the candidate attempts to develop a new model for Photo Voltaic array configuration, and its efficiency has been studied. This chapter proposes a new PV system design to enhance PV system performance under partial shade conditions. The design uses numerous PV modules in constructing the rearranged PV array. In the presence of different shading patterns, the performance analyses of the PV array (9x4) with the proposed configuration and some other superior configurations from literature have been performed. Simulation have been carried out for all three configurations and the obtained the measurements of voltage, current and power which can be considered as output parameters. The shade dispersion effect on PV array with various configurations has also examined. The results show the effectiveness of NS-1 and NS-2 for the photovoltaic array in 9x4 configuration. Results evidently demonstrate that shading cases on these topologies results in a rise in the non-linear effect and in many cases causing multiple maxima. NS-2 has shown better performance in terms of minimum mismatch power loss and enhanced fill factor for all kinds of shading cases.

Chapter 5 presents the novel approach for the maximum power extraction from the solar PV panels efficiently by using the IOT system, the proposed technique ensures the global power optimization for photovoltaic generators irrespective of the irradiance conditions. Individual MPPTs have been implemented and comparative analysis studied for with and without IOT systems and the results depicted that the overall efficiency of the photovoltaic energy production system is augmented. Thus, a reliable high quality and more efficient power can be extracted through the mentioned IOT based system .

In chapter 6 the effect of change in load and irradiance on photovoltaic integrated power system network has investigated. The power system network considered here is IEEE 14 bus system. The simulation is done on MATLAB platform by studying the variation in the three parameters, i.e., Voltage, Power and THD (Total Harmonic Distortion). The results indicate that how power quality of the power system is affected by the irradiance on Photovoltaic cell. The study is performed considering the other environmental factors such as wind velocity, ambient temperature and humidity have a negligible effect on the photovoltaic module. In a steady-state controlled environment, the simulation results depicts that the output voltage, current and its power decrease with time as the irradiance on the photovoltaic panel decreases.

The present work is step forward to develop better technique for improvement of PV System. Therefore, the presented research carried out is expected to be very useful tool to the researchers working in this area and also to all the industries excelled in generating an efficient, clean and sustainable energy to the mankind.

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