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Power Quality Analysis of a Grid Connected PV System

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Abstract - Power quality (PQ) is a critical aspect of electrical systems, especially in renewable energy applications like photovoltaic (PV) systems connected to the grid. A grid-connected PV system can introduce various power quality disturbances such as voltage sags, harmonics, flicker, and frequency deviations. This study investigates the power quality performance of a grid-connected PV system under different operational conditions. The analysis includes monitoring and evaluation of voltage, current, power factor, harmonics, and other electrical parameters to assess their compliance with established international standards. The impact of irradiance variations, temperature changes, and system configuration on the overall power quality is also examined. Furthermore, the integration of power quality improvement techniques, such as the use of filters and advanced inverter control strategies, is explored to mitigate these disturbances and improve system performance. The findings highlight the importance of efficient power quality management in ensuring reliable operation and smooth integration of PV systems with the electrical grid.

The study further emphasizes the importance of proper grid synchronization techniques and real-time monitoring systems that enable operators to detect and address power quality problems promptly. The integration of real-time sensors and smart grid technologies can provide early warnings about power quality degradation and enable corrective actions before any major damage occurs. Moreover, this research highlights the role of standards and regulations in ensuring the compliance of PV systems with acceptable power quality levels. The study draws on international standards such as IEEE 519 and IEC 61000 to evaluate the extent to which grid-connected PV systems adhere to these guidelines.

Finally, this work aims to contribute to the ongoing efforts to improve the reliability and stability of power grids incorporating renewable energy sources. By identifying the specific challenges associated with PV system integration and proposing viable solutions, this research supports the development of more resilient and efficient power grids that are capable of accommodating a higher share of renewable energy without compromising power quality.

Keywords: Power Quality, Grid-Connected PV System, Harmonics, Voltage Sag, Inverter Control, Renewable Energy, Power Factor, Flicker, System Configuration, Photovoltaic, Electrical Disturbances.

1. INTRODUCTION:

1.1 INTRODUCTION

The usage of the grid-connected photovoltaic (PV) system has improved in order to meet the rising request of electrical energy. The non-linear characteristics of the PV array and the dependency of its output power on the array terminal voltage for the same environmental conditions make the task of efficiently utilizing the power generated by PV array challenging. When many such PV modules are connected in series and parallel combinations we get a PV array, that suitable for obtaining higher power output.

The applications for PV energy are increased, and that need to improve the materials and methods used to harness this power source. Main factors that affect the efficiency of the collection process are PV efficiency, intensity of source radiation and storage techniques. The efficiency of a PV is limited by materials used in PV manufacturing. It is particularly difficult to make considerable improvements in the performance of the cell, and hence controls the efficiency of the overall collection process. Therefore, the increase of the intensity of radiation received from the sun is the most attainable method of improving the performance of solar power.

There are two major methodologies for maximizing power extraction in solar systems. They are sun tracking, maximum power point (MPP) tracking both. These methods need controllers which may be intelligent such as fuzzy logic controller or conventional controller such as Perturb & Observe method and Incremental Conductance method. The advantage of the fuzzy logic control is that it does not strictly need any mathematical model of the plant. It is based on plant operator experience, and It is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant. In addition, fuzzy logic simplifies dealing with nonlinearities in systems. The most popular method of implementing fuzzy controller is using a general-purpose microprocessor or microcontroller.

Later on in this thesis, three tracking algorithms are studied and compared on steady-state and transient conditions. The first algorithm is based on P&O, the second is based on ICT and the third is based on FLC algorithm. Also a complete grid connected structure is proposed along with a DC- AC inverter control technique based on VSC (Voltage-Sourced Converter).

1.2 MOTIVATION

Renewable energy is the energy which is collected from the natural resources like sunlight, wind, tides, geothermal heat etc. As these resources can be naturally replaced, for all practical purposes, these can be considered to be limitless unlike the narrowing conventional fossil fuels. The global energy crisis has provided are newed impulsion to the growth and development of clean and renewable energy sources. Another advantage of utilizing renewable resources over conventional methods is the significant reduction in the level of pollution associated. The cost of conventional energy is rising and solar energy has emerged to be a promising alternative. They are abundant, pollution free, distributed throughout the earth and recyclable. PV arrays consist of parallel and series combination of PV cells that are used to generate electrical power depending upon the atmospheric specifies (e.g. solar isolation and temperature). Nowadays, fuzzy logic controllers have an efficient performance over the traditional controller researches especially in nonlinear and complex model systems. Modern manufactures began to apply these technologies in their applications instead of the traditional ones, due to the low cost and widely features available in these controllers.

In Egypt we have a big problem in electrical power generation, since our sources don’t cover all consumer requirements, electrical power have high cost and many daily interruptions, so we need clean renewable energy sources such as solar energy. This motivated to implement FLC techniques to control the MPP of a grid connected photovoltaic systems.

1.3 OBJECTIVES The main objectives of the thesis are building an FLC for maximizing the power output of the solar arrays and comparing the FLC technique with the hill climbing techniques. Then the grid disturbances effects on a grid connected PV array were studied while considering different maximum power point tracking algorithms.

The specific objectives include**:**

- Modeling of the PV array using the MATLAB/SIMULINK.
- Using model to obtain the MPPT of grid connected PV array considering different techniques.
  - P&O method.
  - ICT method.
  - Fuzzy logic method.
- The grid disturbances effects on a grid connected PV array are studied while considering different maximum power point tracking algorithms**.** The grid disturbances involved in this thesis are the different types of :
  - Faults.
  - Voltage sags.
  - Voltage swells.

2. LITERATURE REVIEW:

1. **Ahmed, T., & Khatun, F. (2018).** *Power quality enhancement in grid-connected photovoltaic systems using advanced control strategies*. IEEE Transactions on Power Electronics, 33(5), 3524-3533.
   - This review discusses control strategies for enhancing power quality in grid-connected PV systems, emphasizing advanced power electronics techniques.
2. **Singh, S., & Kumar, A. (2020).** *Analysis of Power Quality Disturbances in Grid-Connected Photovoltaic Systems*. Renewable and Sustainable Energy Reviews, 116, 109414.
   - This review covers the types of power quality disturbances in grid-connected PV systems, including harmonics, voltage sags, and flickers.
3. **López, J. D., & Sánchez, L. (2017).** *Power quality in grid-connected photovoltaic systems: A review of the state-of-the-art*. Solar Energy, 145, 456-468.
   - An extensive review of power quality issues in grid-connected PV systems, with a focus on voltage regulation, frequency control, and harmonic distortion.
4. **Hassan, M. K., & Tushar, S. (2021).** *Power quality issues in photovoltaic systems under grid-connected operation*. Renewable Energy, 152, 853-864.
   - This literature review evaluates the power quality concerns arising from the integration of photovoltaic systems into the grid and their impacts on energy stability.
5. **González-Longatt, F. M., & CIGRÉ Study Committee (2019).** *Power quality analysis of grid-connected PV systems in smart grids*. Springer.
   - A detailed review on how grid-connected PV systems affect power quality within the context of modern smart grid infrastructure.
6. **Chakrabarti, S., & Mishra, A. (2019).** *Power quality improvement in grid-connected PV systems using hybrid control strategies*. International Journal of Renewable Energy Research, 9(1), 352-358.
   - Reviews hybrid control techniques for improving power quality in grid-connected PV systems, including the integration of energy storage systems.
7. **Sharma, A., & Bansal, R. C. (2020).** *Grid integration of photovoltaic systems: Power quality issues and solutions*. Springer Series in Electrical and Computer Engineering.
   - This book provides a comprehensive review of grid integration issues, focusing on power quality, grid synchronization, and voltage regulation.
8. **Zhou, J., & Zhao, F. (2020).** *Grid-connected photovoltaic systems and their power quality analysis*. International Journal of Electrical Power & Energy Systems, 119, 105978.
   - A review of power quality aspects, including voltage sags, harmonic distortion, and inter-harmonics in grid-connected PV systems.

9. **Yadav, M., & Kothari, D. P. (2020).** *Power quality issues in grid-connected solar photovoltaic systems: A case study*. Energy Conversion and Management, 208, 112596.

○ Focuses on real-world case studies of power quality issues in grid-connected solar PV systems and possible solutions to mitigate these challenges.

10. **Sahu, S. K., & Sarangi, A. (2020).** *Influence of grid-connected PV systems on power quality: A comprehensive review*. Journal of Energy and Power Engineering, 14(3), 127-137.

- This review discusses the impact of grid-connected PV systems on power quality in distribution networks and their interaction with the power grid.

11. **Ali, M. M., & Rahman, M. (2018).** *Impact of power quality on grid-connected photovoltaic systems*. IEEE International Conference on Renewable Energy Research and Applications (ICRERA).

- Reviews various power quality issues associated with grid-connected PV systems and the methods used to mitigate such issues.

12. **Patel, S., & Shah, S. (2021).** *Analysis of power quality disturbances in grid-connected photovoltaic systems*. IEEE Transactions on Energy Conversion, 36(3), 1796-1805.

- This paper reviews the common disturbances in grid-connected PV systems and strategies for improving power quality through active filters and other control methods.

3. METHODOLOGY:

3.1 Introduction To Photovoltaic Energy:

Renewable energy sources perform a significant role in electric power generation. There are various renewable sources which used for electric power generation, such as wind energy, PV energy, geo thermal etc. PV energy is a good choice for electric power generation, since the PV energy is directly converted into electrical energy by photovoltaic modules. These modules are made up of semiconductor cells. When many such cells are connected in series and parallel combinations we get a solar PV module. The current rating of the modules increases when the area of the individual cells is increased, and vice versa. The increase of world energy request and the environmental concerns lead to an increase of the renewable energy production over the last decade. Energy sources such as solar, wind or hydro became more and more popular mainly because they produce no emissions and are limitless. PV energy is the fastest growing renewable source with a history dating since it has been first used as power supply for space satellites. The increased efforts in the semiconductor material technology resulted in the appearance of commercial PV cells and consequently made the PVs an important alternative energy source [1]. One of the major advantage of PV technology is the lack of moving parts which offers the possibility to obtain a long operating time (>20 years) and low maintenance cost. The main drawbacks are the high manufacturing cost and low efficiency (15-20 %). As one of the most promising renewable and clean energy resources, PV power development has been boosted by the favorable governmental support [2].One of the most important problems facing the world today is the energy problem. This problem is resulted from the increase of demand for electrical energy and raised of fossil fuel prices. Another problem in the world is the global climate change has increased. As these problems alternative technologies for producing electricity have received greater attention. The most important solution was in finding other renewable energy resources [3], [4].

3.2 Renewable Energy

Each year, the addition of persons to world will increase and the resources required to support them will also increase. Of the resources, one of the most dynamic to support the technological advancing population is energy.

The energy crisis became transparent in the late 1900"s and birthed the desire to find additional energy resources to meet rising energy demands [5].One choice was to increase generation of currently used energy sources such as nuclear, fossil fuel, etc. The other was to explore new renewable energy alternatives. Many different renewable energy sources have appeared as feasible solutions and each one of them has their own positive and negative attributes. As a whole, renewable energy sources all share the fact that their fuel is primarily free and they produce minimal to no waste. These factors are the main motivation for countries to begin incorporating renewable into their energy collection.

A predictable 19% of global energy consumption in 2013 was supplied by renewable energy[6].One more analysis of where the world's energy came from in 2013 is shown in Fig.2.1. Only 19% of global energy coming from renewable may not seem to be a vast amount; however in 2013 nearly half of the new electric power capacity installed was from renewable alone. The percentage of energy from renewable has increased every year for the past several years, and is predicted to continue with this trend in the future.

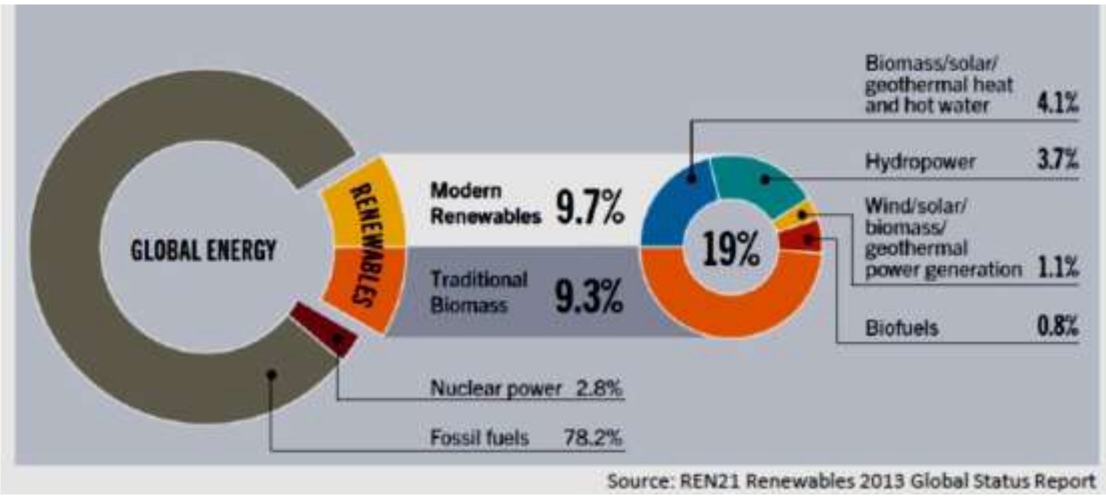


Fig.2.1: Renewable energy share of global electricity production, 2013[6].

Further analyzing Fig. 2.1, the largest source of energy used globally is fossil fuels [7].Two of the largest other sources of energy are nuclear and hydropower. Fossil fuels are non-renewable and generate harmful pollution when burned for energy. Nuclear power plants have the potential to be a great energy source. However, they generate toxic nuclear waste that has to be buried and also always poses the risk of a melt down, which could be catastrophic for the neighboring environment.

Hydropower generation requires damming a river or body of water, disrupting its natural flow, and completely changing the surrounding ecosystem. A form of renewable energy gaining recent popularity is solar [8]. Solar energy is one of the cleanest forms of energy available, converting energy from the sun to electricity without any waste or harmful by products.

3.2 1 Solar Energy

It's the energy which derivative from the sun through the form of solar radiation. Solar powered electrical generation relies on photovoltaic. A partial list of other solar applications includes space and water heating, solar cooking, and high temperature process heat for industrial purposes.

3.2.2 The Photovoltaic Resource

The PV energy is an extremely powerful energy; actually the earth's surface receives enough energy from the sun in one hour to meet its energy requirements for one year [8].PV technology was originally created to power some of the first satellites used in space in the 1950‟s [7].When the technology was in its early form its uses were limited, to such applications as space, due to economic practicality. However, in the last five years the PV market has experienced rapid growth. From2010 to 2012 an additional 60 GW of new PV capacity was added globally, bringing the total world capacity to 100 GW [6].Fig.2.2 shows the exponential increase, especially over the last five years of PV capacity.

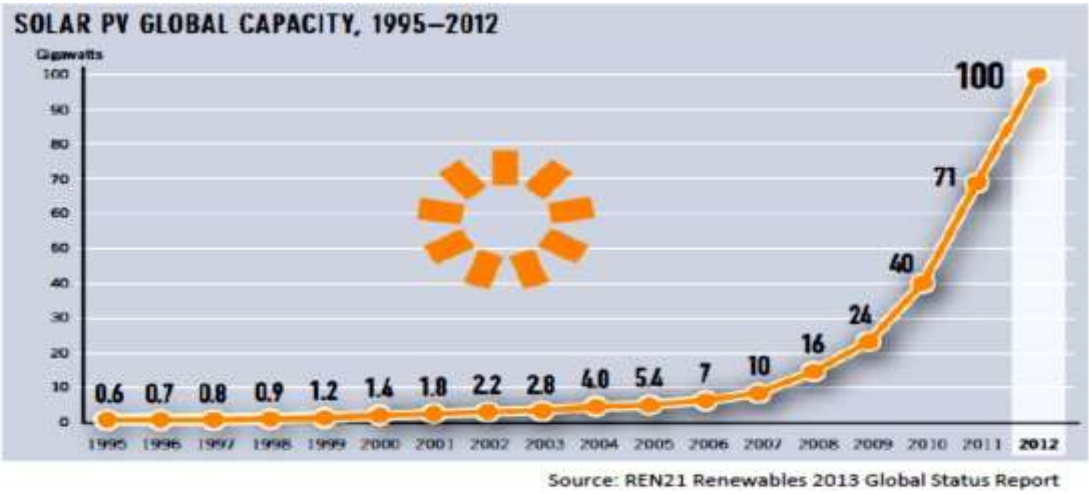


Fig.2.2: Total World Capacity of PV (1995-2012) [6].

The growth of installed PV can be recognized to many factors but the main reasons are increases in environmental considerations, new state laws and regulations, purchase incentives, increases in PV cell technology and efficiency, and decreases in overall system cost [7].

3.3 PHOTO VOLTAIC BACKGROUND

Solar panels are made up of photovoltaic cells; it means the direct conversion of sunlight to electricity by using a semiconductor, usually made of silicon [9], [10]. The word photovoltaic comes from the Greek meaning "light" (photo) and "electrical" (voltaic); the common abbreviation for photovoltaic is PV[11]. Then PV efficiency increased continuously in the following years, and costs have decreased significantly in recent decades. The main material used in the construction of PV cells is still silicon, but other materials have been developed, either for their potential for cost reduction or their potential for high efficiency [11]. Over the last 20 years the world-wide demand for PV electric power systems has grown steadily. The need for low cost electric power in isolated areas is the primary force driving the world-wide photovoltaic (PV) industry today. PV technology is simply the least-cost option for a large number of applications, such as stand-alone power systems for cottages and remote residences, remote telecommunication sites for utilities and the military, water pumping for farmers, and emergency call boxes for highways and college campuses [9]. PV cells are converting light energy, to another form of energy, electricity. When light energy is reduced or stopped, as when the sun goes down in the evening or when a cloud passes in front of the sun, then the conversion process stops or slows down. When the sunlight returns, the conversion process immediately resumes this conversion without any moving parts, noise, pollution, radiation or constant maintenance. These advantages are due to the special properties of semi conductor materials that make this conversion possible. PV cells do not store electricity; they just convert light to electricity when sunlight is available. To have electric power at night, a solar electric system needs some form of energy storage, usually batteries, to draw upon [12].

3.4 PRINCIPLE OF PHOTOVOLTAIC SYSTEMS

Photovoltaic systems employ semi conductor cells, usually several square centimeters in size [13]. Semiconductors have four electrons in the outer shell, on average.

These electrons are called valence electrons [11]. When the sunlight hits the photovoltaic cells, part of the energy is absorbed into the semiconductor. When that happens the energy loosens the electronswhichallowthemtoflowfreely.Theflowsoftheseelectronsareacurrentandwhen you put metal on the top and bottom of the photovoltaic cells. We can draw that current to use it externally, as shown in Fig. 2.3.

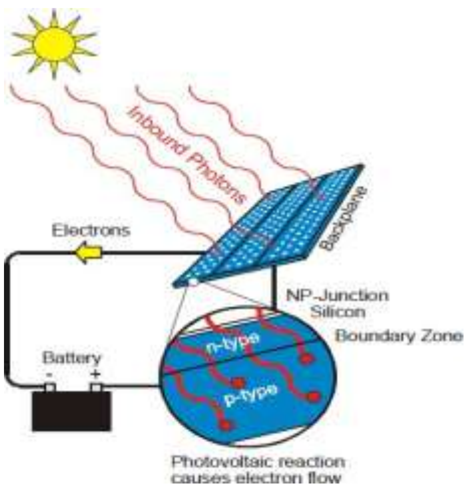


Fig.2.3: Principle of Photovoltaic cells.

Many cells are collected in a module to generate required power [13]. When many such cells are connected in series and parallel combinations we get a solar PV module, the current rating of the modules depends on the area of the individual cells. For obtaining higher power output the solar PV modules are connected in series and parallel combinations forming solar PV arrays.

3.5 TYPES OF PV CELLS

Over the recent decades, silicon has been used for manufacturing more than 80% of solar cells although other materials and techniques are developed. There are different types of solar cellswhich differ in their material, price, and efficiency, since the efficiency is the percentage of solar energy that is captured and converted into electricity. The efficiency values are an average percentage of efficiency, because it's difficult to give an exact number for the different types of solar panels output [10].

- Mono-crystalline Solar cells: They are made from a large crystal of silicon, see Fig.2.4. These types of solar cells are the most efficient as in absorbing sunlight and converting it into electricity. However they are the most expensive. They do somewhat better in lower light conditions than the other types of solar cells. Also, their efficiencyisaround15% - 18%.

Fig.2.4: Mono-crystalline Solar Panels

- Poly crystalline Solar cells: This type of solar cell consists of multiple amounts of smaller silicon crystals, see Fig.2.5.This type is instead of on enlarge crystal have efficiency approximately15%.

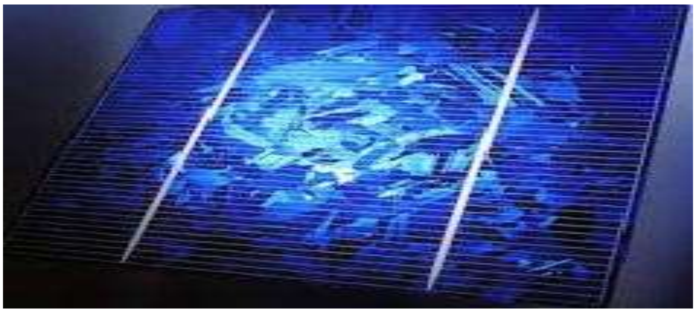


Fig.2.5:Poly crystalline Solar Panels.

They are the most common type of solar panels on the market today. They look a lot like shattered glass. They are slightly less efficient than the mono-crystalline solar cells and less expensive to produce.

- Amorphous Solar cells: This type is consisting of a thin-like film made from molten silicon that is spread directly across large plates of stainless steel or similar material, see Fig.2.6. One advantage of amorphous solar cells over the other two is that they are shadow protected.

That means when a part of the solar panel cells are in a shadow the solar panel continues to charge. These types of solar panels have lower efficiency than the other two types of solar panels, and the cheapest to produce. These work great on boats and other types of transportation [10]. The efficiency of this type is around 8-10%.

Fig.2.6: Amorphous Solar Panels.

3.6 EQUIVALENT CIRCUIT AND MATHEMATICAL MODEL

There are different mathematical models that can be used to model a PV array. From the solid- state physics point of view, the cell is basically a large area p-n diode with the junction positioned close to the top surface [13], [14]. So a practical solar cell may be modeled by a current source in parallel with a diode that mathematically describes the I-V characteristic.

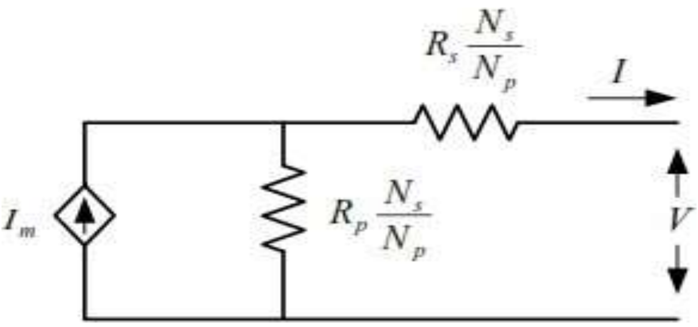
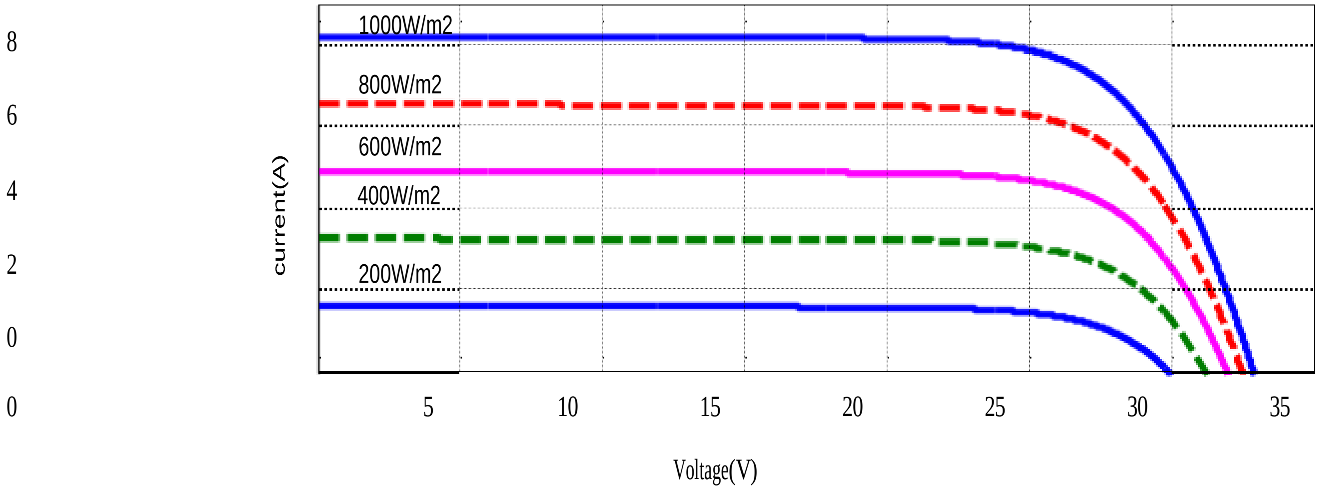


Fig.2.7: Equivalent Circuit of PV module.

The parameters of the PV model used in this thesis are adjusted according to a real PV module (Kyocera KC 200 GT) manufactured by Kyocera [16]. Fig.2.8 shows the I-V and P-V characteristics of the PV module at different irradiances and constant temperature (25°C) and Fig.2.9 shows the I-V and P-V characteristics of the PV module under constant irradiance and different temperature.

PV module:Kyocera KC200GT at constant temperature (25°C)



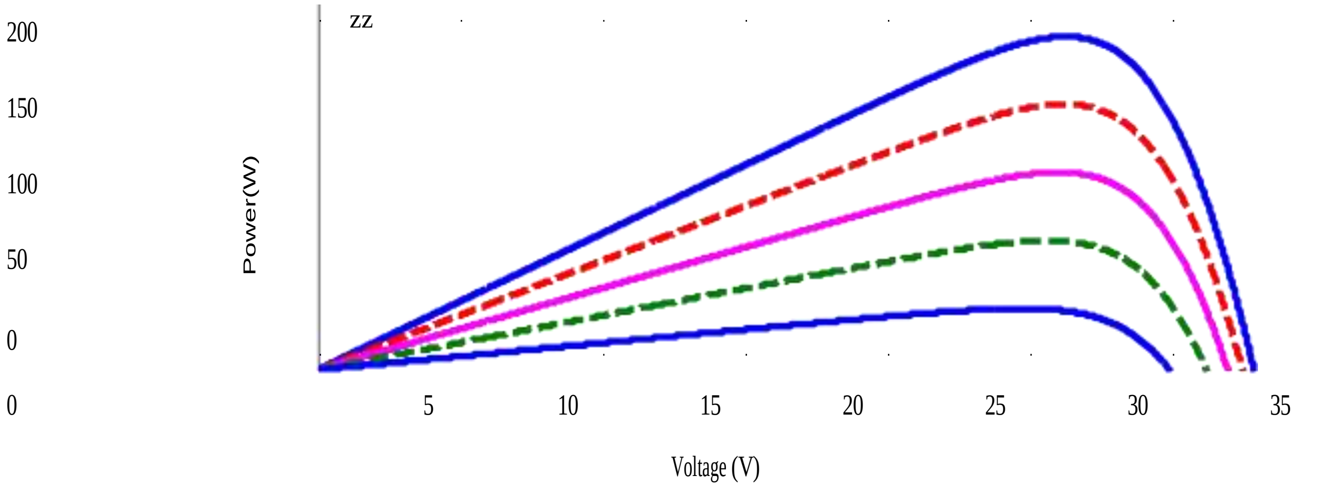


Fig.2.8: I-V and P-V characteristics of the PV module at constant temperature 25°C and various irradiances.

4 CONCLUSIONS:

4.1 CONCLUSION

i. The renewable energy sources such as solar energy play an important role in electric power generation, it is clean and unlimited. A fuzzy logic controller (FLC) was designed to maximize the energy received from solar cells by tracking the maximum power point with the help of DC-DC converter, and then the system is connected to the grid with a DC-AC inverter.

ii. The advantage of the fuzzy logic control is that it does not strictly need any mathematical model of the plant. It is based on plant operator experience, and it is very easy to apply. Hence, many complex systems can be controlled without knowing the exact mathematical model of the plant. In addition , fuzzy logic simplifies dealing with nonlinearities in systems. Also, in fuzzy logic control the linguistic system definition becomes the control algorithm.

iii. The proposed algorithm is by implementing a maximum power point tracker controlled by fuzzy logic controller and using Boost DC-to-DC converter to keep the PV output power at the maximum point all the time. This controller was tested using Matlab / Simulink software, and the results were compared with a perturbation and observation controller and incremental conductance controller which were applied on the same system. The comparison shows that the fuzzy logic controller was faster response in tracking the maximum power point under variable and constant irradiance and gives minimum oscillations around the final operating point compared to the other algorithms.

iv. In this thesis, a 100 kW grid connected photovoltaic array is studied under steady state and transient conditions while utilizing three different maximum power point tracking algorithms. The three algorithms employed are; the Perturb and Observe (P&O) algorithm, the Incremental Conductance (ICT) algorithm and the Fuzzy Logic Control (FLC) algorithm. The simulated results under steady state condition show the effectiveness of the MPPT on increase the output power of the PV array for the three techniques. However the FLC algorithm offers accurate and faster response compared to the others.

4.2 FUTURE SCOPE

- Implementation of a physical model for the fuzzy logic controller technique based MPP using microcontrollers and testing it on a real PV panel. The most popular method of implementing fuzzy controller is using a general-purpose micro processor or micro controller.

- Using optimization method to reduce the rules of the controller such as using Genetic Algorithm with Fuzzy controllers. They can be used in the control algorithm to tune the membership functions so that the inexact reasoning characteristics of the FLC are sufficient to control a system that requires precise control actions.

- Comparing between different inverter control strategies and its effect on power quality from the utility grid point of view.

- Studying the effect of power quality disturbances on the stability of maximum power point tracking controllers.

- Grid Connected Photovoltaic Systems with Smart Grid.

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