Optimization of a Grid Connected Photovoltaic System using Fuzzy Logic Control

Dikio C. Idoniboyeobu, Sunny Orike and Peace B. Biragbara

Abstract—Solar Photovoltaic energy generating system is one of the auspicious renewable energy resources that use the ample energy from the sun with clean, inexhaustible and environment friendly cyclic operations. However, the intermittent nature of the output power of PV systems reduces their reliability in delivering continuous power to customers. In this work, we propose an efficient and precise technique using a fuzzy controller and simulated in MATLAB environment, for tracking maximum power point in PV system. The fuzzy Logic model results were compared with other methods such as Perturb and Observe (P&O) and Proportional Integral Differential (PID) for validation. The results show that the Fuzzy Logic Controller, an Artificial Intelligence technique under various conditions was able to track the peak power point under lesser time - it took the fuzzy model less than 0.4 sees to attain maximum power while the other controllers took more than 0.7 and 0.8 seconds respectively. It was also observed that the fuzzy logic controller showed greater stability when the maximum power point was attained than the other controller. Hence the fuzzy logic controller gave a better overall performance than other conventional controllers.

Index Terms—Fuzzy Logic Controller; Grid; Maximum Power Point Tracking; Optimization; Photovoltaic

I. INTRODUCTION

Investments in renewable energy are rapidly growing worldwide. It is no longer a thing of surprise that renewable energy sources are gaining more attention globally as alternative energy sources than the conventional fossil energy sources [1]. The major deciding factors that have fanned the interest of both engineers and government alike have been issues related to global warming, environmental pollution and diminishing fossil fuel sources [2]. As such, [3] revealed that renewable energy is one of the dependable and efficient source of energy. Solar energy has become the most promising among the other renewable energy sources [4].

Photovoltaic (PV) solar energy can be described as transformation energy or conversion of solar energy (radiation from the sun) to D.C electricity through a phenomenon known as the photovoltaic effect [5]. When energy from the sun reaches a solar panel, the panel by virtue of how it was designed, it transforms the solar energy into electrical power [6]. The quantity of electricity generated by the module is directly proportional to the intensity of solar emission that is incident upon the solar panel. The simplicity and maintainability of its energy conversion as well as its control system and eco-friendliness have made it to gain popularity [7]. There are two categories of photovoltaic applications, they are: Stand-alone Photovoltaic system, and Grid connected photovoltaic systems.

Stand-alone or off-grid photovoltaic systems are widely utilized in distant regions where access to electricity is not viable [7]. This type of system is seriously under consideration for rural electrification [8]. As much as the stand-alone PV system can provide a well-regulated load voltage, its reliability is very much questionable [1]. This means that, the supply of power from stand-alone PV system cannot be guaranteed. Recently, storage batteries or super capacitors are increasingly used to improve its reliability [4]. A grid coupled solar PV system is an electricity generating system that produces electricity from sunlight connected to the utility grid [9]. A grid coupled solar PV system consists of large arrays of photovoltaic modules, inverters, power conditioning units and grid connected interface control [10]. There are also two subdivisions of grid-connected system they are: Grid Tied system with battery backup, and Grid Tied system without battery back-up. Therefore, a grid connected Photovoltaic generates and supply power to the grid during sunshine times and not during the night.

The world is no longer oblivious of the fact that fossil fuel is now posing a serious threat to both man and his environment. Apart from this, operation and maintenance of diesel generators is relatively costly [4]. The environmental issues arising from the use of fossil fuel includes among other things noise and environmental pollution. Fossil fuel generators discharge harmful hydrocarbon in the atmosphere during operations [11]. These emissions cause harmful effects to humans such as eye problems, respiratory disease and also contribute immensely to climatic change [12]. Apart from these objectionable conditions, transportation and storage of fossil fuels is very much demanding in the economic stand-point [13]. For instance, let us for the sake of comparison; compare a diesel generator producing the same amount of electricity as that of the 15MWp photovoltaic system under construction at Yola in Adamawa State. As opposed to fossil fuel energy, solar energy is clean, pollution-free, sustainable and most importantly cost-effective [2].

The paper is organized as follows: Section II reviews the grid connected photovoltaic system; Section III describes the various materials and methods used in the work; Section IV presents the results obtained from the work as well as an
analysis and discussion of the results; while Section V concludes with recommendations.

II. REVIEW OF GRID CONNECTED PHOTOVOLTAIC SYSTEM

Technology is advancing from orthodox power sources to the renewable energy sources due to the fact the renewable energy is environment friendly and cost effective [14], [8]. Hence, it has become imperative to connect renewable energy to the grid. This could be used to enhance the power generating capacity in Nigeria [15]. Control of grid connected Photovoltaic system is essential in the Grid connected photovoltaic system due to its low efficiency [16]. The control of PV system comprised of inverter control and maximum power point tracker control [17]. Numerous methods have been proposed and discussed in literature on control of grid connected photovoltaic system [6].

Reference [10] proposed that Power-Electronic Systems could be used for the grid Incorporation of renewable power Sources and proposed new trends in power electronics for the integration of photovoltaic (PV) power generators and wind. Reference [8] presented a control system for Photovoltaic Systems with output change. Reference [15] proposed a method to integrate the photovoltaic system into distribution network operations. Reference [1] revealed that distributed PV generator could be used to enhance system stability by appropriate control. Reference [8] noted that modulation power quality should remain within specified designed limit. Reference [4] presented a solution for the connection of Renewable energy sources into power distribution. A direct current link was proposed and simulated. Also, a new method for droop control and load sharing was presented by them. Reference [18] proposed bi-directional inverters application for Photovoltaic (PV) systems, battery storage and diesel generators, while [19] described a photovoltaic system as direct current source model.

Reference [7] proposed an architecture that included a Power Electronic Transformer which was practically and isolated high-frequency link AC/AC converter that substitutes a conventional transformer. A maximum power point tracking control technique was presented and result obtained was validated by simulation [14]. Reference [7] presented an energy-balance control strategy for a cascaded single-phase grid-connected H-bridge multilevel inverter linking independent photovoltaic (PV) arrays to the grid, and also presented a scheme for transferring power from the photovoltaic (PV) modules to a storage battery using a solar charge controller based on a dc/dc converter.

Photovoltaic system is an energy system, and like most energy systems, extracting maximum available energy at any point in time is the main subject of interest; more especially, if you consider the poor efficiency of PV panels [14]. There are several ways in which this goal can be achieved. The path traveled to achieve energy optimization or maximization is dependent upon the choice of parameters of interest and its control algorithms [6]. A very good tool that has aided engineers in developing energy strategies to give insights into the technological paths, and future structure of the system over many years is energy optimization model; several studies and experimentations have been carried out to ascertain the feasibility of renewable power systems as alternatives to the fossil fuel generators. Other researchers who have made frantic efforts in this study are [9], their findings revealed that replacing conventional generators with renewable energy is very much feasible. But some issues were also pointed out; issues (concerns) bordering on meteorological conditions as renewable energy systems are mostly reliant on weather conditions [6].

Numerous studies have been made on renewable energy systems and of course, experimental results have been published in several articles, most photovoltaic systems serve the need of far-away buildings and remote villages where the extension of the already available electricity is economically unadvisable. However, this study focused on integrating the PV system into the national grid with the view of improving the efficiency of grid connected PV system. There are several challenges confronting the photovoltaic system:

1. The poor conversion efficiency of sunlight to electricity which is as low as 10 – 17% especially at low insulation levels.
2. The variation of output generated power by the solar modules with fluctuations in climatic conditions.
3. Inefficiency of maximum power point tracking algorithm.

Thus, the output changes sharply as the weather conditions changes even in the slightest way [20]. Furthermore, the power delivered by the PV system is also affected by the level of sunlight intensity, temperature of the cells and the current drawn from the cells [21]. There is a unique point on the power-voltage (P-V) or current-voltage (I-V) characteristics called the maximum power point (MPP). This is the point at which the PV system functions most efficiently and produces its maximum output power [22]. Optimization must do with extracting the possible maximum power out of the PV array. To achieve this, continuous tracking of the maximum power point (MPP) is very much necessary. The various methods and techniques for maximum power point tracking are: Short Circuit current technique; Open-Circuit Voltage; Perturb and observe (P&O); Incremental conductance (IC) and Adaptive perturb and observe (A & O) technique. According to reference [7], there are many aspects in which these methods differ from one another. Their differences are seen in their varying degree of simplicity, speed of convergence, stability of system and the effectiveness of their maximum power point tracking. The three most important questions or challenges confronting MPPT are: How to quickly get to the maximum power point, how to achieve stability at the MPP when it is there and moving from one MPP to another under sharp changing conditions. To achieve MPPT control, the applied terminal voltage to the PV generator must be varied (Zou et al., 2013).

In the PV system, the effectiveness of the MPP control is very much essential. Key to the effectiveness of the controller is the speed at which the MPPT is attained as well as the tracking accuracy. These two factors are directly related to the duty ratio of the power electronic conversion devices. The tracking speed should be accelerated when the

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operating point is away from the maximum power point [14]. In effect, the duty ratio Regulation should be great when operating point is away from the maximum power point and small when the operating point is near or around the MPP [5]. Unfortunately, the methods discussed previously are not capable of meeting these requirements. Some of the many demerits or pitfalls of the aforementioned methods are uncertainty, variations near the MPP, and low adaptability to the exterior surroundings. Due to the factors affecting conventional methods, more intelligent methods have been recently adopted. Some of these are the M – factor adaptive–step MPPT, neural network MPPT, ripple correlation control (RCC) MPPT and of course the central point of discussion of this research work which is the fuzzy logic control based MPPT [23]. Reference [5] revealed that, it will be an oversight to ignore the short-comings of these more intelligent methods. More so, it does not have the mathematical background and stability analysis that is needed for control system design.

III. UNITS

Various methods of tracking the Maximum Power Point have been reviewed in the preceding section and the use of an improved fuzzy logic controller proposed for tracking the maximum power point to optimize the power transferred to the grid and an overview of the mathematical model of a grid connected PV system is discussed in this chapter. Solar panel converts solar radiation from the sun into electrical energy directly. MPPT Algorithm and a boost converter were used to increase the output voltage at the load end, DC-DC converter was inserted in-between the solar panel and the grid. The DC–DC converter which is the core of the entire supply converts DC electrical power at one potential to the electrical power at another potential filtering of any DC ripples from the PV power. The main purpose of the DC–DC converter is to provide constant voltage or current. The MPPT is the section where the algorithm tracking of the maximum power is embedded which controls the duty cycle of the chopper to ensure the highest power is always extracted and the inverter converters this DC to AC.

A. Mathematical Model

Single, double and multiply diode model was analyzed to see how they behave under varying irradiance and temperature before detailed tracking of the MPP

\[
I = I_{ph} - I_D \left[ \exp \left( \frac{V + R_s}{V_T \times N_2} \right) - 1 \right]
\]  (1)

Where:

\( I_{ph} \): Current measured for radiation generated

\( I_D \): Saturation currents of the diodes, D.

\( N_1 \) and \( N_2 \): Factors of purity for diodes, D.

\( I \): current output of the PV cell.

\( V \): voltage across the output of the PV cell.

\( R_s \): Series resistance representing the losses between junctions of the PV cell.

\( V_T \): thermal voltage.

From (1), the current of a single PV cell is an exponential one hence an exponential curve would be formed with varying radiation and the current is on both sides of the equation and cannot be further simplified as the current is also on the exponential side.

\[
I_D = I_0 \left( \frac{T}{T_n} \right)^3 \exp \left[ \left( \frac{q \times E}{q \times k} \right) \left( \frac{1}{T_n} - \frac{1}{T} \right) \right]
\]  (2)

The diode current also varies exponentially and is mainly affected by temperature changes

\[
I_s = \frac{I_w}{\left( \frac{V_{oc}}{a \times V_T} - 1 \right)}
\]  (3)

\[
V_T = N_i \times \left( \frac{K \times T_n}{q} \right)
\]  (4)

\[
I_{ph} = I_{sc} + K_i (T - T_n)
\]  (5)

The current output of the PV cell is given by:

\[
i = I_{ph} - I_D \left[ \exp \left( \frac{V + IR_s}{V_T \times N_2} \right) - 1 \right] - I_{di} \left[ \exp \left( \frac{V + IR_s}{V_T \times N_2} \right) \right] - \frac{V + IR_s}{R_s}
\]  (6)

Where:

\( I_{ph} \): Current measured for radiation generated

\( I_D \) and \( I_{di} \): Saturation currents of the diodes D1, D2.

\( N_1 \) and \( N_2 \): Factors of purity respectively for diodes.

\( V \): Voltage across the output of the PV cell.

\( R_p \) and \( R_s \): Parallel resistance and series resistance representing the losses of the PV cell.

\( V_T \): Thermal voltage.

\( T \): Temperature in Kelvin.

From (6), the current curve is also exponential but the current generated by the double cell model is greater than that of the single cell model. Photovoltaic (PV) cells are made of semi-conductor materials of two layers. One layer is positively charged or contains positive charges while the other layer is negatively charged. When the PV cells are exposed to sunlight which is made of little packets of energy called photons, they absorb some of these photons (packets of energy) even though about 36% of this sunlight (energy) is reflected. The absorbed energy of the sunlight causes the liberation of free electrons [24]. Due to the manufacturing process of the PV material, these liberated electrons migrate to the positively charged layer thus creating a potential difference. This phenomenon is known as the “photovoltaic effect” [5]. PV cells through the PV effect can directly convert the sunlight energy into electrical energy. To generate large magnitude of electricity through the PV cells, multiple cells can be assembled into modules which in turn is wired in an array of any seize depending on the quantity of electricity which the designer intends to generate. There are several advantages of PV systems such as being pollution free, (both environmental and noise), clean, renewable and cost-effective relative to the conventional methods of generating electric power [5].

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B. Electronic Power Converters

Electronic power converters or power conditioners are very essential components of a PV system [14]. These are the parts or components of the PV system that ensures that the power supplied to the grid is suitable and compatible with grid voltage and frequency. In this work, we considered the following two key electronic power converters:

- DC – DC converters (choppers)
- DC – AC converters (inverters)

The chopper converts a DC voltage of a given magnitude to the same DC voltage but of another magnitude, while an inverter converts a DC Voltage to an AC voltage. Optimization of the grid-connected PV system is the main aim of this work. The chopper was developed and used for MPPT, while the inverter will stabilize DC link voltage and match PV frequency to that of the grid [10]. The following are five main architectures of power converters:

- Centralized inverters and chopper structure.
- Centralized chopper and string chopper converter
- Chopper Optimizer Centralized DC-DC converter
- Detached Micro-inverter structure
- String inverter and Central chopper.

In the context of this work, the second architecture is chosen because of cost and it also has the best power harvest relative to the others. The converter architecture comprises of a centralized DC-AC converter for interface of the PV Module to the utility and multiple units of choppers responsible for MPPT of each PV string. This architecture provides the best harvest because each PV string is tracked independently. It also eliminates single point failure in the system.

Table I: Types of Converters and Functions

<table>
<thead>
<tr>
<th>Conversion from</th>
<th>Name</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC to DC</td>
<td>CHOPPER</td>
<td>Constant variable DC</td>
</tr>
<tr>
<td>DC to AC</td>
<td>INVERTER</td>
<td>DC to AC of Desired Voltage</td>
</tr>
<tr>
<td>AC to DC</td>
<td>CONVERTER</td>
<td>AC to Unipolar Current</td>
</tr>
<tr>
<td>AC to AC</td>
<td>CYCLOCONVERTER</td>
<td>AC of desired Frequency</td>
</tr>
</tbody>
</table>

C. Energy Optimization

The sure way of achieving this objective is the use of optimization technique. Fuzzy logic controller is used for the control of the duty cycle of the DC-DC converter due to its improved behavior as compared to the other algorithms discussed in the literature Review. Fuzzy logic with a well-defined membership function is used to extract the maximum power from the PV panel and convert transfer same to the grid. The inputs of the FLC system are the error (E) and change of error (CE) that is defined by (7) and (8).

\[
E(K) = \frac{P_{pv}(K) - P_{pv}(K-1)}{V_{pv}(K) - V_{pv}(K)} \tag{7}
\]

\[
CE(K) = E(K) - E(K - 1) \tag{8}
\]

The output of the controller is given by:

\[
D(K) = D(K - 1) + \Delta D(K) \tag{9}
\]

When the maximum power has been tracked it is converted to a pure DC by the DC-DC boost converter and the pure Direct Current converted to an Alternating Current and inverted then feed to the grid.

D. Topology of Grid-Connected Photovoltaic Systems

The central constituents of a Grid-connected Photovoltaic system involve photovoltaic arrays and power electronics components. To convert the standard AC power (240V/50Hz), the Nominal voltage level of the input DC power should be greater than 240 volts. Although, to meet this voltage condition, the size of the input photovoltaic has to be increased. Given the fact that the size of a general 240W solar panel, which has nominal 30V/8A output, is normally 1.35 m². Throughout calculation, the size of a solar array with a 240V rated voltage is about 108m². Such size may cause multiple issues when the partial shading happens. The partial shading on a photovoltaic array will cause two typical problems, the reduction in power output and thermal stress on the photovoltaic array. The photovoltaic current of solar cells normally diminishes whenever the received irradiation reduces. With the shaded cascaded connection pattern, the photovoltaic current of the PV cells will reduce due to those shaded solar cells. The residual power, which cannot be utilized by the electric load, because of the shading condition, will be partially transformed to thermal energy, which may affect the photovoltaic efficiency. Recently, with the help of micro-inverters, photovoltaic engineers are glad to divide a large-size photovoltaic array to several small-size arrays, for solving the shading effects. Every micro inverter processes power for one panel, and consists of a DC-DC converter and a DC-AC inverter. The DC-DC stage is used to boost the voltage level of the photovoltaic power to about 240 volts for the DC-AC conversion. The MPPT function for the PV panels is achieved centrally at the inverter stage. Hence, each panel can be isolated from other panels in the process of the power transmission.

Similar to the micro inverter, alternative applications for optimizing power of photovoltaic cells are power optimizers. The output of each DC-DC converter is connected in series prior to the DC-AC inverter. At each DC-DC stage, the MPPT function is fulfilled. Different from the micro inverter, the objective of this topology is to deliver the maximized photovoltaic power to a universal bus.

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E. Structure and Modeling of Photovoltaic

The process of PVs converting received light energy into electricity is known as the photovoltaic effect. When the light irradiates the surface of a solar cell, part of the photons of the light may get reflected or consumed immediately when they impact the surface of the solar cell. This is because the energy that they carry is too weak to be converted into electricity. Only the photons, which are absorbed near the P-N junction of the solar cell can work for the photovoltaic effect. By absorbing the energy of the photons, the atoms in the P-N junction generates overflowing hole-electron pairs. Under the force of the electrical field of the P-N junction, the holes carry the positive charge and shift from the N-type layer to the P-type layer. The electrons carrying the negative charge, escape from the P-type layer, and eventually migrate to the N-type layer. By connecting an electric load to the P-N junction, such as resistor, the electrons in the N-type layer flow through the load, and finally enter the P-type layer. The holes in P-type layer combine with the coming electrons. The size of the surface of a solar cell normally varies from 4cm² to 225cm². The nominal power of a solar cell, under standard test condition (STC), is less than 4 watts. The STC means an irradiation of 1000W/m² at 25°C temperature. The nominal voltage of a silicon solar cell is about 0.5 volts, while the nominal current is about 8 amperes. Multiple solar cells are generally interconnected for enhancing the rated power. Connecting solar cells in parallel can increase the rated current, while connecting them in series can increase the rated voltage.

Equation (10) illustrates the mathematical expression related to the photovoltaic voltage and photovoltaic current of a solar cell model. It involves the short circuit current, backward saturation current, temperature, irradiation, diode ideality factor, electron charge, Boltzmann’s constant, series resistance, and shunt resistance.

\[
I = I_{SC} - I_0 \left( \frac{q \left( \frac{V + IR_S}{aKT} - 1 \right) - \frac{V + IR_S}{R_p}}{R_p} \right) \tag{10}
\]

Where:

- \( I \): Photovoltaic current
- \( I_{SC} \): Short circuit current
- \( I_0 \): Reverse saturation current
- \( V \): Photovoltaic voltage
- \( q \): Electron charge
- \( K \): Boltzmann constant
- \( T \): Junction temperature
- \( a \): Diode ideality factor
- \( R_S \): Series resistance in ohms
- \( R_P \): Parallel resistance in ohms

The short circuit current (\( I_{SC} \)) is the output current of a solar cell, when its load impedance is extremely small such as 0.01 ohms and 0.001 ohms. The short circuit current of a solar cell could be reasonably predicted by using (11) and (12).

\[
I_{SC} = (I_{SC \text{STC}} + C \Delta T) \frac{G}{G_{\text{STC}}} \tag{11}
\]

\[
\Delta T = T - T_{\text{STC}} (K) \tag{12}
\]

Where:

- \( I_{SC \text{STC}} \): Short circuit current at standard test condition
- \( C \): Short circuit coefficient
- \( G \): Solar radiation at standard test condition
- \( T_{\text{STC}} \): Temperature at standard test condition
- \( T \): Actual temperature of the solar cell
- \( G \): Actual received irradiation of the solar cell

The open circuit voltage (\( V_{oc} \)) is the voltage between the positive lead and negative lead of a solar cell when the current that flows through the connected load is almost zero. Where \( C_T \) and \( q \) are the open-circuit voltage co-efficient and the diode ideality factor, respectively.

F. Parameters Calculations

The value of the reverse saturation current, \( I_0 \) is rarely provided by the manufactures. However, it may be approximated by using (13).

\[
I_0 = \frac{I_{SC \text{STC}} + C(\Delta T)}{e^{\left( \frac{V_{oc} - STC + \Delta T}{aKT} \right)} - 1} \tag{13}
\]

The value of diode ideality factor generally varies from 1 to 2. The unknown parameters in (14) are \( R_S \) and \( R_P \). The accuracy of these two parameters determines the similarity between simulated I-V and experimentally measured I-V curves provided by manufactures. Fortunately, provides a reasonable approach to compute \( R_S \) and \( R_P \). The core concept is to keep increasing the value for \( R_S \), while simultaneously calculate the value for \( R_P \) to get match the calculated maximum power to the experimental maximum power provided by manufactures. Equation (14) can be used for fulfilling the above procedures.

\[
R_P = \frac{V_{mpp} \left( V_{mpp} + I_{mpp} R_S \right)}{V_{mpp} (I_{SC} - I_d) - P_{mpp}} \tag{14}
\]

Where:

- \( P_{mpp} \): The maximum power point power
- \( I_{mpp} \): The maximum power point current
- \( V_{mpp} \): The maximum power point voltage

The photovoltaic current of the maximum power point is called “Maximum power point current” and the corresponding photovoltaic voltage is called “Maximum power point voltage”. In the following discussions the abbreviations, \( I_{mpp} \) and \( V_{mpp} \) will denote the maximum power point current and maximum power point voltage, respectively. By using (10) through (14), the parameters of a single solar cell can be reasonably computed. However, those equations may not be sufficient for solving the parameters of a solar panel or a solar array, which is a matrix of interconnected solar cells.
\[ I_{po} = I_{sc}N_{p} - I_{o}N_{p} \]

By reviewing the (15), which is provided above, the relationship between the Rs and Rp in a matrix of solar cells may not be sufficiently accurate. Therefore, according to the (14), (15), and the structure of the photovoltaic array, the Rp can be computed by using (16).

\[ R_{p} = \left( \frac{N_{s}}{N_{p}} \right) \left( \frac{V_{mpp}}{P_{mpp}} \right) \]


The photovoltaic Module is made up 86 parallel cells. Each Module has 7 sun power SPR-415E arrays coupled in series. A 3-ph DC-AC converter was modeled using 3-level Mosfet Bridge Pulse Width Modulated-controlled. The inverter chokes RL and a trivial harmonics capacitor C is used to filter the harmonics produced by the Mosfet Bridge. A 250-kVA 250V/132kV 3-ph transformer is used to link the inverter to the grid. The system consists of five main subsystems:

- MPPT Controller: The MPPT controller is centered on the fuzzy logic controller. This MPPT model automatically changes the VDC reference signal of the inverter VDC regulator in to achieve a DC voltage which will extract maximum power from the PV array.
- VDC Regulator: Regulate the necessary Id (active current) reference for the current regulator.
- Current Regulator: works on the current positions Id and Iq (reactive current), the regulator governs the required reference voltages for the inverter. In our example, the Iq reference is set to zero.
- PLL & Measurements: Compulsory for voltage/current measurements and synchronization.
- PWM Generator: Generate firing signals to the IGBTs based on the required reference voltages. The carrier frequency is set to 1980 Hz.

The utility is modeled as a typical Nigerian distribution system. It includes two 33-kV feeders, loads, grounding transformer and an equivalent 132-kV transmission system and load.

I. Fuzzy Logic Controller for MPPT

Fuzzy logic has its roots in ancient Greek philosophy. Aristotle and the philosophers who preceded him made frantic and vigorous efforts towards the systematization of knowledge [2]. They devised a consisted concept that later gave birth to the field of mathematics [1]. This concept of reason was popularly known as the “laws of thought”. Although the law received strong and immediate objections from other philosophers, Plato indicates that there could be a third section outside true and false. Unlike bivalent logic or Analysis, fuzzy logic is a multi-valued logic that allows for transitional values to be defined between conventional values. To further expatriate this, if a lighting system is controlled using a bivalent logic system e.g. digital system, the light comes on when output of logic system is one (1)

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and switches off when the output of the logic system becomes zero (0). Fuzzy logic control system makes it possible to control a system that is based on inexact information [12]. Fuzzy logic was chosen for this work because other intelligent methods of optimization has many short-comings such as supleness in applications and instability at MPP etc.

**J. Justification of Using Fuzzy Logic Controller for PV Systems Optimization**

Proportional Integral controllers are constant-gain feedback regulators. Consequently, it does not recompense the value disparities in the system and cannot adjust to variations in the surroundings. They are slightly responsive to real and relatively rapid variations in state and so the system will be sluggish to reach the reference. Similarly, P&O for MPPT will not reply quickly to rapid variations in insolation. Therefore, the fuzzy controllers can improve the tracking speed as compared with the classical methods for both uniform and non-uniform loads. Also, fuzzy controller is suitable for nonlinear control because it uses simple models. In this work, a fuzzy logic controller is projected for maximum power point tracking of the Photovoltaic module. They are better and comparatively easier to implement as they do not need the knowledge of the main system. But, the designer needs comprehensive information of the PV system behavior. Fuzzy logic controller consists of four major components which are:

- Fuzzification interface
- A knowledge base or rule base
- Fuzzy inference system and
- De-fuzzification interface.

Fuzzification transforms real-valued variables into suitable fuzzy set variables. This transformation process takes place at the input stage of the controller. Parameters E and ΔE are taken as the input values, where E is the error between the set voltage (Vr) and defined voltage (Vo) of the system, ΔE is the change in error in the sampling period. The output parameter is the reference signal for PWM generator U. Triangular membership functions are chosen for all these processes. The range of each membership function is determined by the previous knowledge of the proposed scheme parameters. The real value input is then related to the corresponding fuzzy variables by means of membership values. Knowledge or Rule Base: Central to the working of the controller is the knowledge base. One can deduce that; this component part of the controller is the heart of the control system. It has a group of fuzzy rules. The rules relate the input signals to the output control signal. Inference engine primarily consist of Fuzzy rule base and fuzzy inference sub blocks. The inputs are fuzzified and fed to the inference engine and the rule base is then used. The output fuzzy set are then identified using fuzzy implication method. We used the MIN-MAX fuzzy implication method. Defuzzification is needed once fuzzification ends, and output fuzzy collection is found.

**IV. RESULTS AND DISCUSSIONS**

MATLAB simulation with MPPT and fuzzy controller (FC) is proposed which are suitable for analyzing the Current-Voltage behavior of a Photovoltaic module under varying insolation. The FC results are compared with the conventional techniques such as perturb and observe and proportional integral control techniques which confirm its advantage. The proposed single-diode model was validated by the results of the simulation. The specification of the user defined photovoltaic module is summarized in Table II, which demonstrates the series of parameters that present the characteristics of a user defined PV module operating under standard test conditions.

### TABLE II: SIMULATED PARAMETERS OF THE PROPOSED PV MODULE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>User defined PV module under standard test condition. (1000w/m² and 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>260watts</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>38.9volts</td>
</tr>
<tr>
<td>Maximum power point voltage</td>
<td>30.7volts</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>9.18Ampere</td>
</tr>
<tr>
<td>Maximum power point current</td>
<td>8.47Ampere</td>
</tr>
<tr>
<td>Current coefficient</td>
<td>0.004%/k</td>
</tr>
<tr>
<td>Voltage coefficient</td>
<td>-0.3%/k</td>
</tr>
<tr>
<td>Diode ideality factor</td>
<td>0.98119</td>
</tr>
</tbody>
</table>
The figure above shows the I-V curve and the P-V curve respectively of the proposed photovoltaic cell at different temperatures. It is established that Current-Voltage response are extremely exponential and reliant on solar insolation of the PV module. The arrangement of V and I that maximizes the power rest on the irradiation and temperature of the module. It can be deduced from the diagram above that, the output power of the solar module increases with decrease in temperature with maximum output obtained at 25°C.

TABLE III: SIMULATED PARAMETERS OF THE PHOTOVOLTAIC MODULE AT DIFFERENT SOLAR IRRADIATIONS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>User defined PV module under standard test condition (1000W/m² and 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power</td>
<td>194watts</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>35.6volts</td>
</tr>
<tr>
<td>Maximum power point voltage</td>
<td>28.1volts</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>7.42Amperes</td>
</tr>
<tr>
<td>Maximum power point current</td>
<td>6.19Amperes</td>
</tr>
<tr>
<td>Resistance in series</td>
<td>0.0038 ohms</td>
</tr>
<tr>
<td>Resistance in parallel</td>
<td>5.8737 ohms</td>
</tr>
<tr>
<td>Diode ideality factor</td>
<td>0.98119</td>
</tr>
<tr>
<td>Current coefficient</td>
<td>0.004%/k</td>
</tr>
<tr>
<td>Voltage coefficient</td>
<td>-0.3%/k</td>
</tr>
</tbody>
</table>

By observing Fig. 2, increasing irradiation obviously leads to maximum power point voltage ($V_{mpp}$) and maximum power point current ($I_{mpp}$) when the temperature condition is invariant i.e. held constant. Besides the irradiation condition, the cell’s temperature can also affect the characteristics of photovoltaic. Fig. 1 illustrates I-V and P-V curves of the PV module which operates under different temperature conditions and a fixed irradiation condition of 1000 W/m². The various temperature conditions do not heavily change the $I_{mpp}$ of the PV module, while they obviously affect the $V_{mpp}$ and show the effect of the variation of power with change in voltage under varying irradiance conditions when the temperature is constant at 25°C, this show that under ideal condition i.e. when the series resistance ($R_s$) of the diode is zero and the shunt resistance ($R_{sh}$), tends to infinity, it shown that the under ideal conditions the MPP increases with increasing irradiance level. The smooth slope of the curve shown the ideal behaviour of a standard PV cell under standard conditions with a Nominal temperature of 25°C and irradiance of 1000w/m², the behaviour of the PV cell varies exponentially and gets to the maximum power point and after which reduces to zero from the curve it can be seen that under changing irradiance the effect of a change in voltage is very negligible as compared to a variation in power of the cell, as the variation in open circuit voltage remains constant with varying irradiation it also means that the fill factor also remains approximately constant and hence the PV cell of the cell is increased under changing irradiation at constant temperature.

Fig. 1. Simulated I-V and P-V Curves of the Photovoltaic Module under different Temperature Conditions.

Fig. 2. Simulated I-V and P-V Characteristics of PV Module under different Solar Irradiation Conditions.

Fig. 3. Plot of Power-Voltage under Varying Irradiance
The design of appropriate DC-DC buck-boost converter was adopted. Firstly, the study developed a FLC with appropriate membership functions. The FLC was used to study and examines solar PV system performance under variable and dissimilar meteorological conditions, especially using both simulation tools study and cross-verify the I-V and P-V characteristics photovoltaic cells. It was discovered that a customary PV module with one shaded cell is the worst situation that distorts proper function of a photovoltaic Array. In conclusion, with bypass diodes, the performance of PV device is more complicated and different from the traditional understanding of the photovoltaic P-V behavior and every photovoltaic array. However, bypass diode will have the most significant improvement in the behavior of a PV module/array under uneven shading conditions. The work developed a DC-DC booster link with other power electronic devices such as Pulse Width Modulation (PWM) and Insulation Date Bipolar Transistor (IDBT) to stabilized and enhance the performance of system. These were simulated using MATLAB/SIMULINK, and it was discovered that they caused a significant improvement on the system performance when connected with the above power electronics devices.

The work concluded that the fuzzy Logic algorithm can be used to enhance the efficiency of the PV module by reducing the energy losses when the change of temperature and irradiation is recurrent rather than the conventional methods such as Proportional Integral (PI) and Perturb and Observe (P&O) techniques. It also confirmed that the MPPT fuzzy logic controller can be used to reduce time responses of PV system, mitigate fluctuations (oscillation) around the Maximum Power Point, shown effectiveness in tracking maximum power under variable environmental conditions, and overall good performance in a Grid connected PV systems. However, the results shown that the energy Conversion using the MPPT in the controllers, there is a concession between rapidity in transient and stability in steady state. These used controllers’ results can be compared to other MPPT methods of control in the future study. Through software simulation, we conclude that the proposed MPPT approach (using fuzzy logic controller) has the least oscillation and the best stability. The sampling rate upset the variable solar irradiance levels are measured in the comparison.

Based on the above conclusion, we make the following recommendations:

- A Programming microcontroller for the grid interactive in all-weather condition for a three phase system should be considered in future study.
- The stability analysis of the fuzzy controller should be considered since this plays a vital role in determining the actual operating region (s) of the controller and may be useful in making the right choice of membership functions.
- The fuzzy processing considered in this work is the Mamdani type and centroid defuzzification method. Other defuzzification methods like bisector may be used. It will be ideal to try the Sugeno fuzzy processing type and any defuzzification method in the design of the fuzzy logic controller.

REFERENCES


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