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Research Paper

FUZZY LOGIC CONTROL BASED MPPT FOR STANDALONE PHOTOVOLTAIC SYSTEM WITH BATTERY STORAGE

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Abstract— **Considering its favorable characteristics, photovoltaic energy is widely recognized as highly beneficial to the environment. To achieve continuous maximum output power across the PV system, an efficient control strategy is developed after studying several maximum power point detection (MPPT) techniques. Consequently, this paper presents a useful control technique for maximizing power extraction from PV systems under varying conditions. The paper focuses on the design of a fuzzy logic control (FLC)-based maximum power point tracking (MPPT) system for a standalone photovoltaic (SAPV) system with battery storage. The FLC is employed to extract the maximum power from a PV module and integrate it with the battery to supply the load. The FLC offers advantages over conventional MPPT methods, such as accurate and rapid response to changes in environmental conditions, including solar irradiance and temperature. The PV system exhibits low total harmonic distortion (THD), making it ideal for household appliances, and can deliver 230 Vrms of single-phase output AC power. The system is designed and implemented in MATLAB/Simulink, incorporating a solar module, DC-to- DC converters, battery storage, and an inverter for supplying AC loads. Simulation results for selected test conditions are presented and discussed. The system performance is evaluated through steady state tests and dynamic tests in simulations**

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I. INTRODUCTION

The application of photovoltaic (PV) has achieved an exponential rise for past two decades from off grid to grid connected PV systems. The electric energy produced by the PV array can be utilized in the best way by delivering it directly to utility grid, without using storage system (battery banks). The performance analysis of newly developed systems requires mathematical functional models for PV module research Field professionals do not readily adopt these developed systems for minimizing failure rate. Therefore, it requires simplified Simulink modeling of PV module for analysis purpose. In the literature basic structure of single diode PV system have been represented. For adjusting the I-V curve by using artificial intelligence some authors have put forward some indirect methods. Although interesting but these methods are complex, inapplicable and needs more calculation. Modeling was confined to PV module characteristics simulation in all the above. The mathematical expressions determining the PV module (as well as PV cell) are also represented. For each expression, Simulink model is represented with numerical results for constant irradiation values (1000W/m2) and temperature. When building a new photovoltaic power system it is very important to consider maximum power point tracking (MPPT) as it is required for extraction of maximum power output from a PV array under varying atmospheric conditions for maximum power output. Many researchers and industry delegates from all over the world have developed several MPPT algorithms. Some of these algorithm like perturbation and observation(P&O) method, fuzzy logic control method, linear approximation method, incremental conductance method, voltage feedback method, hill climbing method, actual measurement method and so on. Appropriate MPPT methods along with good weather conditions are required for implementing maximum performance of a photovoltaic system. This paper mainly focuses on studying and comparing execution efficiency, advantages, disadvantages for two power-feedback type MPPT methods, including perturbation & observation (P&O) and fuzzy logic (FL) methods. For implementation of modeling and simulations tasks, and to compare execution efficiency and accuracy for selected MPPT methods Matlab/Simulink is used in this paper.

II. PV ARRAY

Model A PV array comprises many solar cells wired in series and in parallel. A solar cell model is shown in Fig. 1.

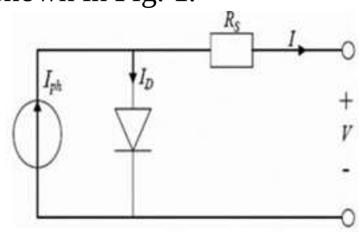

Figure 1: Simplified equivalent circuit of solar cell

In this study adaptive neural fuzzy inference system (ANFIS) was used to formulate the MPPT algorithm. ANFIS combines the learning abilities of ANN and the ability of fuzzy logic to handle imprecise and ambiguous data in non-linear and time varying problems. Fuzzy Logic and control Fuzzy systems are knowledge-based or rule-based systems. The main part of the Fuzzy systems is the IF-THEN rules in the sense that all the other three components (fuzzy inference engine, fuzzifier, and defuzzifiers) are used to interpret these rules and make them usable for specific problems. The first step involves formulation of the rules from human experts or domain knowledge. The next step is to combine these rules into a single system. Fuzzy logic can be applied to systems that are nonlinear and difficult to model using mathematical tools, especially those that are too vague or too complicated to be described by simple mathematical equations. A fuzzy inference system (FIS) essentially defines a nonlinear mapping of the input data vector into a scalar output, using fuzzy rules. The fuzzifier maps input numbers into corresponding fuzzy membership functions. This is required in order to activate rules written using linguistic variables.

The defuzzifier then maps output fuzzy sets into a crisp number. Given a fuzzy set that encompasses a range of output values, the defuzzifier returns one number, thereby moving from a fuzzy set to a crisp number.

when sunlight conditions fluctuate due to cloud cover, time of day, or angle of the sun.

$$K_{mppt} = \frac{0.5}{\tau T \alpha V_{oc}}$$

In addition to enhancing energy output, MPPT helps in minimizing energy losses. Without MPPT, the PV system would operate at a suboptimal voltage, potentially generating much less power than its full potential. By dynamically adjusting to the changing conditions, MPPT ensures the solar panels are always working as efficiently as possible.

Ultimately, MPPT plays a crucial role in modern solar power systems, whether in residential, commercial, or utility-scale installations. It enables solar inverters to extract as much power as possible from the PV array, improving both the economic viability of solar energy systems and their contribution to a more sustainable and renewable energy grid.

III. FUZZY LOGIC CONTROLLER MPPT METHOD

Even though Fuzzy Logic Control method MPPT has some difficulties to construct, it has facility to find maximum power point of PV panels. Fuzzy logic MPPT method doesn't need the knowledge about model of the system, Inputs of the fuzzy logic controller are the error of the system which is E and the change of error is CE the following equations clarify E and CE.

$$E(k) = \frac{\Delta P}{\Delta V} = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}$$

$$CE(k) = E(k) - E(k-1)$$

where P_k is power, V_k is voltage of the PV panel and P_{k-1}, V_{k-1} are the previous power and voltage of PV panels.

In our MPPT, the FLC is designed as a multi- input, single-out system. The inputs, V and insolation, are designed with seven and MFs respectively while the output, duty cycle, has seven MFs. The controller then uses IF-THEN rules to adjust the duty cycle of the buck-boost converter. Seven fuzzy subsets: Negative Big (NB), Negative Medium (NM) Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM) and Positive Big (PB) were chosen for ~V and duty cycle D while three fuzzy subsets Small(S), Medium (M) and Big (B) were chosen for radiation. A total of twenty one (21) fuzzy IF-THEN rules were formulated to guide the FLC controller to vary the duty cycle so that

$$i_{pr} = \Delta I + \int K_{mppt} \left(\frac{dP}{dt} \frac{\Delta I}{\alpha} \right) dt$$

the system operates at the maximum power point. Sample control rules from Table 1 are given below.

Table 1. Rule base of fuzzy logic controller

V_{pv} I_{pv}	NB	NS	ZE	PS	PB
NB	NB	NS	NS	ZE	ZE
NS	NS	NS	ZE	ZE	PS
ZE	ZE	ZE	PS	PS	PS
PS	ZE	PS	PS	PS	PB
PB	PS	PS	PS	PB	PB

- Fuzzification: this process involves converting specific input values into degree of membership of fuzzy sets through the use of membership functions. The membership functions scale and normalize the voltage and current measurements. In this fuzzy control system, the linguistic variables are assigned membership function values using five fuzzy subsets: negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB). Triangular membership functions are employed in the fuzzy control design.
- Fuzzy rule base: this is the "brain" of fuzzy logic inference, storing all the "IF-THEN" rules required for fuzzy inference. For example, a rule may state: "IF (I_{pv} is NB)

AND (Vpv is PB), THEN (ΔD is ZE)," which means that when the current PV is "negative big" and the voltage PV is "positive big," the resulting duty ratio is set to "zero" in order to decrease the output voltage. These rules are typically described by experts using natural language based on their experience. The rule base of the FLC is presented in Table 1.

- Inference method: this refers to the approach used to derive the final fuzzy conclusion based on the degree of membership of input variables to fuzzy sets and the detailed fuzzy rules. There are various methods for fuzzy inference, and the choice of method can lead to different conclusions. Among the methods, the Mamdani inference method based on the max-min compositional rule is commonly employed.
- Defuzzification: this process involves converting the fuzzy conclusions into specific output values. The most commonly used method is the center of gravity (CoG) method. The output of the FLC represents the duty cycle that controls the DC-to-DC converter's switch through the generation of pulse width.

The output of the FLC represents the duty cycle of the DC-DC converter, as illustrated in Figure 4. Membership functions are used to scale and normalize the voltage and current measurements. Five fuzzy subsets, namely negative big (NB), negative small (NS), zero (ZE), positive small (PS), and positive big (PB) are assigned membership function values for the linguistic variables. Triangular membership functions are employed in the fuzzy control system developed in this study. The rule base of the FLC, shown in Table 1, utilizes voltage (V_{pv}), current (I_{pv}), and duty ratio (ΔD) as inputs to the converter.

The output from the PV module is fed into the boost converter. The voltage (V_{pv}) and current (I_{pv}) of the PV module serve as inputs to the fuzzy MPPT controller. The fuzzy MPPT generates control pulses for the boost converter, using the duty cycle output.

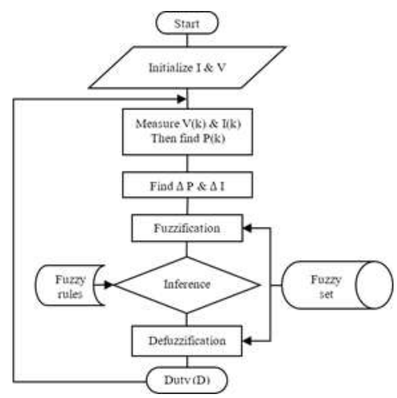

Fig.2. FLC MPPT flow chart

IV METHODOLOGY

The proposed fuzzy logic control (FLC) based maximum power point tracking (MPPT) system for standalone photovoltaic (SAPV) with battery storage is depicted in Figure 3. The solar module converts incident solar radiation into DC electricity within the system. The boost converter, controlled by FLC based MPPT, maximizes power extraction from the solar module while accounting for variations in solar radiation, temperature, and protects the battery from overcharging and under-discharging. The battery stores excess energy when the solar module generates more power than the load demand or supplies power to the load during periods of low solar generation, such as cloudy or rainy days or at night. The inverter converts the DC power into AC power at the same voltage level and frequency as the power grid, enabling the use of standard AC loads and electric appliances. As the output power of the solar array is subject to weather conditions, the successful operation of the SAPV system relies on determining the optimal size of the solar module and battery to meet the load demand.

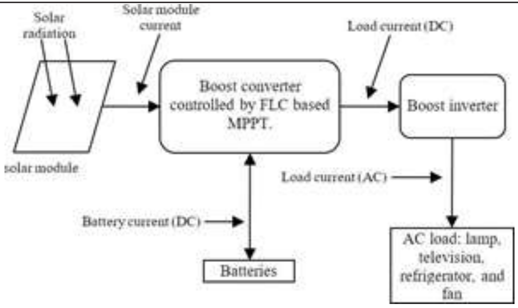

Fig. 3. SAPV system.

MPPT technology continuously monitors and adjusts the operating point of the solar panels to track the MPP, ensuring that the system is always operating at its highest efficiency. This is typically achieved using an MPPT controller or inverter, which adjusts the input voltage to match the changing MPP. By doing so, MPPT significantly increases the overall efficiency of the solar system compared to a system without MPPT, ensuring that as much power as possible is extracted from the PV modules, even under varying environmental conditions. This leads to higher energy production and better utilization of the available sunlight.

V. TESTs

A. STEADY-STATE TEST

The steady-state or static state refers to the operation of the MPPT algorithm under constant solar irradiance and temperature. In this study, simulation results were generated using a solar irradiance of G=1000 W/m² and a cell temperature of T = 65 0C. Figure 4 shows the simulation results of the AC voltage, which is 230 Vrms, and the AC current, which is 1.22 Irms. The simulation involves a boost conversion from 180 V (nominal voltage) and 200 Ah (rated capacity) batteries. Overall, the results in this section demonstrate that the proposed fuzzy algorithm performs well, exhibiting a fast response time, low total harmonic distortion (THD), and no overshoot, undershoot during steady-state operation.

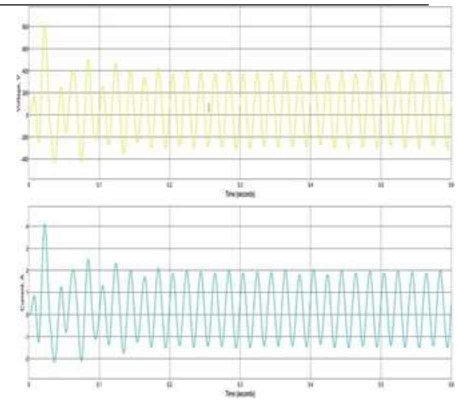

Fig. 4 AC voltage and AC current at solar irradiance, G = 1000 W/m² and cell temperature, T = 65 °C

B. DYNAMIC TEST

In the second part, the dynamic response of the MPPT is tested by varying the solar irradiance and module temperature. The MPPT dynamic response test is conducted using a staircase irradiance and temperature profile, which is a commonly used method for analyzing the performance of MPP trackers. In the simulation, the solar irradiance and temperature are linearly increased from 600 W/m² at 45 °C to 1000 W/m² at 65 °C, as shown in Figure 5. Simulations were conducted to observe the overall response of the system over a period of 1 second. In real conditions, solar radiation can change in as little as 300 ms, necessitating rapid response from MPP tracker

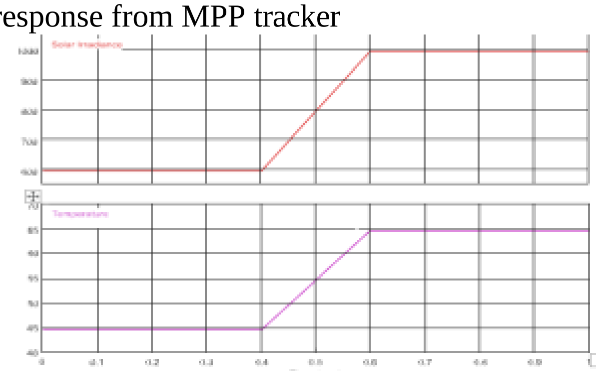

Fig.5. The solar irradiance and temperature are increased linearly from 600 W/m² with 45 °C to 1000 W/m² with 65 °C.

Figure 6 shows the DC output voltage at 194 V and current at 1.94 A. Despite the linear increase in solar radiation and temperature, there is no significant impact on the voltage and current values. Once a DC voltage is present at the battery terminal, it is sent to the DC boost inverter to be converted to AC. The inverter efficiently transforms the DC voltage of 180 V to an AC voltage of 230 V_{rms} and a readily available AC current of 1.167 I_{rms} for residential loads, without the need for a transformer. The simulation results are depicted in Figure 7. The AC output of the inverter dynamically adjusts with the variations in solar radiation, temperature, and the maximum power point reached in each second. From the figure, it can be observed that the voltage (V_{mp}), current (I_{mp}), and power (P_{mp}) reach their respective maximum points smoothly, without any overshoot or undershoot.

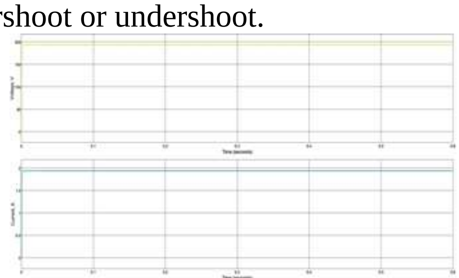

Fig.6. DC voltage and DC current as solar irradiance and temperature increase linearly from 600 W/m² at 45 °C to 1000 W/m² at 65 °C.

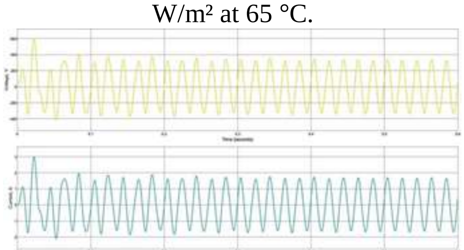

Fig.7. AC voltage and AC current as solar irradiance and temperature increase linearly from 600 W/m² at 45 °C to 1000 W/m² at 65 °C

For the AC load shown in Figure 8, the total harmonic distortion (THD) of the proposed system is measured at 2.06%. This value is well within the compliance limits set by the IEEE 519 standard, which states that the total harmonic current distortion (THDi) of rated inverters should be less than 5%. This achievement brings both economic and technical advantages. The simulation results demonstrate that the system can efficiently adjust the fuzzy parameters, ensuring fast response, good temporary performance, and insensitivity to external interference variations. The system effectively supplies energy to the utility grid with low harmonics. Furthermore, the results indicate that the harmonic distortion of the output inverter current waveform can be maintained close to the regulatory limits set for the utility, even at different solar panel voltage levels.

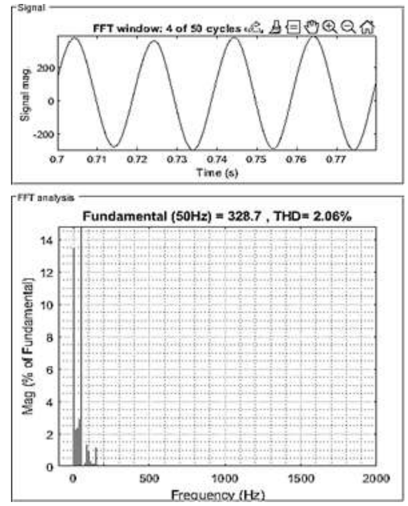

Fig.8. The total harmonic distortion of the proposed system.

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VII. CONCLUSIONS

The proposed FLC-based MPPT system for SAPV system with battery storage has been determined to be a cost-effective and efficient conversion system. This system converts the output DC voltage from a PV module to AC 230 V_r , which can power a single-phase domestic load at 230 V_{rms}. To enhance energy conversion efficiency, an intelligent control technique based on fuzzy logic control is integrated with the MPPT controller in this study. Compared to traditional voltage source inverters, the boost inverter used in this system offers both economic and technological advantages. Simulation results on various loads demonstrate that the system operates within the permissible THD range. This proposed technique offers several benefits, including lower overall system costs, smaller size, and higher efficiency.

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