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A Solar Energy Control System for On-Grid Energy Storage Device

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***Abstract* — Renewable energy sources could be harnessed to provide intermittent power and their integration into the grid has improved power availability. Nonetheless, ensuring the stability of the output of such a system has been a major concern. The inability to control the output of renewable resources such as solar results in operational challenges in power systems. To compensate for the fluctuating and unpredictable features of solar photovoltaic power generation, electrical energy storage systems have been introduced that may be integrated into the grid. In this paper, a solar photovoltaic model for an on-grid energy storage device was developed using MATLAB/Simulink, and the model was optimized using a fuzzy logic algorithm. The overall simulation results show that the output of the PV model can be controlled using a fuzzy-based optimization algorithm. The result of the fuzzy logic controller gave a better performance with good voltage stability. Also, the fuzzy-based optimization helps boost the voltage profile of the system.**

***Keywords* — Energy storage; fuzzy logic controller; grid; PID controller; solar PV; sunlight intensity; temperature.**

I. INTRODUCTION

There is great potential in the use of fossil fuels as a major source of electricity production, and several countries have harnessed this potential. This implies that individuals are subjected to the environmental pollution that comes with the use of fossil fuels for traditional power. Likewise, it requires an extensive and costly infrastructure to be put in place. Environmental concerns, global warming, and fossil fuel prices are creating a shift in the expectations of end-users and industries to move towards renewable energy resources. Solar energy is globally promoted as an effective alternative power source to fossil fuels because of its easy accessibility and environmental benefits [1-4]. Thus, solar photovoltaic (PV) systems are one of the fastest-growing types of renewable energy sources being integrated worldwide. There are many solar PV application categories that have been developed, such as batteries and electric vehicles that are connected to the grid. As may be observed in Fig. 1, the use of solar PV installations has grown globally at a rapid pace in recent years. In Fig. 1(a), the annual solar PV installations around the globe for the periods from 2000 to 2013 are presented. As may be observed, with about 37000 MW of solar PV power installed in 2003, solar PV power capacity increased by about 35% in 2013 [5]. More recently, the capacity has increased drastically (Fig. 1(b)). PV installations around the globe are expected to experience a growth of 20% or more in 2022 and surpass the 200 GW DC barrier for the first time as reported by clean energy technology [6]. This shows that the demand for solar PV installations is on the rise, which is expected to continue in the future.

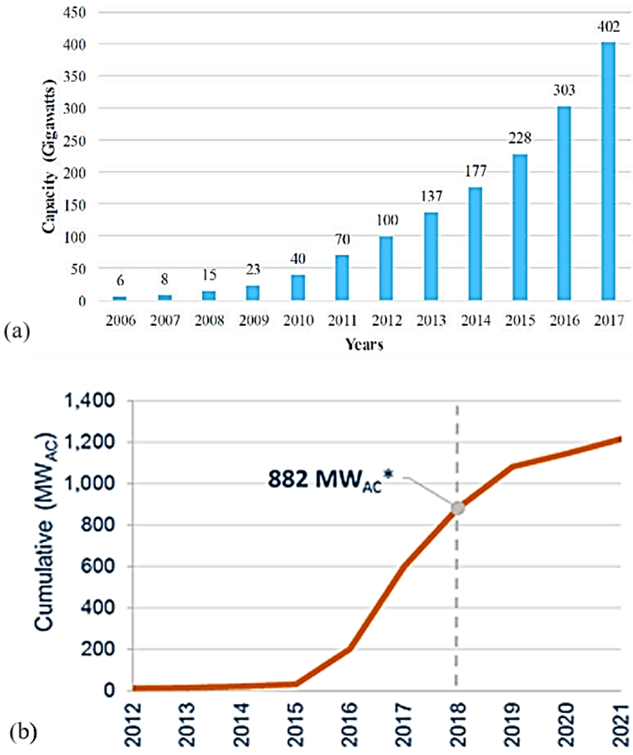

Fig. 1. Global solar PV installations (a) annual installation 2000-2013 (MW) (b) cumulative capacity from 2012-2021 [5].

In a solar PV system, tracking the sun’s energy is vital. Solar tracking makes more solar energy be generated because the solar panel is able to maintain a perpendicular profile to the rays of sunlight. Several research studies in this area can be found in the literature [7]–[11]. Nguyen [7] developed a laboratory prototype of a solar tracking system that enhances the performance of the photovoltaic modules

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in a solar energy system. The prototype was able to keep the photovoltaic modules constantly aligned with the sunbeam, which maximized the exposure of the solar panel to the sun's radiation. In Arsalan [8], the efficiency of the solar panel was maximized by aligning the panel with the sun on a single solar axis. The developed system uses a microcontroller 8051 with a simple circuit and sun-tracking software. The Microcontroller 8051-based circuit was used with a minimum number of components and the stepper motors, thus enabling accurate tracking of the sun. Also, Anuraj and Gandhi [9] developed a solar tracking system using a stepper motor controlled using an ATMega16 microcontroller. This is programmed to detect sunlight through the LDRs and then actuate the stepper motor to position the solar panel where it can receive maximum sunlight. Similar to other research studies mentioned earlier, the stepper motor used is more controllable, more energy-efficient, steadier, has high tracking accuracy, and suffers from few environmental effects [9]. The results presented show that the solar tracking system with single-axis freedom can increase energy output by approximately 20%. Several studies on the use of sun-tracking systems may be found in the literature [10]-[16]. In these studies, it has been demonstrated that the sun tracking systems can collect maximum energy than fixed panel systems, and relatively high efficiency can be achieved through the tracker.

Renewable energy sources have been able to provide intermittent power and their integration into the grid has improved power availability. Nevertheless, the output from such a system is not stable. Thus, controlling the output from such a system is vital. The inability to control the output of renewable resources like solar results in operational challenges in power systems. To compensate for the fluctuating and unpredictable features of solar photovoltaic power generation, electrical energy storage systems have been introduced [17]-[20] which may be integrated into the grid. A grid-tie battery storage photovoltaic system (see Fig. 2) consists of multiple photovoltaic modules, which are used to convert sunlight to DC electricity. Every grid-tie photovoltaic system needs one or more inverters to transform DC power received from solar panels to AC power for connecting with the electrical grid.

Photons in sunlight radiation that hits a solar panel is absorbed as energy in the semiconducting material. Research studies, such as the one presented by Nahar [21], show that solar energy levels reach around 1366 w/m^2 on the earth's surface. This implies that the system will collect nearly 1 kW of solar energy for every square meter of surface area on the solar collecting platform that faces the sun [22]. Solar panels convert radiation or rays from the sun into electrical energy. The PV power output maximum point varies according to the radiant sunlight intensity and temperature. Therefore, the current flow is controlled by the Energy Hub to track the changing maximum power point. For each energy controller module, numerous optimization algorithms could be used to enhance the performance of the controller. In this paper, a fuzzy-based optimization algorithm is utilized.

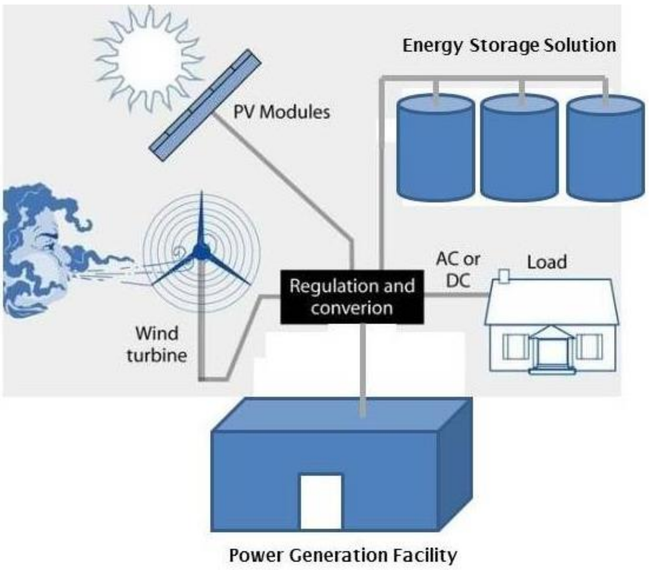

Fig. 2. A typical grid-tie battery storage photovoltaic system.

II. RESEARCH METHOD

A. Overall System Model

Fig. 3 shows the block diagram of a grid-connected PV system. For grid-connected PV systems, an inverter is a primary component. The PV system produces small DC power, which must be converted to AC power up to the level of need of the grid by means of an inverter. Sox, the PV inverter plays a very important role in the grid-connected PV system. In a grid-interactive system, all excess power is fed into the grid. Also, during the absence of or inadequate solar radiation, a supply of power is maintained from the grid, and thus the battery is eliminated. As PV produces DC power, it is first converted to AC power by an inverter, harmonics are filtered, and then only AC power is fed into the grid after adjusting the voltage level.

B. Boost DC-DC Converter Module

The DC-DC converter was used to track the maximum power point of the PV system. There are two hardware topologies for maximum power point tracking (MPPT): one-stage and two-stage PV systems. Because it offers an additional degree of freedom in the operation of the system, we have chosen the two-stage PV energy conversion system. To minimize high frequency harmonics, we have connected a capacitor between the PV array and the boost circuit. The DC-DC converters boost and step up the PV voltage to the level of the allowable maximum line voltage and to the stable required DC level without storage elements.

C. Mathematical Model of Photovoltaic Panel

The PV model used for the simulation is the SunPower Kyocera solar KC200GT. The model parameters were selected so as to give a maximum power point of 1.22 KW at 25 ^{o}C and 1000 W/m^2 irradiation as the Standard Test Condition (STC). The input values of an MPPT algorithm are the voltage and current of a photovoltaic panel. As environmental variables such as temperature and solar irradiation power affect the photovoltaic panel power curve, a mathematical model of photovoltaic panels was built to observe the effects on MPPT tracking. The temperature increases the energy of electrons and reflects velocity.

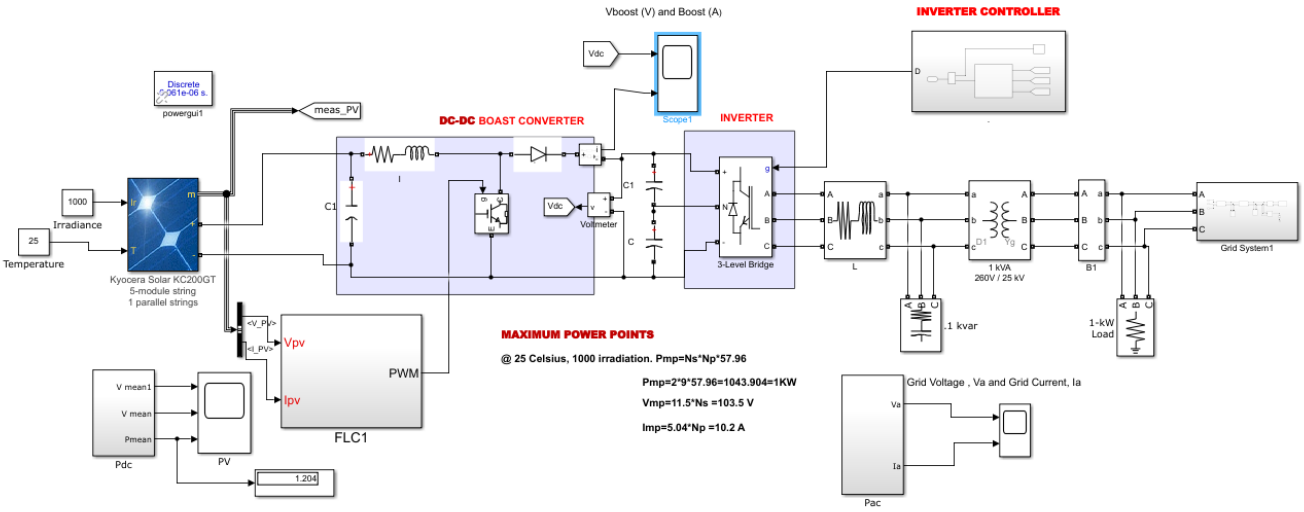

Fig. 3. Simulink module of a photovoltaic grid.

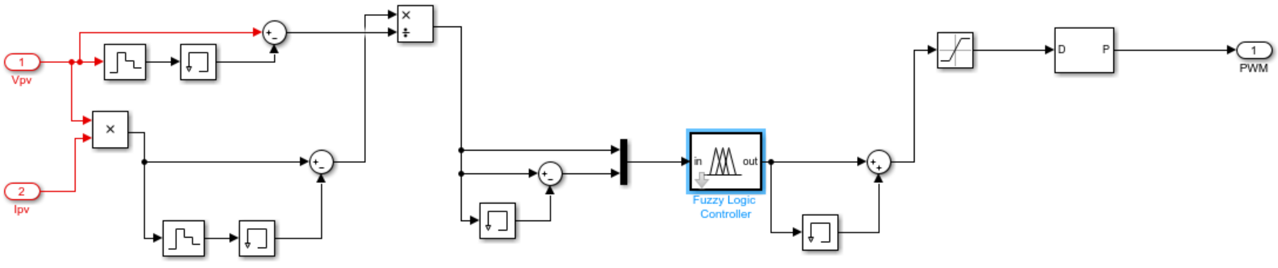

Fig. 4. Simulink model of a fuzzy logic controller.

These two parameters become the most important parameters that could affect the PV panel's operating state. PV cells can be configured in series to form modules. Then modules can be connected in parallel or series to form arrays. When modules are connected in series, they must have the same current to produce an additive voltage output.

Similarly, to produce larger currents, modules must have the same voltage when connected in parallel. PV cells can be modeled as a current source in parallel with a diode. When there is no solar radiation present to generate any current, the PV cell behaves only like a diode. As the intensity of incident light increases, the current is generated by the PV cell. In an ideal cell, the total current I is equal to the difference between the current I_1 generated by the photoelectric effect and the diode current I_d, according to (1).

$$I = I_1 - I_d \tag{1}$$

The current through the diode is expressed as:

$$I_d = I_o\left(e^{\frac{qv}{kT}-1}\right) \tag{2}$$

Therefore,

$$I = I_1 - I_o\left(e^{\frac{qv}{kT}-1}\right) \tag{3}$$

where, I_o is the saturation current of the diode, q is the electronic charge (1.6×10^{-19} coulombs), k denotes the Boltzmann constant (1.38×10^{-23} J/K), T is the cell temperature in Kelvin, while v is the measured cell voltage that is either produced (power quadrant) or applied (voltage bias).

The model represented by (3) is a single diode model. A two diode model may also be used. Simplifying (3) further gives the simplified circuit model represented by (4).

$$I = I_1 - I_o\left(\exp^{\frac{q(v+IR_s)}{nkT}-1}\right) - \frac{V+IR_s}{R_{sh}} \tag{4}$$

In (4), I is the photocurrent in (A), n is the diode ideally factor (typically between 1 and 2), and R_s and R_{sh} represent the series and shunt resistances respectively.

D. Controller Module

A PID controller is utilized for this module. PID controllers are the most widely used type of controller for industrial applications [23]. The three main parameters involved are Proportional (P), Integral (I), and Derivative (D). The proportional part is responsible for following the desired set point, while the integral and derivative parts are responsible for the accumulation of past errors and the rate of change of error in the process, respectively [24]. For the PID controller presented above, its output u(t) can be expressed as;

$$u(t) = K_p e(t) + K_i \int_0^t e(t).dt + K_d \frac{d}{dt} e(t) \qquad (5)$$

where K_p denotes the proportional gain, K_t represents the integral gain, K_d is the derivative gain, $u(t)$ is the control gain and $e(t)$ is the error that gives the difference between the setpoint and the plant.

The photovoltaic model was developed using MATLAB/Simulink, and the controller was optimized using a fuzzy logic algorithm. The Simulink model of the fuzzy logic controller is shown in Fig. 4. Input reference is used through two supply lines to the model and each controller of a different parameter. Input ports are photovoltaic voltage (V_{pv}) and photovoltaic current (I_{pv}) and the output port is pulse width modulation (PWM). A fuzzy logic method is used for tuning algorithms to optimize the performance of the controller. Since the model was built for the actual solar panel product, a tuned gain can be found using simulation. To obtain the maximum power point, a fuzzy logic controller shown in Fig. 4 was used to control the duty cycle. Table 1 relays the simulation parameters.

TABLE I: SIMULATION PARAMETERS

Parameters	Value
Grid voltage	250 kV
Frequency	50 Hz
Filter inductance	0.05 H
Filter capacitance	100 mF

III. RESULTS AND DISCUSSIONS

A. *Voltage and Power Profile*

Fig. 5, Fig. 6, and Fig. 7 represent the Simulink results for the grid-connected inverter. In Fig. 5, the irradiance, boost voltage, and power against time was presented. The irradiance of the system was stable and constant at 1000 Wm^{-2} and the power of the grid remained constant and stable at 1.2 kW. This implies that over 1 kW of power was supplied to the grid, and the sinusoidal wave from the graph showed the grid system is safe, despite sending more than 1 kW of power to it. As may be seen in Fig. 5, as the solar radiation remained stable at 1000 W/m2 the voltage stability is maintained, thus, the voltage remains stable at 150 V as shown in Fig. 5(b). In Fig. 5(c), the power also remains at 1.2 kW power supplied to the system. Nevertheless, these values were boosted to increase the PV efficiency and output power as shown in Fig. 6 and Fig. 7. (a). Fig. 6 illustrates the AC output power for the grid-connected system before and after optimization. In Fig. 6, (b), the plot of the output power before the optimization is displayed. There are fluctuations in the output power due to the intermittency nature of the solar source, particularly with inconsistent solar irradiance and temperature. Therefore, the PV system uses a fuzzy-based optimization algorithm to obtain the maximum and most stable power from the PV panels. In Fig. 6(a), which shows the results of the output power after optimization, it is seen that the power becomes stable after optimization was performed.

B. *Boost Voltage and Current*

Boosting voltage profile within the limits of the power system was considered one of the most important factors of power flow characteristics. Fuzzy-based optimization was also used to improve the voltage profile of the system. Simulation results shown in Fig. 7 revealed that the voltage was boosted from 150 V to 600 V. Fig. 8 shows the boost current of the system against time. This figure shows the output current of a solar system as it varies with time at standard test conditions. Optimization of the circuit current was introduced to reduce the fault current produced by the PV generation and also to minimize the short circuit levels. Optimization allocation to the current also helps to minimize fault levels within the acceptable limits as in Fig. 8.

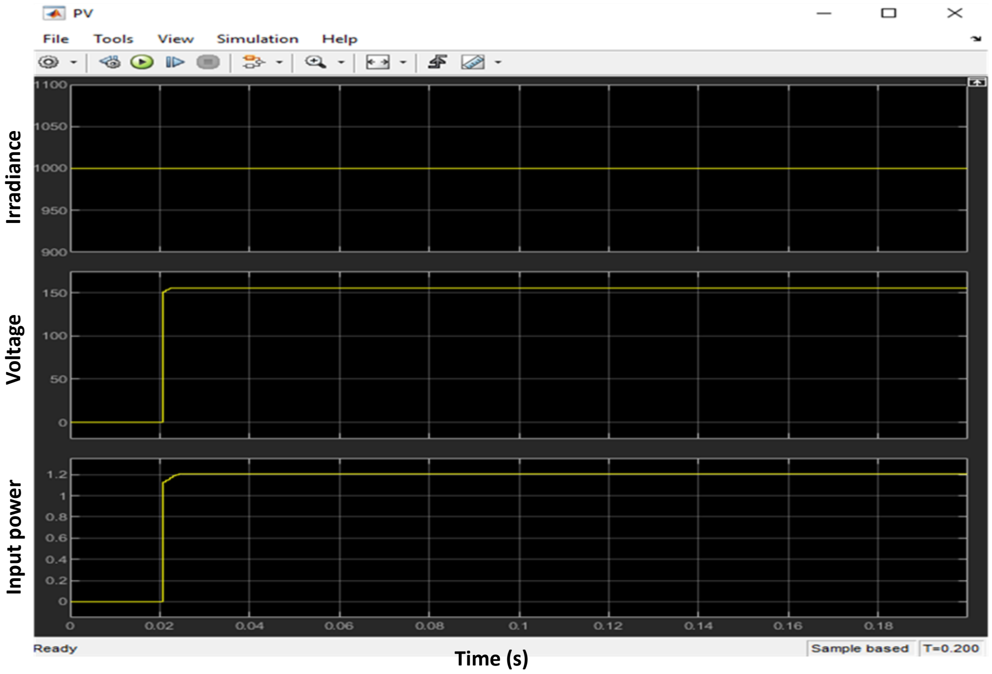

Fig. 5. Plot of (a) irradiance against time (b) voltage against time (c) input power against time.

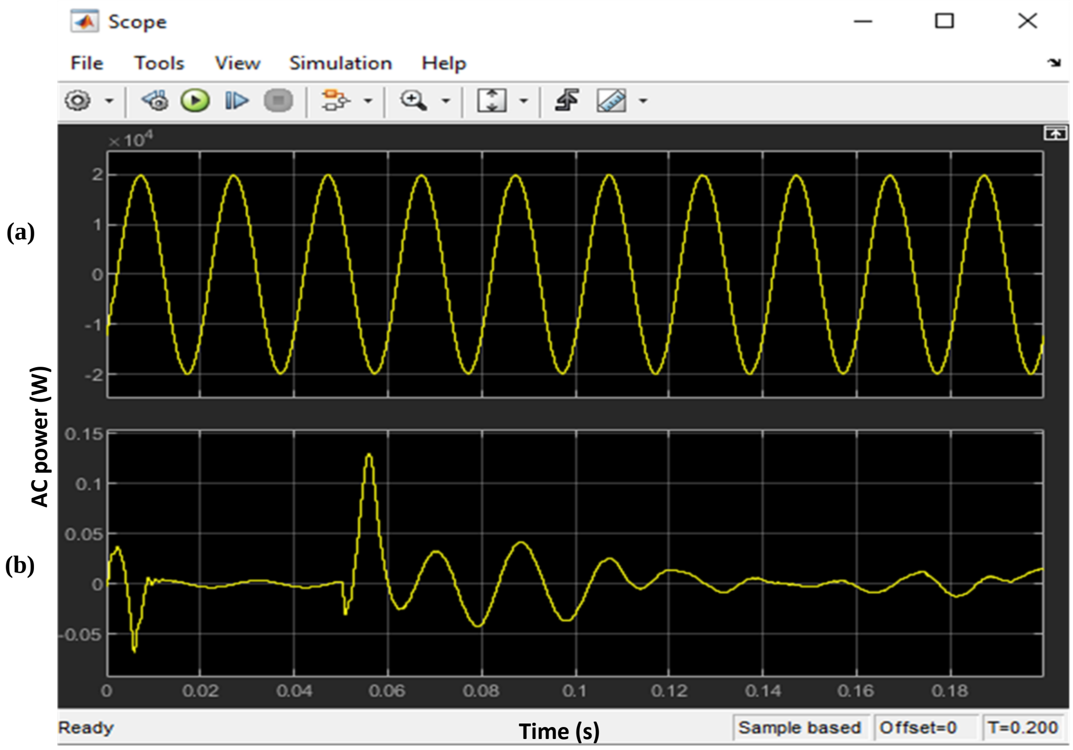

Fig. 6. AC power output of the system against time (a) after optimization (b) before optimization.

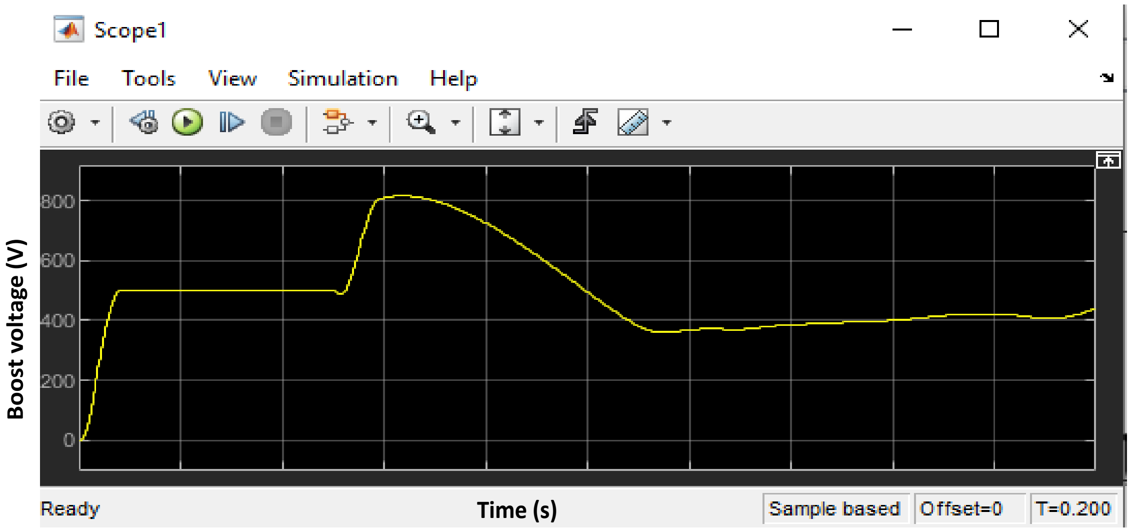

Fig. 7. Plot of boost voltage of the system against time.

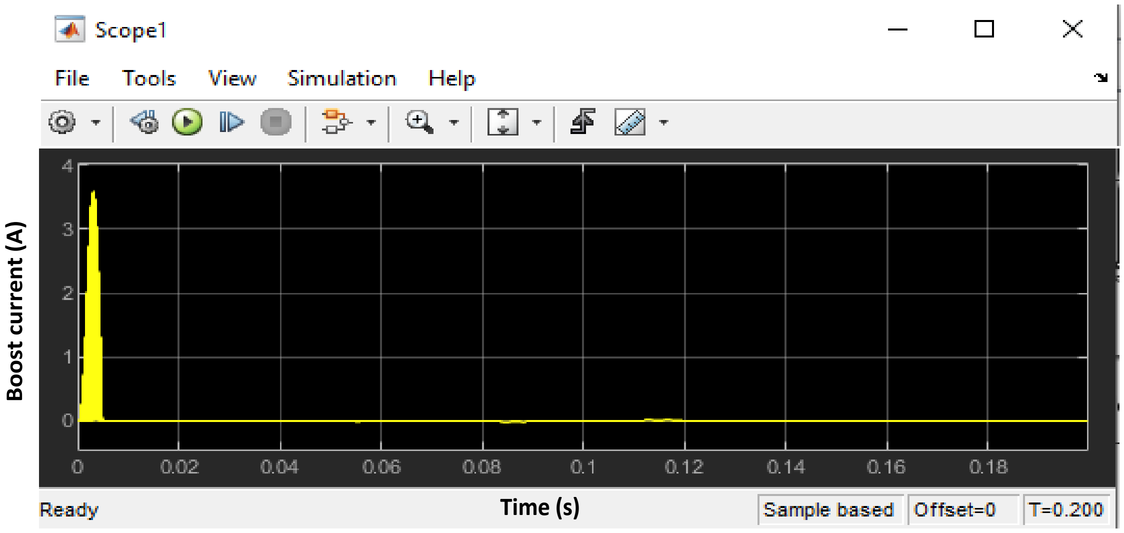

Fig. 8. Plot of boost current of the system against time.

IV. CONCLUSION

Solar photovoltaic applications are promising alternative approaches for power supply and are widely designed to be grid-connected. Unfortunately, the inability to control the output of such renewable energy sources results in operational challenges in power systems. The operational challenges of renewable resources can be compensated by the use of energy storage systems that may be integrated into the grid. In this paper, a solar energy system for an on-grid energy storage device was developed using MATLAB Simulink and the output of such a system was controlled using a fuzzy logic tuning technique. The results obtained show that voltage stability is maintained. Also, the output power remains stable when fuzzy-based optimization is applied. Thus, the voltage remains stable as the energy balance keeps the DC link voltage at a stable level. In addition, the fuzzy-based optimization assists in improving the voltage profile of the system. Simulation results revealed that the voltage was boosted from 150 V to 600 V.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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