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Voltage Regulation and Power Management of DC Microgrid with Photovoltaic/Battery Storage System Using Flatness Control Method

Ashraf Abdualateef Mutlag [1*], Mohommed Kdair Abd [2], Salam Waley Shneen [3]
[1, 2] Electrical Engineering Department, University of Technology, Iraq
[3] Energy and Renewable Energies Technology Center, University of Technology, Iraq
Email: [1] eee.21.10@grad.uotechnology.edu.iq, [2] 30098@uotechnology.edu.iq, [3] salam.w.shneen@uotechnology.edu.iq
*Corresponding Author

Abstract—**This research aims to propose a power management strategy (PMS) based on the flatness control method for a stand-alone DC microgrid system. The goal of the proposed strategy is to create an efficient PMS using nonlinear flatness theory in order to provide a constant DC bus voltage and the best possible power-sharing mechanism between the battery and the PV array. A maximum power point tracking (MPPT) technique based on an artificial neural network (ANN) to optimize the PV's power. Moreover, the suggested PMS technique was tested in a simulation environment based on MATLAB®/Simulink. The obtained results demonstrate that the proposed PMS method can stabilize the bus voltage under variations in load or solar radiation. Additionally, the PMS method reduced bus voltage spikes and guaranteed good power quality, which extended the battery's lifespan and increased its efficiency. Also, the proposed approach outperforms the standard PI approach in terms of tracking efficiency and has a lower rate of overshoot in the bus voltage under different load scenarios. Therefore, the method is effective when compared with the classical PI approach. The overshoot in the PI method is 58 V, while the overshoot in the DC voltage is 5 V in the proposed method. The tracking speed of the proposed system is very low, and the slower speed was observed in the classical method, and the rise time of PI was 7.9ms, while the proposed method equals 2.2ms.**

Keywords—Flatness Control; DC Mircrogrid; Nonlinear Control; Photovoltaic; Battery; Microgrid; MPPT; DC Voltage.

I. INTRODUCTION

Because of significant technological advancements in the field of power generation, several countries are seeking to increase reliance on renewable energy (RE) sources in order to reduce carbon emissions and pollution caused by huge central plants that burn fossil fuels. Solar panels and wind energy are the most common renewable energy sources employed [1][2].

Solar photovoltaic (PV) systems are widely used in remote areas due to their energy independence, lack of fuel requirements, low environmental impact, distribution losses, minimal maintenance requirements, community empowerment, energy security, and electrification of off-grid areas [3][4]. PV systems provide an independent source of energy, which reduces dependence on energy from central plants that are dependent on fossil fuels. Thus, PV is considered a reliable and sustainable energy source [5][6].

In remote areas far from city centres, transporting power from central stations is difficult and expensive, making photovoltaic energy a cost-effective solution. Photovoltaic energy systems are also considered an environmentally friendly source and produce power without emitting gases, noise, or air pollutants. In addition, PV systems require minimal maintenance requirements, making them suitable in remote areas where maintenance personnel are far away and transportation of spare parts is difficult [7][8].

In order for the PV system to operate at the highest level of power generation, it needs special algorithms for this purpose known as Maximum Power Point Tracking (MPPT) algorithms, which work to increase the power production of the panels by adjusting the operating points according to different environmental conditions. It constantly monitors climatic variables such as temperature and solar radiation and adjusts the operating point of the panels, keeping the system operating at or near the maximum power point (MPP) [9][10][11].

DC Microgrid (DC MG) is often defined as a group of power sources made up of electricity RE sources. They also include power storage units, in addition to loads and power converters. They help to increase the quality and dependability of local energy sources and systems [12].

However, it is recommended to use DC MG due to its ease of control as well as the absence of problems in network synchronization or harmonics, in addition to using a smaller number of power converters, thus resulting in lower conversion losses compared to other types [13][14]. In remote places, the PV system integrates with battery storage, storing excess solar energy during daylight hours and using it during absences or at night to provide continuous electricity. For the microgrid system, including continuous power supply, system independence, and load shifting according to generation periods [15][16]. This reduces dependence on the utility grid, especially in areas with limited or no access to power transmission lines. The process of shifting loads achieves a balance in energy generation and consumption, and this increases the efficiency of the microgrid. Overall, PV and batteries provide a reliable and sustainable energy solution in remote areas. Optimal power generation, storage, and utilization can be achieved by implementing a variety of control techniques and power management algorithms, where reliability of the power supply, efficient operation, and stable network integration are the goals of the control system [17][18]. Moreover, one of the goals of using control algorithms is to manage the battery system and ensure safe operation, prevent overcharging or over-discharging, and monitor the health of the batteries in addition to their current charge level [19][20]. Control methods, including traditional linear control approaches like the proportional-integral (PI) control method, are used to regulate the DC bus voltage and power flow when the system is subjected to anomalous load changes [21][22][23].

In the literature, several studies have used linear PI control and advanced control methods to control the DC microgrid or PV systems. In [24] , the authors proposed a forecasting technique that is based on a Long Short-Term Memory Network (LSTM) that is built in order to anticipate the amount of power that is available from PV and batteries. These learning data were taken from a place in Africa that has a tropical environment, which makes it an ideal location for PV power applications. The primary purpose of the method that has been developed is to regulate the various loads in accordance with the anticipated energy availability of the system as well as the anticipated state of charge (SOC). In [25], in order to Reduce bills of home consumption and develop demand side management (DSM), the authors proposed the use of compression air energy storage Technology (CAEST) suitable for use in tandem with regular renewable energy sources that are useable. Here, CAEST in combination with small wind turbines, is activated when needed to reduce emissions, electricity bills, and energy consumption through the use of smart meter (SM) control. The results mainly demonstrated the effect of the CAEST on bill reduction, with the electricity bill decreasing by nearly 23%.

The authors in [26] proposed a power management control (PMC)-based optimization for a wind/battery system. This method was developed and connected to the recommended two-level MPPT controller. By allowing the effective and best operation of two MPPT algorithms, the PMC in use ensures that the storage batteries employed experience the lowest level of stress possible. The PMC-based system's main objective is to supply the load's required power. Secondary objectives include minimizing power outages, keeping the battery bank's state of charge, and extending the batteries' valuable lives. The authors in [27] presented an intelligent strategy that is based on fuzzy logic (FL). The purpose of this technique is to guarantee that a PV system operates at maximum power under dynamic climatic circumstances. Different cases have been conducted on the energy management of batteries with the purpose of managing the charge level in dynamic climate situations. The findings of the study that are reported in the study make a significant addition to the implementation of fuzzy theory in order to enhance power as well as system performance. In [28], autonomous photovoltaic and battery systems might benefit from the Power Management Strategy (PMS) that is based on Model Predictive Control (MPC). For the purpose of forecasting the load and environmental factors, the suggested technique incorporates an auto-regressive integrated moving average (ARIMA) prediction algorithm. The controller that has been presented can have the following capabilities: efficient power management and the reduction of transients during disturbances. To meet global energy demand, low-emission, environmentally friendly renewable energy systems must be developed to prevent greenhouse gas production and resource depletion. Therefore, the study in [29] presented a hybrid renewable energy system (HRES) for automotive applications. More precisely, we combine a PV array that is put on the roof with a PEM fuel cell/NiCd battery that is already running shuttle routes on the University of Delaware campus. A logic-based “algebraic controller” as well as a typical PI controller are needed in order to accomplish the system's overall operational goals, which include meeting the entire power requirement of the bus and keeping the required SOC.

Stand-alone PVs generate output voltage variations due to fluctuating irradiance, temperature, and load conditions, posing control challenges. Despite fluctuations in either the voltage input or the load, the objective of the study in [30] is to successfully maintain a constant output voltage at the load. The use of a DC converter guarantees that the voltage output of such systems will remain constant, irrespective of any variations in the manufactured voltage or load characteristics. The solution to this issue is to make use of the control that is included in a DC boost converter. As a result, the Incremental Conductance (IC) method has been used as an MPPT algorithm, and a PID has been optimized. For the purpose of optimizing the suggested PID via the specified cost function, the Particle Swarm Optimization (PSO) method has been used. Also, in reference [31], an MPPT algorithm that combines PSO and hybrid neural networks is used. This was tested against the fundamental PSO method and in partial shading conditions. The ANN uses a variety of sensors to measure irradiance; however, imperfect sensors might cause issues for actual systems. It suggests doing away with these sensors by focusing exclusively on the I-V curve, but this would have the drawback of requiring more data and a better-trained ANN.

In this paper, a nonlinear control method was used to control the DC bus voltage and maintain a stable load supply with both PV and battery under variations of the demand load, which represents the community loads. The main objective of the study is to propose a robust control method for the DC MG to stabilize the bus voltage during the changes in the irradiance or variations in load using the nonlinear flatness control theory. The results obtained from the nonlinear flatness control theory were compared with the results obtained through the classical PI control method used in the research paper [21]. The proposed system was simulated via MATLAB/Simulink software version 2021a by PC Intel(R) Core(TM) i7-10750H CPU @ 2.60GHz- 2.59 GHz. The research contributions are :

i. Introducing a highly efficient PMS for the DC MG system.

ii. Minimizing the overshoot in the DC bus voltage under fast changes in irradiance or load conditions.

iii. Increasing the lifetime of the batteries by controlling the charging/discharging process with high efficiency.

This paper is organized as follows: Section II is reserved for system description. The first subsection is reserved for the presentation of the photovoltaic panel; the second sub-section is reserved for the study of the design of the MPPT controller; the third sub-section is reserved for the study of the battery energy storage system, and the fourth sub-section is reserved for describing loads. In Section III, the nonlinear control strategy has been explained, the simulation results are presented, and there is a discussion in Section IV. Finally, the conclusion is provided in Section V.

II. SYSTEM DESCRIPTION

Modelling a DC microgrid with a solar PV system in a circuit involves representing the key components of the system and their electrical characteristics. The main components of a DC microgrid system, as shown in Fig. 1, contain solar panels (photovoltaic modules), a DC-DC boost converter with MPPT controller, a DC-DC bidirectional converter to control on battery and energy storage (if applicable), and an inverter for converting DC power to AC power (if needed for grid-tied systems or powering AC loads).

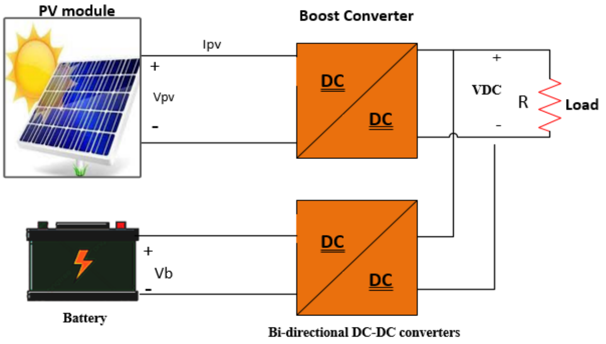

Fig. 1. Structure of the DC microgrid

A. Solar PV System

1) PV module equation

In general, a photovoltaic system contains modules connected in parallel or series, each consisting of several photovoltaic cells [32]. The equivalent circuit for solar cells is seen in Fig. 2. The solar PV current of the cell or module can be written as (1) [33][34].

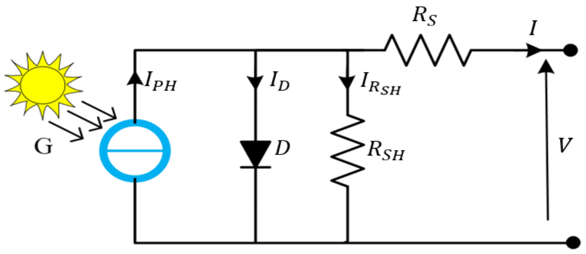

Fig. 2. PV module circuit based single-diode

$$I = I_{PH} - I_S\left(exp\left[\frac{(V+IR_S)}{V_{th}\delta}\right]-1\right) - \frac{(V+IR_S)}{R_{SH}} \qquad (1)$$

Where I indicates for the module's current, V indicates for the module's voltage, I_{PH} indicates for the photocurrent of the module, I_S indicates for the diode current at saturation, R_S indicates for the series resistor, R_{SH} indicates for the shunt-resistor, δ indicates the diode constant, and V_{th} indicates the thermal voltage.

2) PV array characteristics

In this work, the PV system capacity is 60 KW. As shown in Fig. 3, the solar system is made of a PV array of Ns = 15 panels and Np =20 panels. The curves of the solar system under different solar irradiances can be shown in Fig. 4. As shown in this figure, the MPP of the system depends on the value of the irradiation, which varies from 0 KW/m^2 to 1 KW/m^2. The high power, or MPP, of the system, indicates a current of 152.2A and a voltage of 394.5 V, which produce a maximum power of 60KW. Table I shows the parameters of the solar panels used in this study.

The DC-DC boost converter is used to perform the MPPT algorithm. The control of the boost converter is done by adjusting the duty ratio via a PWM signal from the MPPT circuit, as shown in Fig. 5.

TABLE I. THE PARAMETERS OF THE SOLAR PANELS

Parameter	Value
Maximum power(PMPP)	200.143 W
Maximum power point voltage (VMPP)	26.3 V
Open-circuit voltage (VOC)	32.9 V
Maximum power point current (IMPP)	7.61 A
Short circuit current (ISC)	8.21 A

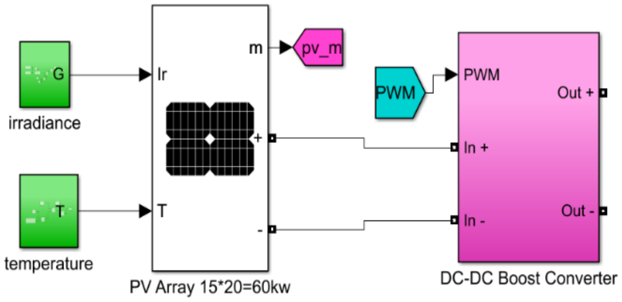

Fig. 3. The solar PV system with Boost converter

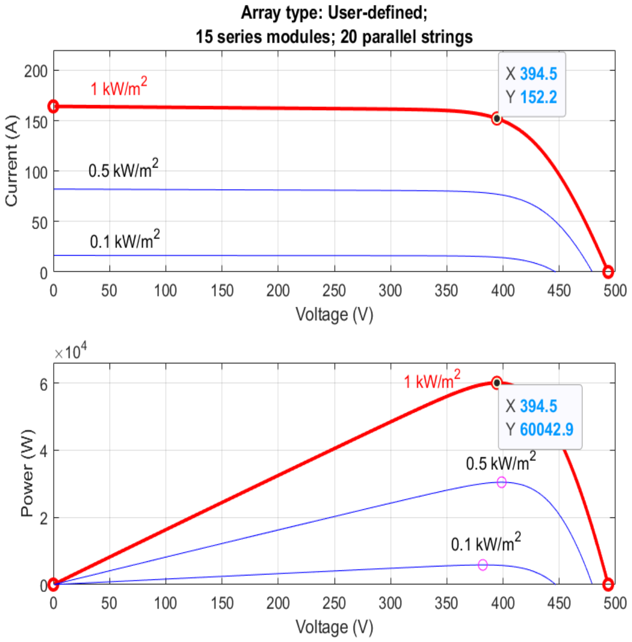

Fig. 4. Solar array curves

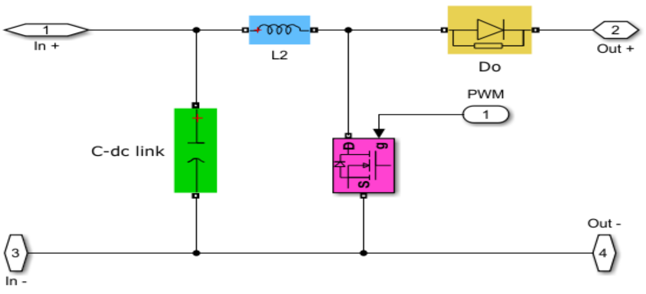

Fig. 5. DC-DC boost converter

B. *Proposed ANN-PI based MPPT Control*

In order to accomplish effective MPPT, the duty cycle of the DC-DC converter must be adjusted via MPPT controllers; it produces a reference voltage signal with a variable duty cycle that serves as input to the PWM generator. In order to successfully control the converter's switch, the necessary pulses need to be generated. Overall, the switch forces the PV to operate at the MPP, which controls the voltage across the source.

In this work, a hybrid neural network (NN-PI)-based MPPT control was used. The block diagram of this method is illustrated in Fig. 6. The PI was utilized to improve the ANN's performance and eliminate its problems because training and testing require dependable data. The PI controller adjusts the voltage errors between the measured and reference values and applies the necessary adjustments to the process. At the same time, the ANN tracks the MPP by finding the reference voltage using real-time information like temperature (T) and solar radiation (Irr) [35][36]. The continuous PID equation is impacted by the values of K_p, K_i, and K_d. PID gains are modified via a variety of techniques, including the Ziegler-Nichols approach and genetic algorithms [37][38][39].

The advantages of using the ANN-PI technique are due to the following reasons [40][41]:

- Enhances Nonlinear Modeling Capability: ANNs capture complex, nonlinear behaviours of solar PV systems, enabling accurate prediction of the optimal operating point under varying conditions.
- Adaptability to Changing Environments: ANNs are able to optimize the operating point and make dynamic adjustments in response to changes in the environment.
- Enhanced tracking Accuracy: Artificial Neural Networks (ANNs) facilitate more precise and effective maximum power point monitoring by leveraging past data to enhance the approximation of the best operating point.
- Optimization of Energy Harvesting: ANN-PI control strategy maximizes energy harvesting efficiency by dynamically adjusting the operating point, improving energy yield.
- Adaptive Learning: ANNs continuously learn and adapt based on real-time data, enabling the MPPT control to evolve and improve performance over time.
- Handling Partial Shading: ANNs effectively handle scenarios with partial shading, ensuring better performance.
- Reduced Oscillations and Settling Time: ANN-PI control leads to smoother and faster responses to changes in operating conditions, improving system stability.

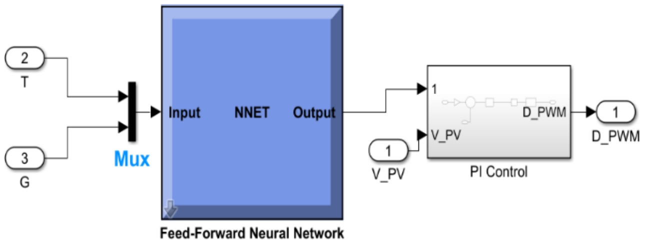

Fig. 6. proposed NN-PI based MPPT control

C. *Battery Energy Storage System*

In this work, the BESS of the lithium batteries was used to supply the community load when solar was not available [42]. Lithium batteries have more features than conventional batteries, such as high energy density, low self-discharge rate, long cycle life, fast charging capability, and high discharge current [43].

The proposed BESS using MATLAB can be shown in Fig. 7. The system consists of a lithium-ion battery with rated values, as shown in Table II. Also, the DC-DC bidirectional converter with two MOSFETs is used to control the flow of the current from the DC bus to the battery undercharging mode operation or to flow the current from the battery to load via the supply of the required power under discharging mode operation. The converter details can be shown in Fig. 8.

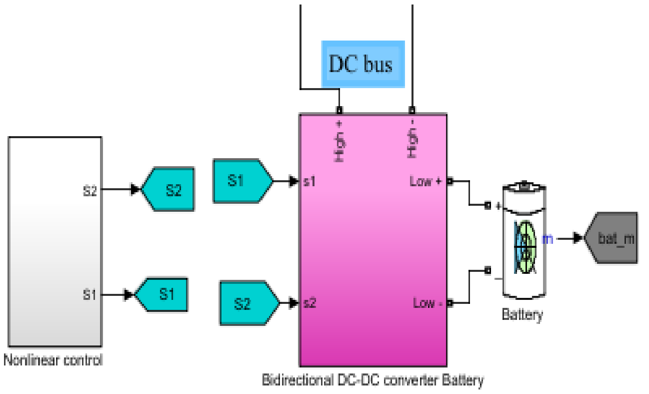

Fig. 7. BESS with its control and circuit

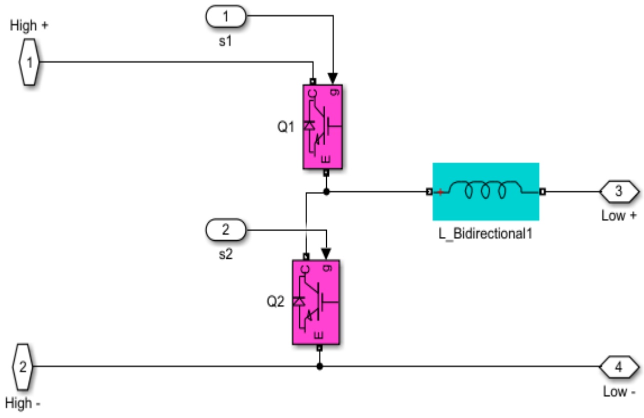

Fig. 8. DC-DC bidirectional converter of the battery

TABLE II. PARAMETERS OF THE BESS

Parameter	Value	Unit
Voltage	200 V	V
Nominal discharge Current	434 A	A
Capacity	1000 Ah	Ah
SOC	70 %	-
Internal resistance	0.002	Ω
Time of response	1	Sec

D. Community Load Modeling

A community load, which is the aggregate electrical demand or power consumption of a community or a group of interconnected consumers, was used in this work. In the context of electricity and energy management, the community load is important for planning, distribution, and ensuring a reliable power supply to meet the collective needs of the community. Fig. 9 shows the schematic diagram of the power flow and data information of the example community load building. The load profile used in this work can be presented in Fig. 10.

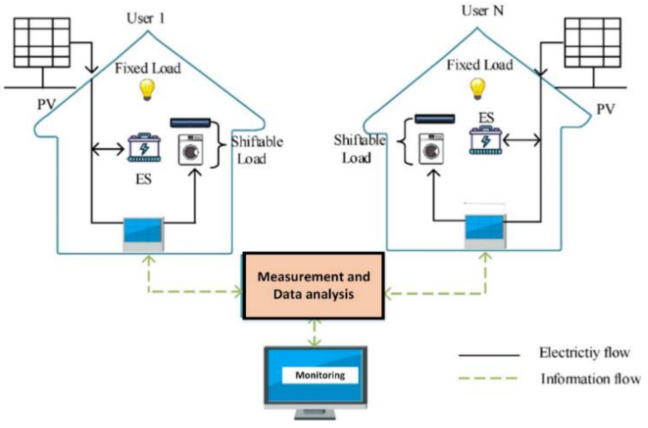

Fig. 9. A community load with PV and BESS supply

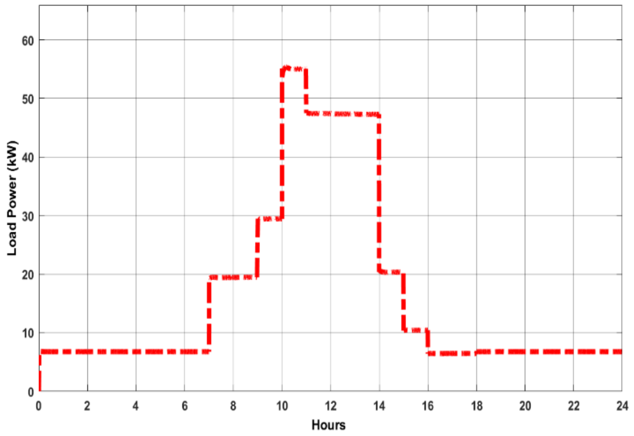

Fig. 10. Hourly load profile of the building

III. FLATNESS NONLINEAR CONTROL

Nonlinear control strategies are employed in DC bus systems for various reasons, particularly in applications where the dynamics of the system exhibit nonlinear behaviour or where advanced control techniques are needed to address specific challenges. Nonlinear control strategies are well-suited to handle the inherent nonlinearities in microgrids and can provide improved performance over traditional linear control methods [44].

Furthermore, the DC bus of MG or PV systems can operate under various situations, including variations in load, input voltage, and temperature. Nonlinear control techniques can better adapt to these changeable operating conditions, producing robust and dependable system performance [47]-[55].

In this article, the DC bus voltage is controlled using a flatness nonlinear control method. The DC bus system's transient response can be improved with the use of flatness control techniques. This is especially crucial for situations where quick and precise reactions to abrupt changes in load or input conditions are required.

The term "flatness" describes a dynamic system's ability to represent some of its outputs as functions of a set of flat outputs and their derivatives. Controllers based on flatness are intended to precisely track desired trajectories. In contrast to linear controllers, which may display tracking errors, this indicates that the control system can exactly follow intended output trajectories, resulting in improved performance [45][46].

The control law of the DC bus energy (y_{bus}) is derived from the equations (2) and (3).

$$y_{bus} = \frac{1}{2}\ C_{bus}\ {v_{bus}}^2 \qquad (2)$$

$$y_{bus,ref} = \frac{1}{2}\ C_{bus}\ {v_{bus,ref}}^2 \qquad (3)$$

Where C_{bus} indicates the DC bus capacitance, and V_{bus} indicates the bus voltage. The bus trajectory law control for the flatness control can be expressed as (4).

$$\dot{y}_{bus} = P_{PV} + P_{Bat} - P_{load} \qquad (4)$$

Where P_{PV} and P_{Bat} indicate the generated power from the PV system and battery, respectively. In order to the DC bus, the power reference of the battery must be tracked as (5).

$$P_{Bat\_ref} = P_{Bat} = v_{Bat}\ i_{Bat} \qquad (5)$$

Where v_{Bat} and i_{Bat} indicate for the voltage and current of the battery, respectively.

The power reference of the PV system is tracked by the MPPT, which produces the required power from the PV system. As a result, the load and PV generation used in Eq. (4) are put in the main control law equation, which represents the battery power reference expressed in Eqs. (2)-(5) as (6).

$$P_{Bat,ref} = 2P_{Bat,max}\left(1-\sqrt{1-\sqrt{\frac{\dot{y}_{bus}+P_{load}-P_{PV}}{P_{Bat,max}}}}\right) \qquad (6)$$

Equation (6) was modelled in MATLAB, as seen below in Fig. 11. The PWM block is used to produce the signals of the switches via controlling the battery current based on the PI controller unit. Fig. 12 shows the proposed nonlinear flatness control model.

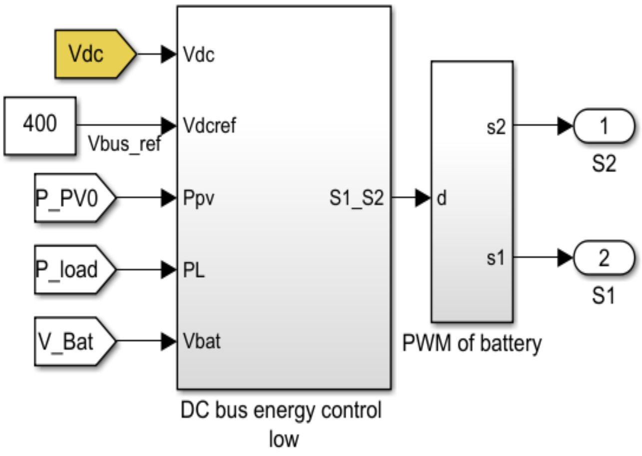

Fig. 11. Control law of the DC bus

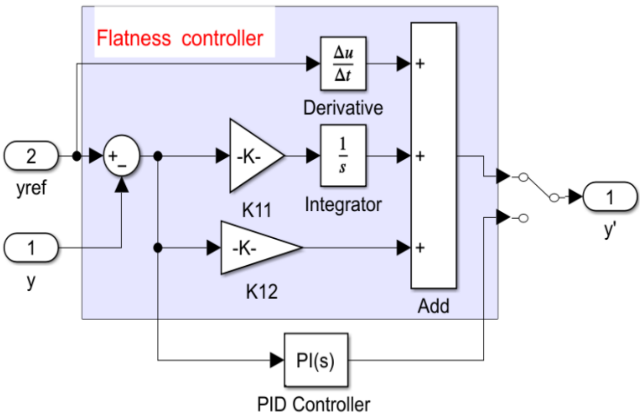

Fig. 12. The proposed nonlinear flatness control model

IV. SIMULATION RESULTS

The simulation results for this paper are presented based on the MATLAB/Simulink software. The proposed system for all components was made in Simulink, as described in previous sections. The solar irradiance and the temperature of the site selection in Al-Anbar City, Iraq, are presented in this simulation, as shown in Fig. 13. The real irradiance and temperature profiles are collected from the PVGIS online tool to prove the effectiveness of the proposed control methods. The PV voltage, current, and power of the PV system can be shown in Fig. 14.

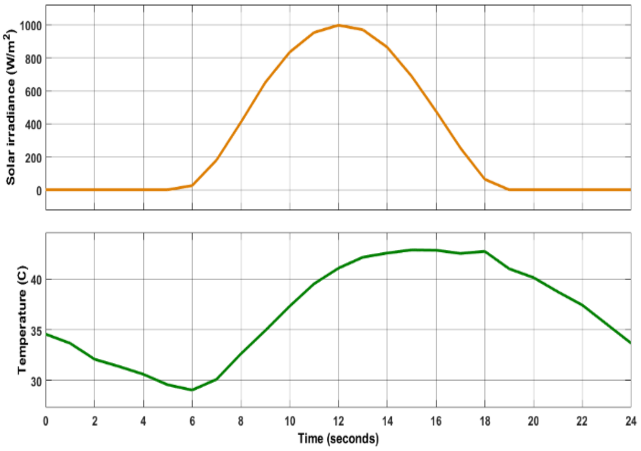

Fig. 13. Hourly solar irradiance and temperature

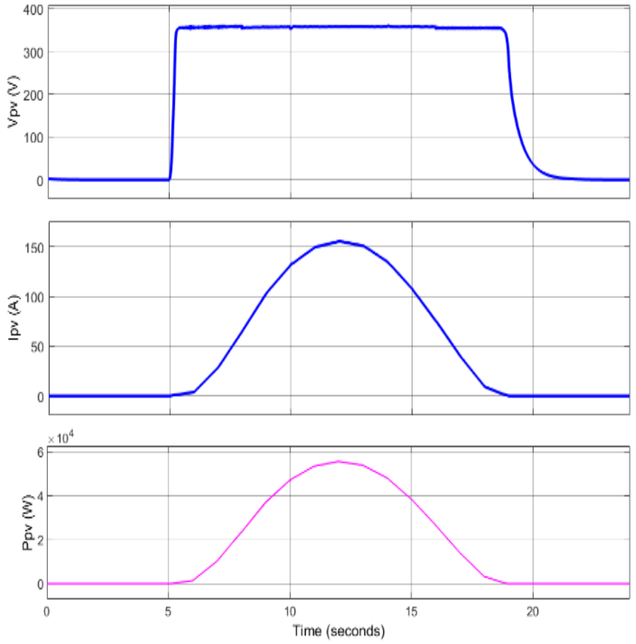

Fig. 14. Results of the PV system

The obtained results are simulated for a simulation time of 24 seconds. The obtained power curves for the community load, PV plant, and battery are indicated in Fig. 15. Because of the shape of the photo-current source, the PV system's curve resembles the irradiance curve. Based on the irradiance values, the battery bank supplied or absorbed the necessary power from the DC bus. The PV system supplies the required load when the irradiation is high.

Against, when the demand load increases at times 7 s and 10 s, the battery system switches from charging to discharging mode to cover the additional demand in the load. In this state, the solar system cannot cover the load. As a result, the battery, in this case, is operated to stabilize the DC bus voltage and track the power reference controlled by the flatness control law.

The battery results in terms of voltage, current, and SOC, are shown in Fig. 16. It is clear that the battery SOC is changed based on the state of the load. When the load is greater than the PV generation (PL>Ppv), the SOC is reduced due to the battery in discharging mode. If the load is less than the PV generation (PL<Ppv), the battery stays in charging mode. So, the current is flowing in the reverse direction based on the PWM control and the MOSFETs of the converter.

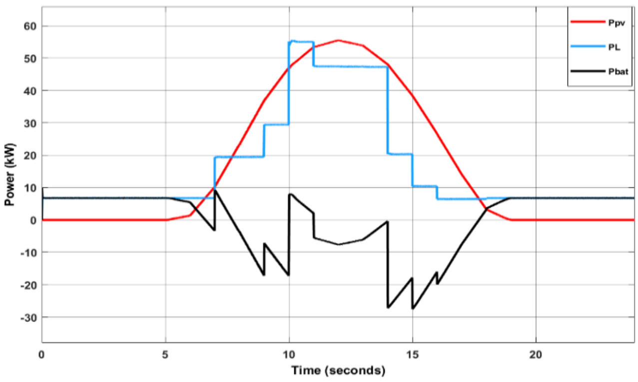

Fig. 15. Power results of the proposed system

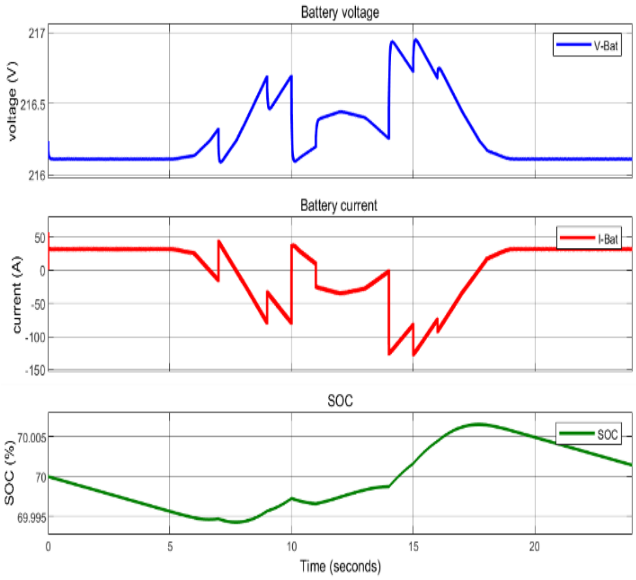

Fig. 16. The results of battery

In order to demonstrate the novelty of the proposed method, a comparison with the classical PI control method is done. The obtained curves of DC bus voltage can be seen in Fig. 17. It is clear that the proposed method is better than PI control in terms of overshoot, tracking speed, and variations.

The DC bus voltage is effectively controlled by the proposed nonlinear control, regardless of the load circumstances. The effectiveness of the suggested method is shown by this figure, which demonstrates that it is capable of achieving stability in DC bus voltage, minimalizing ripple content, and providing outstanding power quality. The overshoot in the PI method is 60 V, while the overshoot in the DC voltage is 5 V in the proposed method. The tracking speed of the proposed system is very small, at 0.003 s. The slower speed was observed in the classical method, which is 0.7s.

To clarify the novelty of this work, a comparison with PI is made, as presented in Fig. 18. The power quality of the load is improved using the proposed control, as shown in Figure 18. The obtained power curves in both classical PI and the proposed method are achieved, which indicates that the obtained power in flatness is more stable. A flatness-based control method can exhibit reduced sensitivity to variations in system parameters. As observed, the suggested flatness control is faster than traditional PI control because of its model-based approach, accurate linearization, trajectory planning, and reduced overshoot and settling time. This method is based on a precise mathematical model of the system that encompasses its dynamics and enables the computation of control inputs. This direct technique eliminates the trial-and-error tuning procedure required in PI control, resulting in faster response times. Feedforward control uses feedforward components to predict the required control action based on the desired output trajectory, allowing the system to respond to changes before they occur. The method can also decouple system dynamics, simplify control difficulties, and allow for more precise and rapid control operations. Its precise linearization yields faster and more.

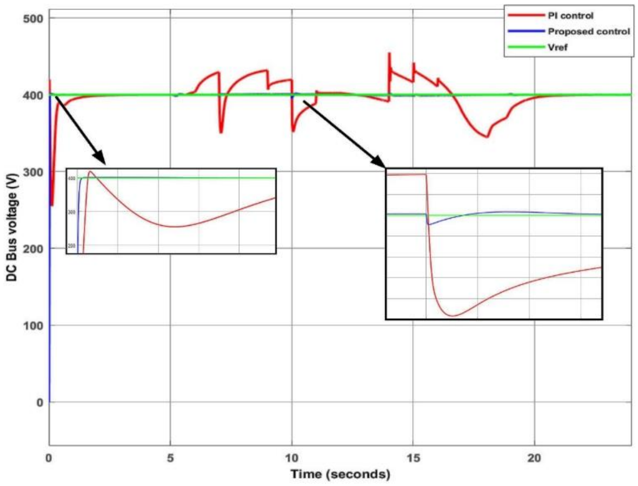

Fig. 17. DC bus voltage curves

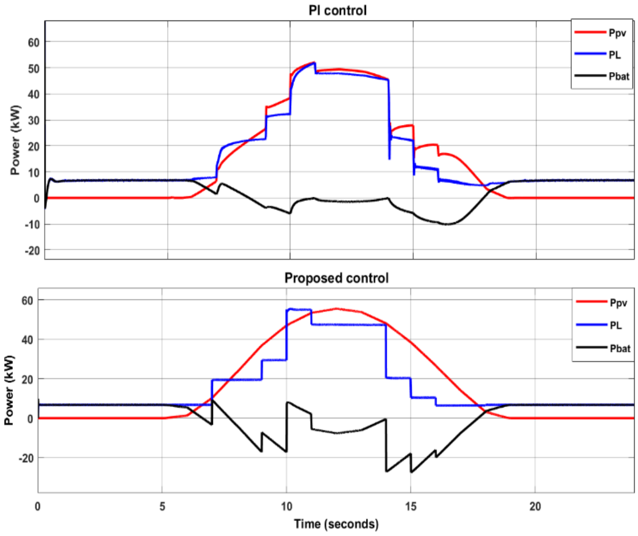

Fig. 18. Comparison between the proposed control and the PI method

Fig. 19 displays the superiority of the proposed method based on flatness compared to the classic method of PI control through the state of battery charge, as the SOC curve in the proposed method is more responsive, so charging is better and discharging is less, thus prolonging the battery life.

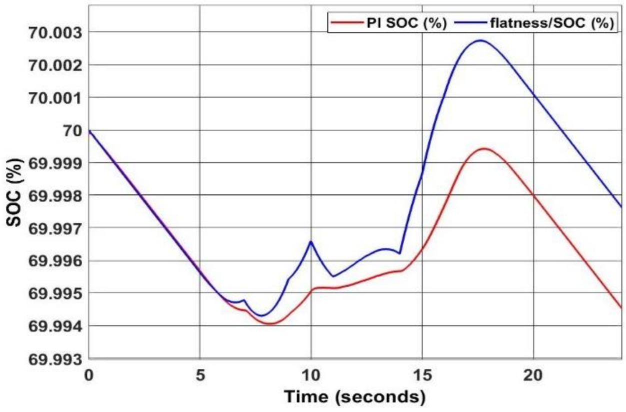

Fig. 19. Comparison SOC between the flatness control and the PI control

V. CONCLUSION AND FUTURE WORK

The article describes a nonlinear control-based flatness theory for controlling the output community load or DC bus voltage. This theory is analyzed using mathematical equations, and it is moulded using MATLAB simulation version 2021a. The simulation was done under different load and irradiance conditions as well as the real conditions of temperature and irradiation. The findings demonstrate that the suggested control method offers more stability in a DC bus under varying solar irradiance and load conditions. As a result, it provides higher power quality for the hybrid system (PV/battery). Moreover, the results obtained are compared with those of the traditional PI control method in terms of power and voltage. The achieved results are robust, and the suggested method improves the system response in terms of overshoot, tracking the reference voltage (400 V) with a minimum overshoot value of 5 V and a faster response of less than 3 msec.

The research highlights the following as potential future topics of inquiry: (1) Investigate the effects of different solar panel orientations on solar radiation incidence and energy generation using a real implementation of DC MG. (2) Optimize the ANN algorithm to maximize the power of the PV system using metaheuristic algorithms. (3) Combine fuzzy logic control with nonlinear control-based flatness control theory to stabilize bus voltage regulation and enhance power generation.

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