Optimal Control of Bi-directional Converter to Enhance the Performance of an off-Grid Hybrid System

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ABSTRACT

This paper presents a new method based on Artificial Intelligence (AI), for the optimal control of a bidirectional converter. The goal is to improve the DC bus voltage efficiency of a grid-independent hybrid system. The proposed design consists of a Photovoltaic System (PVS), a Wind Energy Conversion System (WECS), a Battery Storage System (BSS), and a variety of electronic power devices to extract the maximum energy from the generation sources. A bidirectional converter is featured in the use of an Adaptive Network-based Fuzzy Inference System (ANFIS) based controller, to improve the energy quality of the DC bus. The proposed approach provided good results compared to the Proportional Integral (PI) controller and the Fuzzy Logic controller (FLC). The use of this approach reduced the value of oscillations, improved the response time of the system, and contributed to the elimination of the problem of overshoot. This experiment was conducted using Matlab and Simulink.

Keywords-bi-directional converter; PI-controller; ANFIS; hybrid system; renewable energy

I. INTRODUCTION

The interest in the utilization of Renewable Energy Sources (RES) has increased dramatically. This is due to a decline in the worldwide reserves of fossil fuels, which has a considerable impact on both the ozone layer expansion and environmental contamination [1]. Because of the increasing demand for energy, fossil resources have grown more expensive. Renewable resources can be used in local or stand-alone networks to serve agricultural applications in military barracks, islands, and even rural areas that are not connected to electrical grids [2]. Since the energy sources based on fossil fuels are expensive and have a negative influence on the environment, renewable energy has become essential for the electricity production [3].

Solar and wind energy are among the most reliable sources of clean energy due to their availability, ease of use, and environmentally friendly features [4]. The intermittent and unexpected nature of Photovoltaics (PVs) and wind generators, along with the fluctuating demand for power, brought out the critical need for the integration of the storage system in RES

[5]. The hybrid systems in RES appear in the form of AC bus, DC bus, or a mixture of the two. Due to its simple structure, the DC bus is easy to manage and control. On the contrary, control and energy flow management in the AC bus, is considered difficult. It is necessary to closely design the frequency transmission and achieve high accuracy of information in controlling the frequency and reactive power. Despite these difficulties, the continuous current transmission is vital, especially in daily uses or in cases of energy transfer. The installation of hybrid systems in RES must ensure smooth operation and stable energy supplies in all cases. Many technologies and strategies have emerged to manage energy flow in such systems. Authors in [6] presented an independent hybrid system, where the wind and sun sources were responsible to generate energy and store it in the batteries. In this work, the goal was to manage the energy flow within the system, because the PI controller of the bidirectional converter had to balance the power flow between generation sources and load. Therefore it had to maintain the stability of voltage at the DC bus. Authors in [7] presented a strategy to manage the energy flow of a hybrid system with an FLC. The sources of sun and wind were the initial generation sources. A hybrid storage system consisting of batteries and a Super Cpacitor (SC) was used. They also added a diesel generator as a reserve procedure. Authors in [8] conducted an experimental study of a hybrid system consisting of PVS, WECS, FC, and storage batteries. In this experiment the researchers relied on the battery charging status, to build and design a strategy to manage energy flow within the system. They also used a Fractional-Order-Proportional Integral Derivative (FOPID) controller to preserve the stability of the voltage in the DC bus. Authors in [9] proposed a small electrical production station based on renewable sources to support the electric car charging stations. The researchers focused on developing the Particle Swarm Optimization (PSO) technology to manage the system efficiently and improve the energy quality of the DC bus. Authors in [10] presented a hybrid system connected to the network. Their work focused on analyzing different methods of energy management in a system, such as PI, FLC and Artificial Neural Network (ANN).

The present study aims to improve the efficiency of the hybrid system and enhance its performance by improving the energy quality of the DC bus. The following are the most notable contributions addressed in this work:

- Reducing the percentage of overshoot and oscillation at the DC bus voltage.
- Improving the efficiency of the storage system and enhancing its performance via intelligent control, using ANFIS-PI technology.

II. SYSTEM DESCRIPTION

Figure 1 shows the configuration of the proposed hybrid energy system based on renewable energy sources.

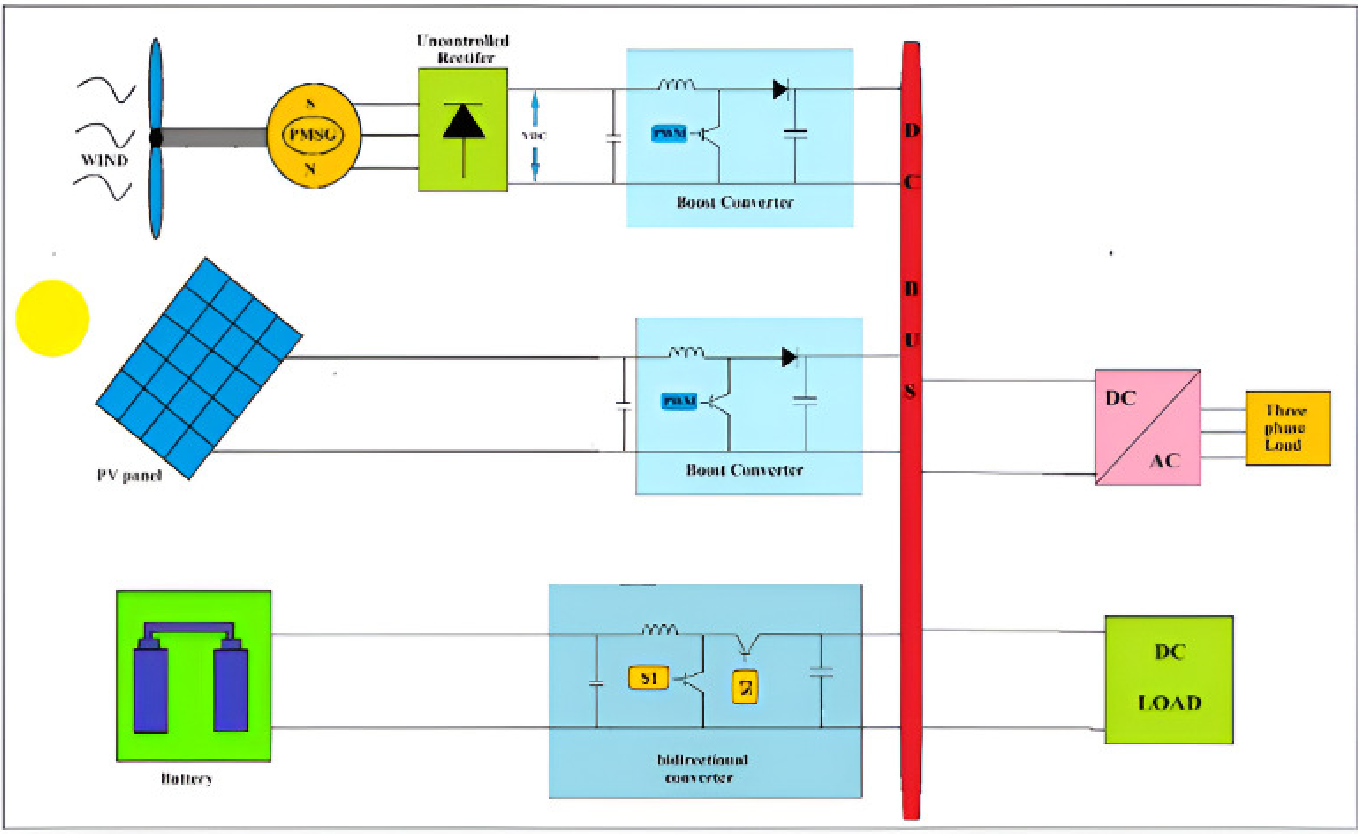

Fig. 1. Structure of the proposed hybrid system.

TABLE I. HYBRID SYSTEM PARAMETERS

System	Parameter	Value	Unit
PV	Maximum power Parallel strings Series per string	250 4 10	W - -
PMSG	Power Stator phase resistance Armature inductance	12 0.5 0.000975	Kw Ohm H
Battery	Nominal voltage Nominal discharge current	500 32	V A
Bi-directional converter	Cpacitor Inductor Switching frequency	1.27 0.61 20	m F m H K Hz

This system includes two sources for generating electrical energy, sun and wind, and is supported by a storage system. These sources are connected to the electrical load through a DC bus. The solar energy system consists of PV panels that convert solar radiation into direct current electrical energy. The PV is connected to a boost converter. The wind power conversion system is based on a Permanent Magnet Synchronous Generator (PMSG) and consists of a wind turbine, a three-phase diode rectifier, a DC-DC Boost converter, and a direct bus. The wind turbine drives the PMSG at a variable rotational speed without a speed multiplier. The result of this, is directly connected to the input of the rectifier bridge to rectify the alternating voltage generated to the DC. Then, a DC-DC converter is used to increase or decrease the DC voltage according to that of the DC bus defined in the previous step. As for the storage system, a lithium-ion battery connected to a bidirectional converter was utilized to improve power quality and maintain voltage stability on the DC bus [11-13]. The parameters of the components of the proposed system are presented in Table I.

III. OPTIMIZATION DC BUS PERFORMANCE

A. Overview of the Adaptive Network-based Fuzzy Inference System Controller

ANFIS is a hybrid system that integrates ANNs and fuzzy logic controllers. ANFIS is employed in diverse applications, such as Maximum Power Point Tracking (MPPT) for PV and wind systems. It functions as a voltage regulator and current controller in bi-directional converters within storage systems.

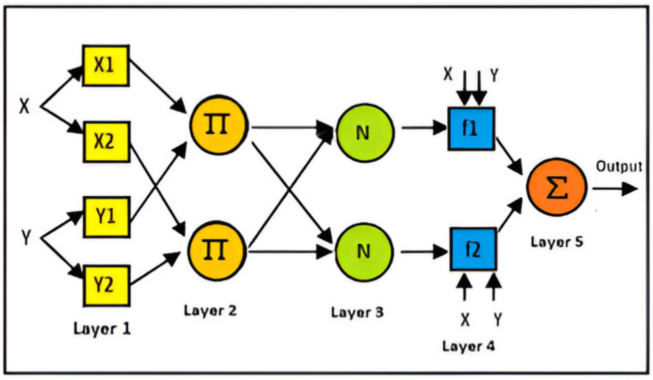

Fig. 2. ANFIS structure.

The ANFIS architecture consists of five layers: rules, fuzzification, normalization, consequent, and addition [14-16], as illustrated in Figure 2.

B. Structure Description of the Bidirectional Converter

The main goal of using a bidirectional converter along with a storage system is to maintain the stability and consistency of the voltage at the DC bus. In this case, the battery charge state is not taken into account because the goal in this section of the proposed work is to maintain voltage stability. In the case of charging, T1 is activated, where the converter operates in boost mode. In the case of battery discharge, the converter operates in buck mode.

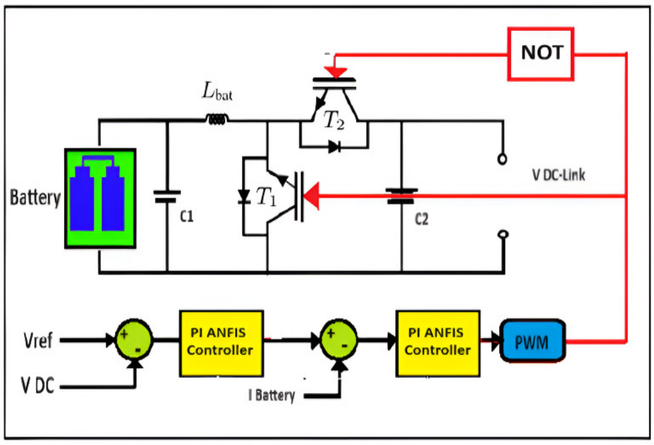

Fig. 3. Block diagram of the Buck-Boost converter.

The control method that was applied to this converter is shown in Figure 3. The control methodology contains two loops. The first loop controls the voltage, so that T1 is activated in the event that the DC bus voltage is less than the reference voltage that was taken in the current work (550V). In case the DC bus voltage is greater than the reference voltage, T2 is turned on. The second loop is about controlling the current at the DC bus. The comparison between the reference voltage and the DC bus voltage, allows creating an error that is processed by the proposed ANFIS-PI controller to produce a reference current for the battery.

The reference current is compared with the battery current to create another error, which is processed by the second PI-ANFIS controller to create a Pulse Width Modulation (PWM) signal to directly control the switches T1 and T2.

C. Description of the structure of the proposed controller

The general model of the ANFIS-PI controller is presented in Figure 4. It was designed to regulate the operation of a bi-directional DC-DC converter in order to improve the quality of energy at the DC bus and maintain voltage stability at the required values.

In the proposed controller, the error E(k) and the change in the error (Δ_(E(k))) were selected as ANFIS inputs. The PI controller parameters (k_i, k_P) were considered as outputs.

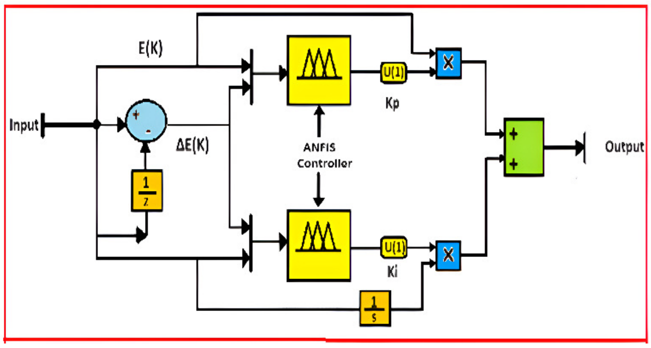

Fig. 4. Block diagram of the proposed controller (ANFIS-PI).

The PI controller was trained in a variety of operating conditions, including sudden change in loads, wind speeds, solar radiation. By analyzing the data extracted from the PI controller, ANFIS was trained, and this allowed it to learn the ideal relationship between system inputs and control parameters. When running the system, ANFIS updates different values of k_i and k_p in an ongoing way, based on the variable conditions that are applied to the system. This enables the controller's response to be adjusted dynamically, thus allowing the proposed approach to achieve a faster response and reduce the fluctuations in the DC bus voltage. This results in the improvement of the overall performance of the system, compared to the traditional PI controller with fixed values. Figures 5 and 6 provide a graphical representations of how E(k) and Δ(E(k)) vary for different values of k_i and k_p.

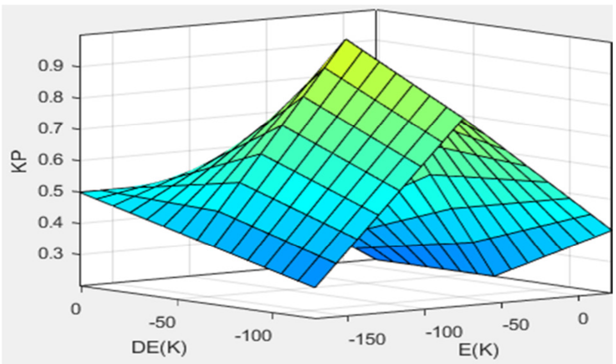

Fig. 5. A surface between input error and change of error vs k_P.

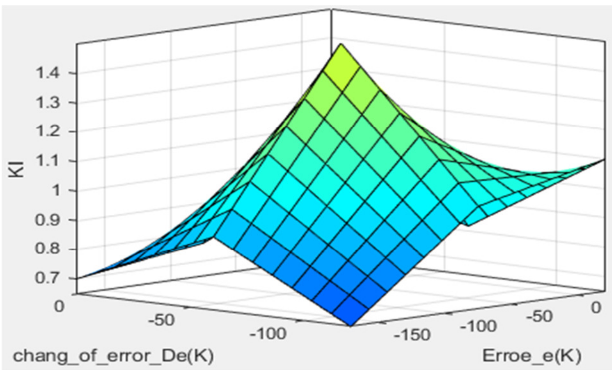

Fig. 6. A surface between input error and change of error vs k_i.

IV. SIMULATION RESULTS

In order to present the dynamic behavior of the DC bus, a simulation of the studied hybrid system was conducted using the PI controller and the proposed approach. Many simulation tests were carried out under different conditions (solar radiation, wind speed, loads) and will be presented in this section.

A. DC Bus Performance for Variable Power Sources

In the first test, the performance of the DC bus will be assessed in variable conditions of solar radiation, a constant temperature at 25 C° for the PVS, and variable wind speed for the WECS. The load was taken at a constant value of 8 KW. Figure 7 illustrates the solar radiation profile and the wind speed applicable in this experiment.

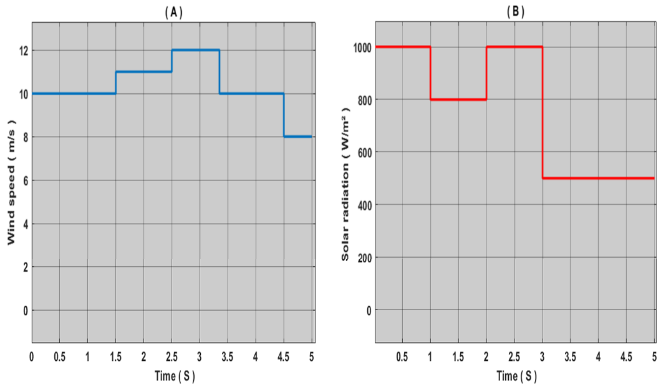

Fig. 7. Meteorological Parameters for: (a) wind speed and (b) sun radiation.

Figure 8 presents the results of simulating a hybrid system using the PI controller, where the change in the power produced and the offset by the change in the battery power are observed. The load power was kept stable at 8 KW. Although the PI controller has maintained the stability of the power at the value needed by the load, some oscillation and overshoot of the battery power at the sudden change of the power produced can be observed. This is due to the traditional nature of the PI's behavior. A clear overshoot rate of the load power at the start of the simulation can be also noticed, due to the overshoot at the DC bus. Therefore, it can be said that the PI controller can maintain power stability, but not with good quality and performance.

Figure 9 shows the results of simulating the hybrid system using the proposed ANFIS-PI approach, where the change of the power produced and the offset by a change in the battery power are demonstrated. The load power was kept again constant at 8 KW. Although there are constant changes in the energy produced, the proposed approach has kept the energy stable at the value of 8 KW, while the problem of oscillations and overshoot characteristics of the PI controller has been eliminated. It should be noted that the proposed approach allows charging and discharging energy from the battery with a good energy quality, free from oscillations and overshoot at sudden changes in the energy produced. Moreover, the value of the load power overshoot ratio has been significantly degraded due to the elimination of the DC bus overshoot ratio. The proposed approach contributes to the improvement of the performance and quality of power at the DC bus.

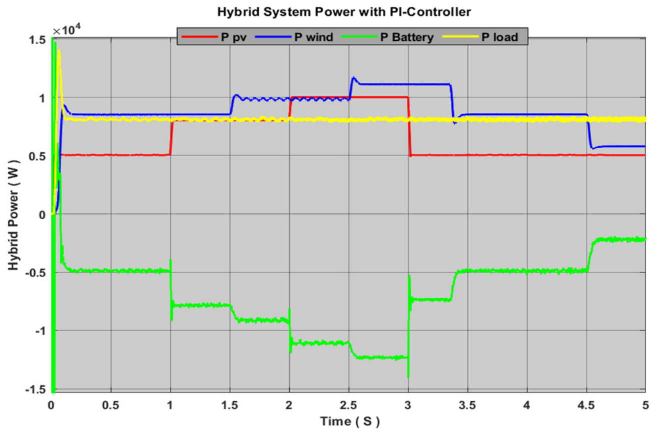

Fig. 8. Simulation results of the hybrid power using the PI controller in case of variable power sources as input.

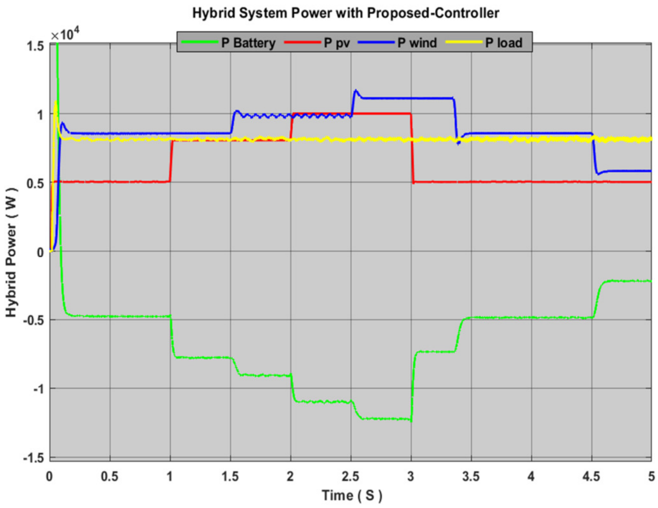

Fig. 9. Simulation results of the hybrid system using the proposed controller in case of variable power sources as input.

Figure 10 displays the results of the DC bus voltage simulation. It presents a dynamic comparison between the proposed approach and the PI controller. The results of this experiment showed that the PI controller suffered from a slow response time and clear oscillations. It also had an overshoot ratio of 10%. On the other hand, the proposed approach exhibited a better ability to adapt to changes occurring in the system. The problem of overshoot and oscillations was eliminated and a faster response time was provided compared to PI. These results reflect the effectiveness of the proposed approach in improving the voltage stability of the DC bus, rendering it a more efficient option for application in hybrid systems.

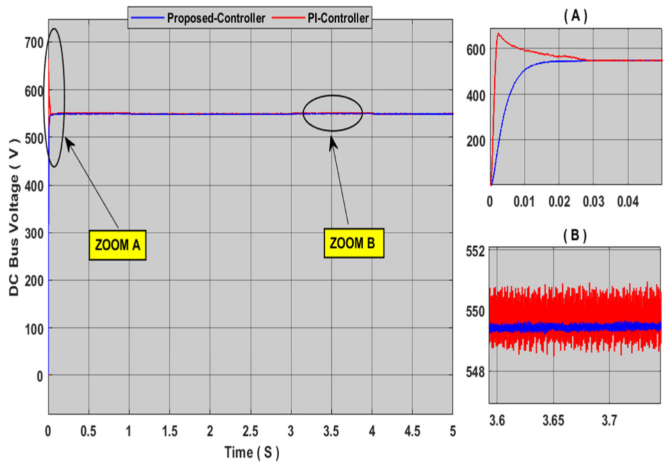

Fig. 10. Dynamic comparison of the DC bus voltage between the proposed approach and the PI controller in case of variable power sources as input.

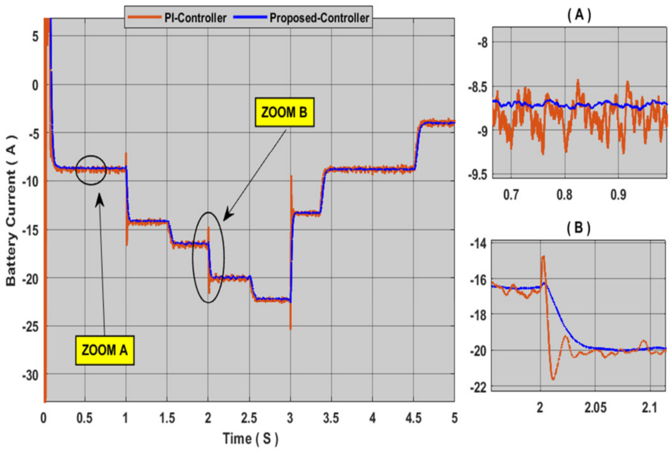

Fig. 11. Dynamic comparison of the battery current between the proposed approach and the PI controller in case of variable power sources as input.

Figure 11 depicts a dynamic comparison of the battery current between the proposed approach and the PI controller. The simulation results showed that the PI controller provides a relatively stable response but it suffers from obvious oscillations at the battery current. It also demonstrates a noticeable overshoot rate when a sudden change of power is produced. All these factors are disadvantages that will reduce battery life. On the contrary, the proposed approach displayed a good response and the value of oscillations almost did not exist. The percentage of overshoot has also been eliminated. This improves the efficiency of charging and discharging the battery, which contributes to prolonging battery life and improving system performance in general.

B. DC Bus Performance for Variable Load

The second test will examine the performance of the DC bus under variable conditions of loads. Both solar radiation and wind speed are stabilized in order to test the performance and effectiveness of the proposed approach in case of a sudden change of loads.

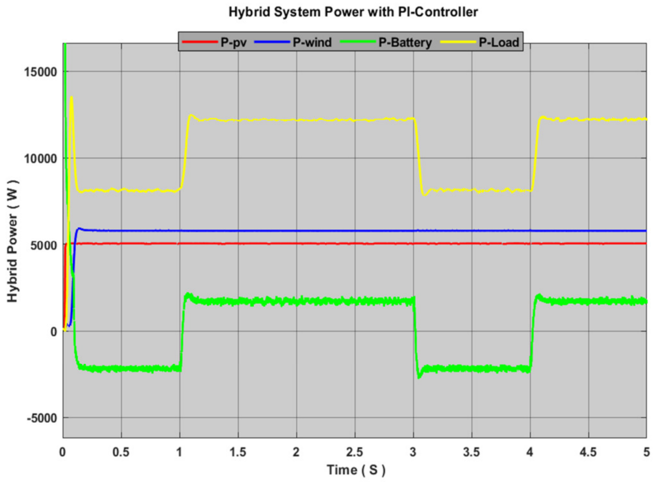

Fig. 12. Simulation results of the hybrid power using the PI controller in case of variable loads.

Figure 12 shows the results of simulating a hybrid system using a PI controller. As evidenced, there is a change in load power and the offset by a change in battery power. Although the PI controller has kept the power stable at the value needed by the load, some oscillation in battery power can be seen, which is due to the traditional nature of the PI behavior. A clear overshoot rate of the load power at the beginning of the simulation is also evidenced, owing to the overshoot in the DC bus.

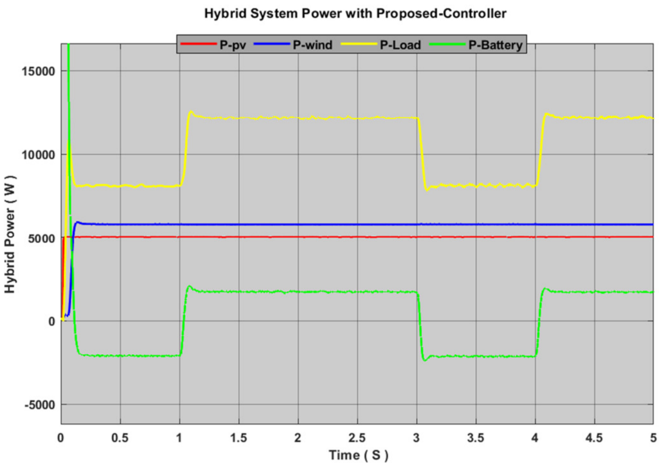

Fig. 13. Simulation results of the hybrid power using the proposed controller in case of variable loads.

Figure 13 illustrates the results of simulating a hybrid system using the proposed ANFIS-PI approach. A constancy in the produced power, a change in the load power between 8 KW and 12 KW, and the offset by a change in battery power are observed. Although there are changes in the load demand, the proposed approach has contributed to eliminating the problem of oscillations and the overshoot characteristic that characterized the PI controller. It should be mentioned that the proposed approach allows charging and discharging power from the battery with good power quality, free from oscillations and overshoot when a sudden change in demand for the solution occurs. As for the percentage of overshoot regarding the load power, it has been significantly reduced due to the elimination of the DC bus overshoot ratio. It can be again concluded that the proposed approach improves the performance and power quality in the DC bus, in the event of a change in load demand.

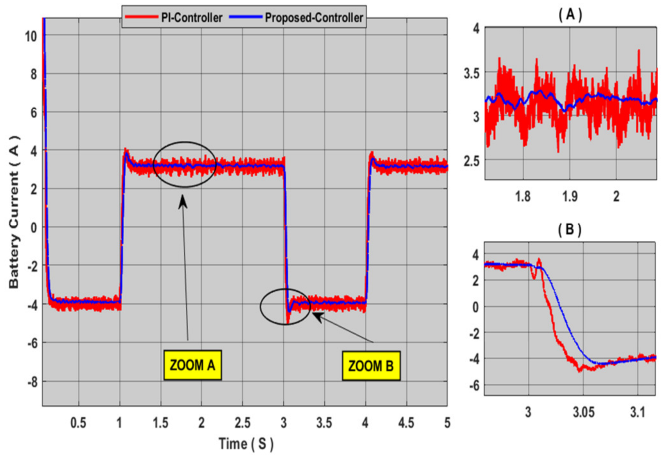

Fig. 14. Dynamic comparison of the battery current between the proposed approach and the PI controller in case of variable loads.

TABLE II. DYNAMIC COMPARISON OF THE PROPOSED APPROACH WITH WORKS OF LITERATURE/PREVIOUS RESEARCH

References - Controller using	Overshoot	Oscillations	Response time
[7] - PI	High 12%	Big	Weak 0.5 (S)
[8] - FLC	Medium 5%	Big	Medium 0.3 (S)
[10] - Fuzzy-PI	Medium 5%	Medium	Good 0.2 (S)
Our work - ANFIS-PI	Weak 1%	Weak	Good 0.2 (S)

Figure 14 portrays a dynamic comparison of the battery current between the proposed approach and the controller PI in the case of variable load demand. The results revealed that the PI controller provides a relatively stable response but suffers from obvious oscillations at the battery current. This test also shows a noticeable overshoot rate at the sudden change of load demand. On the contrary, the proposed approach exhibited a good response bringing the value of the oscillations almost to zero. The overshoot ratio was also eliminated, which improves the efficiency of charging and discharging the battery, thus contributing to the extension of battery life.

Table II provides a detailed analysis of the performance of the proposed approach through a dynamic comparison with other related works.

V. CONCLUSIONS

Due to the increase in energy consumption in the last decade, the interest in Renewable Energy Sources (RES) has been increased. This has led researchers to develop and improve energy production systems based on renewable sources.

This research paper delves into the improvement of the DC performance of a solar-wind-based hybrid system and the improvement of the storage system's performance. It also builds a strong foundation for contributing to future improvements.

The efficiency of the DC bus voltage and the current passing through the battery can be improved thanks to the proposed controller, which showed satisfactory results compared to the Proportional Integral (PI) controller.

The proposed approach contributed to eliminating the overshoot rate, minimizing the value of oscillations and improving response time. The current study also verified the efficiency of the proposed approach under changing conditions of weather and loads. The MATLAB environment was a reliable tool for the simulations of this experiment.

This paper presents a novel development of the PI-ANFIS controller for controlling the bi-directional converter. This approach contributes to enhancing the efficiency and stability of the hybrid system.

In future research, the development of hybrid systems can be further expanded based on Artificial Intelligence (AI). Other production sources can also be added and various hybrid storage systems can be exploited in isolated areas or areas connected with car charging stations.

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