Hybrid Wind/PV/Battery Energy Management-Based Intelligent Non-Integer Control for Smart DC-Microgrid of Smart University

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This work was supported by the Research Groups Program through the Deanship of Scientific Research, Taif University, Ministry of Education, Saudi Arabia, under Grant 1-440-6140.

ABSTRACT Global environmental changes, nuclear power risks, losses in the electricity grid, and rising energy costs are increasing the desire to rely on more renewable energy for electricity generation. Recently, most people prefer to live and work in smart places like smart cities and smart universities which integrating smart grid systems. The large part of these smart grid systems is based on hybrid energy sources which make the energy management a challenging task. Thus, the design of an intelligent energy management controller is required. The present paper proposes an intelligent energy management controller based on combined fuzzy logic and fractional-order proportional-integral-derivative (FO-PID) controller methods for a smart DC-microgrid. The hybrid energy sources integrated into the DC-microgrid are constituted by a battery bank, wind energy, and photovoltaic (PV) energy source. The source-side converters (SSCs) are controller by the new intelligent fractional order PID strategy to extract the maximum power from the renewable energy sources (wind and PV) and improve the power quality supplied to the DC-microgrid. To make the microgrid as cost-effective, the (wind and PV) energy sources are prioritized. The proposed controller ensures smooth output power and service continuity. Simulation results of the proposed control schema under Matlab/Simulink are presented and compared with the super twisting fractional-order controller.

INDEX TERMS Renewable energy, smart university, DC-microgrid, energy management control, fuzzy logic control, fractional order control.

NOMENCLATURE AND ABBREVIATIONS

PV, WT Photovoltaic and Wind turbine
PMSG Permanent Magnet Synchronous Generator
BSS Battery Storage System
SSCs Source-Side Converters
LSCs Load-Side Converters

The associate editor coordinating the review of this manuscript and approving it for publication was Alexander Micallef1.
The production of electrical energy in the world generates various types of pollution. Thermal power plants (coal, oil) are responsible for atmospheric emissions linked to the combustion of fossil fuels. On the other hand, nuclear power plants, whose development intensified following the oil crisis, have not had a negative impact on air quality. On the other hand, they produce radioactive waste which causes major problems in terms of storage, processing, and transport. Today, the fear of using only one energy source with all its risks, and the opening of the electricity production market are all factors that give renewable energies (hydraulic, oil) are responsible for atmospheric emissions linked to various types of pollution. Thermal power plants (coal, oil) are responsible for atmospheric emissions linked to the combustion of fossil fuels. On the other hand, nuclear power plants, whose development intensified following the oil crisis, have not had a negative impact on air quality. On the other hand, they produce radioactive waste which causes major problems in terms of storage, processing, and transport. Today, the fear of using only one energy source with all its risks, and the opening of the electricity production market are all factors that give renewable energies (hydraulic, wind, solar, biomass, etc.) an important place in electricity production [1], [2].

The demand for energy by consumers is generally not evenly distributed over time and problems of the phasing of energy produced versus energy consumed arise. The stability of the grid depends on the balance between production and consumption [3]. The increase in the penetration rate of renewable energies will therefore be conditioned by their participation in these different services, which will be favored by the association with these clean energy sources, of electrical energy storage systems [4]. Storage is therefore the key to the penetration of these energies in the electricity grid. Not only does it provide a technical solution for the grid operator to ensure a real-time balance of production and consumption, but it also enables the best possible use of renewable resources by avoiding load shedding in the event of overproduction. Combined with local renewable generation, decentralized storage would also have the advantage of improving the robustness of the electricity network by allowing islanding of the area supplied by this resource. Also, a well-placed energy storage system (ESS) increases the quality of the power supplied by providing better control of frequency and voltage and reduces the impact of its variability by adding value to the current supplied, especially if the electricity is delivered during peak periods [5], [6].

The integration of renewable energies together with the energy storage system in a standalone micro grid is an emerging research area. Generally, it is preferred to integrate different renewable energies such as tidal, wind, and PV to yields a positive impact on the maximum capacity of the energy storage system. Usually, ESS is constituted by a combination of a battery and supercapacitors, which helps extend battery life-time and offers a fast system response to compensate the transients [7]. However, loads are necessary when all (energy sources and battery storage systems (BSS)) are connected; thus, the AC grid is used instead of supercapacitors [8]. A micro grid is classified into DC, AC, or a combination of both types. Compared with AC microgrid, DC microgrid shows several benefits such as fewer parameters to control, facilitate integration, and simple structure. On the other hand, AC type needs more information like the synchronization of the frequency and reactive power, which makes the control design process a challenging task. Moreover, a DC micro grid offers the possibility to work in different modes like AC microgrid, standalone, or integrated with the AC microgrid [9], [10].

Due to the latest development in power electronics, the autonomous DC microgrid can work at its maximum performance. However, because of the renewable energy sources stochastic nature, the smooth operation and continuous power transmission to the loads need a supplementary energy management unit. Numerous research works on the energy management control dedicated to AC microgrids can be found in the literature, but given the important differences between the AC and DC microgrid dynamics, these control strategies cannot be adopted for DC microgrids. In fact, in the standard design of the DC microgrid, the load converters and the energy sources are parallely connected where the energy is consumed or supplied through the DC-link. Thus, the control of the DC-link voltage is needed for an efficient and stable operation of the DC microgrid [11], [12]. Several control strategies have appeared in the literature to address the issues of the DC-link voltage. In [13], a review of the recent trends and development in hybrid micro grid topology with energy resource planning and control is presented. In [14], a combined fuzzy controller and voltage control are proposed to regulate the DC voltage. In [15], a fuzzy logic control strategy with reduced rules is investigated. In [16], a dual proportional-integral controller is adopted. However, the aforementioned control strategies are linear and can regulate the DC-link in a small operating interval. Thus, to overcome this restriction, nonlinear controls have been investigated in...
the literature. In [17], an adaptive droop controller algorithm is proposed. Energy management-based optimal control is investigated in [18] for multiple energy storage system in a microgrid. In [19], robust $H_{\infty}$ control strategy is developed. Robust sliding mode strategy is proposed in [20]. In [21], an adaptive backstepping control method is designed. A Lyapunov-based strategy is presented in [22]. Feedback linearization control is discussed in [23]. A hybrid combined backstepping and sliding mode controller is investigated in [24]. However, the previous proposed nonlinear controls show limitations in performances in the case of droop control strategy and optimal energy management has given the multiple integrated energy storage system, poor stability for the $H_{\infty}$ method, chattering issues concerning the sliding mode. Also, the major part of these controls highly depends on fixed gains which are very sensitive to parameter uncertainties and external disturbances. Finally, the last part represents the energy management unit.

In the same context, in the present work, a new fractional order PID controller is proposed combined with a fuzzy logic method to address the problems faced by the conventional integer controls in hybrid energy management. Fractional-order controllers offer additional advantages over integer order controls such as robust behavior to oscillations and the measurement noise and high degree of freedom. The proposed new controller is integrated with an energy management unit for a DC-microgrid integrated with several stochastic sources and essential DC loads illustrated by Figure 1. The proposed intelligent Fractional-Order PID (IFO-PID) controls will be used as a low-level controller, when the energy management unit serves as high-level controller which generates appropriate references for the IFO-PID and monitors the generated and consumed power.

This paper addresses the following two main objectives: controlling the source-side converters (SSCs) to extract the maximum power from the renewable energy sources (wind and PV) using the proposed IFO-PID. The second task is to improve the power quality supplied to the DC-microgrid by regulating the reactive power and the DC-link voltage to their references using the energy management unit (EMU).

The novelty and contribution of the present work are summarized as follows:

- The new fractional order PID (FO-PID) controller combined with a fuzzy logic strategy is developed for a DC-microgrid integrated with several stochastic sources and essential DC loads.
- The fuzzy logic method is selected as a fuzzy gain supervisor to adaptively adjust gains of the FO-PID which greatly enhances the robustness of the proposed approach against various uncertainties external disturbances.
- The essential characteristic of this approach is the extremely reduced number of the fixed gains used by the proposed strategy which avoids its sensitivity to parameter uncertainties, which highly improves the robustness property and global stability of the system.
- The global stability of the system and is ensured and further validated by extensive simulation results.

The present work is organized such as the mathematical description of the hybrid energy system is given in section 2. Section 3 deals with the design of the proposed hybrid controller strategy. In section 4, the numerical results are
II. MATHEMATICAL DESCRIPTION OF THE HYBRID ENERGY SYSTEM

The studied hybrid energy system integrated smart DC-microgrid is illustrated by Figure 1, where three main parts can be distinguished: the hybrid energy sources constituted by the wind energy, solar energy, and the battery storage systems connected to the DC-link through their respective converters. The second part represents the loads assumed to be a priority which in the case of a smart university may include laboratory experimentation benches, fans, and lighting. A maximum power point tracking algorithm is used on both the wind and solar (PV) conversion systems to force them to operate at maximum power. The energy management unit computes the total consumed and produced energy to select the adequate control modes.

A. WIND SYSTEM MODEL

The mathematical model of the wind power that can be transformed by the turbine is given by [25]:

\[ P_m = \frac{1}{2} \rho C_p(\beta, \lambda) A v^3 \]  
\[ T_m = \frac{P_m}{\omega_t} \]  
\[ C_p(\beta, \lambda) = \frac{1}{2} \left( \frac{116}{\lambda_i^3} - 0.4 \beta - 5 \right) e^{-\left( \frac{21}{\lambda_i} \right)} \]  
\[ \lambda_i^{-1} = (\lambda + 0.08 \beta) \lambda^{-1} - 0.035 \left( 1 + \beta^3 \right)^{-1} \]  
\[ \lambda = \frac{\omega_t R}{v} \]  

where, \( v \) denotes the wind speed, \( \beta \) represents the pitch angle, \( \omega_t \) denotes the turbine speed, \( R \) represents the blades radius, \( C_p \) denotes the power coefficient, \( \lambda \) denotes the tip-speed ratio, \( \rho \) denotes the water density, and \( A \) represents the area of the blades. The wind conversion system is based on a permanent magnet synchronous generator (PSMG) which is expressed as [25]:

\[ v_{dq} = R_d i_{dq} + L_d i_q + \psi_{dq} \rho m \]  
\[ J \ddot{\omega}_m = T_m - T_e - f_j \omega_m \]  
\[ T_e = \frac{2}{3} p \psi_T^T i_{dq} \]

where, \( i_{dq} = \begin{bmatrix} i_d \\ i_q \end{bmatrix} \) represents the stator current vector, \( T_e \) represents the electromagnetic torque, \( f_j \) represents the viscous friction coefficient, \( L_{dq} = \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \) represents the dq inductances matrix, \( J \) is the moment of inertia, \( \psi_{dq} = \begin{bmatrix} \psi_d \\ \psi_q \end{bmatrix} \) represents the flux linkages vector, \( v_{dq} = \begin{bmatrix} v_d \\ v_q \end{bmatrix} \) represents the voltage stator vector, and \( R_{dq} = \begin{bmatrix} R_d & 0 \\ 0 & R_q \end{bmatrix} \) represents the stator resistance matrix. To design the proposed control method, the model of the SCCs needs to be expressed. Thus, the model of the wind source converter (see Figure 2) is given as [26], [27]:

\[ \frac{dV_w}{dt} = \frac{I_w}{C_w} - \frac{I_{Lw}}{C_w} \]  
\[ \frac{V_w}{L_w} = \frac{dI_w}{dt} + (1 - U_1) \frac{V_{dc}}{L_w} - D_1 \]  
\[ \frac{dV_{dc}}{dt} = (1 - U_1) \frac{I_{Lw}}{C_{dc}} - \frac{I_{Ow}}{C_{dc}} + D_2 \]

where, \( I_w \) denotes the wind current rectified, \( L_w \) denotes the inductance, \( I_{Lw} \) denotes the current of the inductor, \( V_w \) denotes the voltage input rectified, \( U_1 \) denotes the control signal, \( V_{dc} \) denotes the link voltage, \( D_1 \) and \( D_2 \) denotes dynamics uncertainty in the energy stage parameters. Depending on the state of the storage system, which it will be discussed in the energy management section, the wind system can be operated under MPPT for maximum power extraction or off-MPPT for power balance as shown in Fig. 2. The MPPT algorithm is detailed in the flowchart of Fig. 3.

B. SOLAR POWER SYSTEM MODEL

The solar conversion system (SCS) is constituted by the PV panel connected to the DC-link through a DC-DC boost converter. The SCS mathematical model is given as below:

\[ \frac{dV_{pv}}{dt} = \frac{I_{pv}}{C_{pv}} - \frac{I_{pv}}{C_{pv}} \]  

where, \( P_L \) is the load power and \( P_w \) is the power from the wind energy system.

In case of power generation excess and no storage capacity in the battery system, the proposed energy management unit (EMU) switches the wind controller from the MPPT mode to the off-MPPT mode in order to reduce the generated power and maintain a balanced power in the standalone system. In off-MPPT, the voltage reference is carried out as [23]:

\[ V_{ref} = \frac{P_L - P_w}{I_w} \]  

Finally, the main conclusions and future works are established in section 5.
$V_{pv} = \frac{dI_{pv}}{dt} + (1 - U_2) \frac{V_{dc}}{L_{pv}} + D_3$ (14)

$\frac{dV_{dc}}{dt} = (1 - U_2) \frac{I_{Lpv}}{C_{dc}} - \frac{I_{opv}}{C_{dc}} + D_4$ (15)

where, $I_{pv}$ denotes the PV current, $L_{pv}$ denotes the inductance, $V_{pv}$ denotes the voltage of the PV panel, $L_{Lpv}$ denotes the current of the inductor, $U_2$ denotes the control signal, $D_3$ and $D_4$ denotes dynamics uncertainty in the energy stage parameters as given by Figure 3. Here also, according to the state of the storage system, the PV conversion system can be operated under MPPT for maximum power extraction or off-MPPT for power balance as shown in Figs. 4 and 5. Furthermore, in case of power generation excess and no storage capacity in the battery system, the proposed energy management system switches the PV controller from the MPPT mode to the off-MPPT mode in order to reduce the generated power and maintain a balanced power in the standalone system. In off-MPPT, the voltage reference is carried out as [23]:

$$V_{ref} = \frac{P_L - P_{pv}}{I_{pv}}$$ (16)

where, $P_L$ is the load power and $P_{pv}$ is the power from the PV panel energy system.

C. BATTERY SYSTEM MODEL

In this application, a standard battery is connected to the DC-link through a bidirectional DC-DC back-boost converter connected at the DC-link of the microgrid (see Figure 6). The role of this converter is to maintain the DC-link voltage constant despite the power changes in the sources and the load. The DC-link voltage is regulated at it references to compute the reference current of the battery and then design the voltage controller through the proposed strategy as shown in Fig. 6. The Battery State of Charge (SOC) model is
modelling as described below [26]:

\[
SOC = 100 \left(1 + \int I_{bat} dt \right) / Q
\]  

(17)

The SOC, the amount of electricity stored during the charge, is an important parameter to be controlled. The battery SOC must detect by the proposed supervisory system to make decisions according to its status and the required power. In a battery, the ampere-hours stored during a time \( t \) corresponds to a nominal capacity \( Q \) and a charging current \( I_{bat} \). The battery charge-discharge depends on the available power, the demand and the SOC. The energy constraints of the battery are determined based on the SOC limits:

\[
SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}}
\]

(18)

where, \( SOC_{\text{min}} \) and \( SOC_{\text{max}} \) are the minimum and the maximum allowable states for the battery safety. The model of the BSS converter is given as:

\[
\begin{align*}
V_b &= \frac{dI_b}{dt} + U_5 \frac{V_{dc}}{L_b} - D_5 \\
\frac{dV_{dc}}{dt} &= U_3 \frac{I_b}{C_{dc}} - \frac{I_{ob}}{C_{dc}} + D_6
\end{align*}
\]

(19)

(20)

where, \( I_b \) denotes the current of the battery, \( V_b \) denotes the voltage of the battery, \( U_3 \) denotes the controller signal, \( D_5 \) and \( D_6 \) denotes dynamics uncertainty in the energy stage parameters. The maximum power allowed during the charge/discharge of the battery system is fixed to 6525 Watts during the charge phase and to 10440 Watts during the discharge phase, according to the parameters of the battery storage system given by ref [27].

\[
\frac{dV_{dc}}{dt} = (1 - U_4) \frac{I_{Lg}}{C_{dc}} - \frac{I_{og}}{C_{dc}} + D_8
\]

(23)

where, \( I_g \) denotes the rectified current of the grid, \( V_g \) denotes the voltage input rectified of the grid to the boost converter, \( U_4 \) denotes the controller signal, \( D_7 \) and \( D_8 \) denotes dynamics uncertainty in the energy stage parameters, \( I_{Lg} \) denotes the current of the inductor, and \( C_{dc} \) denotes the DC-link capacitor. From the model (9)-(15) and model (21)-(23), a generalized compact form can be deduced as given below:

\[
\begin{align*}
\frac{dV_i}{dt} &= \frac{I_j}{C_j} - \frac{I_{Lj}}{C_j} \\
\frac{V_j}{L_j} &= \frac{dI_j}{dt} + (1 - U_i) \frac{V_{dc}}{L_j} - D_i \\
\frac{dV_{dc}}{dt} &= (1 - U_i) \frac{I_{Lj}}{C_{dc}} - \frac{I_{Oj}}{C_{dc}} + D_{i+1}
\end{align*}
\]

(24)

(25)

(26)

where, the subscript \( j \) denotes the given sub-terms \( w, pv, b, \) and \( g \) of each converter. The subscript \( i \) denotes 1 in case of wind, 2 in case of PV, 3 in case of Battery, and 4 in case of AC grid.

Remark 1: It should be reminded that in the present work the MPPT algorithm is only used on SSCs, thus the supply of the grid energy is assumed to be constant.

E. LOAD SIDE CONVERTERS (LSCs) MODEL

In Figure 1 it can be seen that a parallel DC-DC buck converter is used to connect the DC priority loads which their power loads are constant. These parallel converters are adopted to minimize the converters’ stress and divide the load. The mathematical model of several parallel converters is given as below:

\[
\begin{align*}
\frac{U_pV_{dc}}{L_p} &= \frac{dI_p}{dt} + \frac{V_{Loadp}}{L_p} - D_{I_p} \\
\frac{dV_{Loadp}}{dt} &= \frac{I_p}{C_p} - \frac{V_{Loadp}}{R_{Lp}C_c} + D_{V_{Loadp}}
\end{align*}
\]

(27)

(28)

where, \( U_p \) denotes the control law, \( L_{lp} \) denotes the current of the inductor, \( V_{Loadp} \) denotes the load voltage, \( D_{V_{Loadp}} \) denotes dynamics uncertainty of the voltage, and \( D_{I_p} \) denotes dynamics uncertainty in the current.

III. PROPOSED CONTROLLER DESIGN PROCESS

The purpose of the proposed intelligent fractional-PID order is to compute the SCCs controller law shown in the generalized model (24)-(26) represented by \( U_i \) and to compute the LSCs controller law shown in the generalized model (27)-(28) represented by \( U_p \) as illustrated by Figures 1-5.

Two steps are needed to design the proposed IFO-PID: first, the controller laws are calculated by the FO-PID and then, the fixed gains are adopted by the Fuzzy gain supervisor, which makes the proposed controlleradaptive and robust against parameter uncertainties. In [26], a proportional-integral (PI) control is proposed to compute the controllers of the source-side converters and load-side
converters. However, it is well known that fixed gains are very difficult to calculate under parameter uncertainties or variations [27]. Thus, the IFO-PID controller is introduced to improve the robustness and resolve the problems faced by the PI loops.

### A. SSCs CONTROLLERS DESIGN

To compute the SSCs controller law $U_i$, the following Lyapunov function as:

$$V_{j1} = 0.5 e_j^2$$  \hspace{1cm} (29)

where, $e_j = C_j(V_j - V_j^*)$ is the voltage error and $V_j^*$ denotes the desired voltage controller. From (24) and the derivative of $e_j$ it yields:

$$e_j = I_j - I_{lj} - C_j V_j^*$$  \hspace{1cm} (30)

To design the voltage controller, the desired current $I_{lj}^*$ is needed which is deduced from (30) as given below:

$$I_{lj}^* = I_j - C_j V_j^* + k_j e_j$$  \hspace{1cm} (31)

From Eq. (31) derivative of (29), it gives:

$$\dot{V}_{j1} = -k_j e_j^2$$  \hspace{1cm} (32)

where, $k_j > 0$ is the gain matrix. The BSS desired current is generated by the energy management unit. Thus, to design the controller law $U_i$, the fractional order-PID (FO-PID) control is adopted as illustrated in Fig. 8. For more information about controller law $U_i$ generated by the energy management unit. Thus, to design the

$$U_i = k_{ij} e_{ij} + k_{2j} e_{ij} D_i^{-\alpha} + k_{3j} e_{ij} D_i^\beta$$  \hspace{1cm} (33)

where, $k_{ij}$, $k_{2j}$, and $k_{3j}$ denotes the gain matrix, $D_i^{-\alpha}$ represents order $\alpha$ of fractional integration and $D_i^\beta$ represents the order $\beta$ of differentiation, and $e_{ij}$ denotes the current error expressed as:

$$e_{ij} = (I_{lj}^* - I_{lj})$$  \hspace{1cm} (34)

where, the desired current $I_{lj}^*$ in Eq. (31) is computed using the FO-PID as below:

$$I_{lj}^* = k_{ij} e_{2j} + k_{2j} e_{2j} D_i^{-\alpha} + k_{3j} e_{2j} D_i^\beta$$  \hspace{1cm} (35)

where, $e_{2j}$ denotes the DC-link voltage error expressed as:

$$e_{2j} = (V_{dc} - V_{dc}^*)$$  \hspace{1cm} (36)

![FIGURE 8. SSCs controller law computation with the IFO-PID.](image)

However, as mentioned previously fixed gains are very sensitive to parameter changes. Thus, the fuzzy method is selected as fuzzy supervisor is used for the adaptation of the gains $k_{ij}$, $k_{2j}$, and $k_{3j}$ thus, it solves the problem caused by imprecise parameters. The fuzzy inputs are chosen as the current error in the case of the controller law computation given by Eq. (33) and its derivative or the DC-link error in the case of the desired current given by Eq. (35) and its derivative. Triangular and trapezoidal types symmetrical and uniformly distributed are used to select the membership functions as given in Fig. 9. The method of partitioning these functions is given according to Lee and Takagi [29] and Yubazaki et al. [30]. Their method is based on the idea of sharing the same parameter by several membership functions.

The advantage of this method is that the number of parameters of the membership functions is significantly reduced. The decision-making output is obtained using a Max-Min fuzzy inference where the crisp outputs are calculated by the center of gravity defuzzification method. In Table 1, the linguistic variables corresponding to the inputs-outputs of the fuzzy gain scheduling are chosen as: Negative Big (NB), Negative Small (NS), Zero (Z), Positive Big (PB), and Positive Small (PS) [29].

**Remark 2:** The fuzzy logic controller chosen to compute the gains of the fractional order-PID controller is justified by the fact that fixed gains are complicated to calculate when the system is exposed to parameter changes. Also, the stability and robustness proof of the fractional order are clearly demonstrated in [27] and [38], thus they are not considered in the present work.
TABLE 1. Fuzzy logic rules of the SSCs and LSCs.

| \( \Delta e_{j,p} \) | NB | NS | Z | PS | PB |
|---------------------|----|----|---|----|----|
| e_{j,p}             | NB | NB | NS | NS | Z  |
| NB                  | NB | NB | NS | PS | Z  |
| NS                  | NS | NS | Z  | PS | PB |
| Z                   | NS | NS | Z  | PS | PB |
| PS                  | NS | Z  | PS | PB | PB |
| PB                  | Z  | PS | PB | PB | PB |

FIGURE 10. SSCs controller law computation with the IFO-PID.

B. LSCs CONTROLLER DESIGN

The expression of the controller law \( U_p \) is given as (see Fig. 10):

\[
U_p = k_1p e_{1p} + k_2p e_{1p} D_1^{-\alpha} + k_3p e_{1p} D_1^{\beta} \tag{37}
\]

where, \( k_1p, k_2p, \) and \( k_3p \) denotes the gain matrix, and \( e_{1p} \) denotes the current error expressed as:

\[
e_{1p} = (I_{t,p} - I_{2,p}) \tag{38}
\]

where, the desired current \( I_{2,p}^* \) in Eq. (38) is computed using the FO-PID as below:

\[
I_{2,p}^* = k_1p e_{2p} + k_2p e_{2p} D_1^{-\alpha} + k_3p e_{2p} D_1^{\beta} \tag{39}
\]

where, \( e_{2p} \) denotes the load voltage error expressed as:

\[
e_{2p} = (V_{Loadp} - V_{Loadp}^*) \tag{40}
\]

C. ENERGY MANAGEMENT UNIT (EMU)

The energy management unit aim is to coordinate and control all the operations in the microgrid system. From Figs. 2-7, it can be seen that the energy management unit described by the MPPT Mode/of-MPPT mode algorithm is used to generate the references of the SSCs and load-side converters controller law. The energy management unit generates the references based on the measured input power available and the consumed for both the SSCs and LSCs. The renewable sources are prioritized as mentioned previously on the loads.

The BSS works in charge/discharge mode and regulates the DC-link voltage at its reference value. The power in the microgrid is balanced under different power generation forms of the renewable sources and the load demand condition. When the source-side converters generate abundant power, the supply power is used to charge the battery storage system. In case the power generated by the source-side converters is not enough, the power in the AC grid is used to supply the loads as shown in Fig. 1. The mathematical model of the power balance is given as [17], [26]:

\[
P_W + P_{pv} + P_g = P_{Load} + P_{Battery} \tag{41}
\]

IV. NUMERICAL RESULTS

The present paper proposed a combined hybrid energy system integrated smart DC-microgrid is illustrated by Fig. 1, where three main parts can be distinguished: the hybrid energy sources constituted by the wind energy, solar energy, and the BSS connected to the DC-link through their respective...
converters. The second part represents the loads assumed to be a priority which in the case of a smart university may include laboratory experimentation benches, fans, and lighting. A maximum power point tracking algorithm is used on both the wind and solar (PV) conversion systems to force them to operate at maximum power. The energy management unit computes the total consumed and produced energy in order to select the adequate control modes.

The simulation results of the proposed system are performed under Matlab/Simulink and the used parameters can be found in [27]. The DC-link reference value is fixed to 240 V. The simulation test is focused on the energy management unit performances illustrated in Fig. 11. Firstly, the DC load of 8000 watts is connected to the DC-link through two load-side converters when the battery storage system state of charge (SOC) is initially at 80%. Fig. 13 shows the wind profile between 8-13m/s. Fig. 14 shows the generated wind power which is varying between 4000 and 10000 watts) according to the wind speed. A 3000 watts PV power is generated as shown in Fig. 15 under a radiance of 600 watts/m² and a temperature of 25°C. Fig. 16, depicts the generated power $P_{dg}$ from both PV and wind sources. According to the present response, the generated power $P_{dg}$ varies between 7000 and 13000 watts.

Figs. 17 and 18 show the battery power and its SOC. From the presented results, the battery supplies the microgrid with about 2300 watts in the time intervals [0-1.4] s when...
TABLE 2. Comparative analysis of the proposed strategy with recent references.

| Ref. | Microgrid elements | Method | Main contribution | The novelty of the proposed strategy |
|------|---------------------|--------|-------------------|-------------------------------------|
| [14] | Wind-PV+BSS-DC loads (Houses) | Distribution Voltage Control | FLC + Gain scheduling | *A new adaptive and intelligent controller is proposed. The controller is used to control both SSCs and LSCs contrary. |
| [15] | PV-Wind-BSS-Residence | Energy Management | Two low-complexity FLC | |
| [16] | PV-Wind-BSS-SOFC-Loads | Coordinated control | Two Feed-Back control loops and Feed-Forward control loop | |
| [17] | PV-BBSS-Loads | Energy Management | adaptive droop control | |
| [21] | PV-Wind Generator-BSS-Loads | Energy Management | Adaptive Backstepping | |
| [27] | PV-Wind-BSS-Load | Energy Management + SSCs control | Super Twisting Fractional Order | |
| Proposed strategy | Wind-PV-BSS-Loads | Energy management + SSCs Control | Fuzzy Supervisory-Fractional Order-PID control | |

**FIGURE 15.** Solar power.

**FIGURE 16.** SSCs power.

**FIGURE 17.** BSS power.

**FIGURE 18.** The battery SOC.

SOC > 20%, while in the time intervals [1.4-2.3] s the generated $P_{dg}$ is more than the load power. Thus, the battery is charged with about 4500 watts from the microgrid. Fig. 19, shows the DC-link voltage of both the SSCs and LSCs for the PI and proposed IFO-PID, where it can be seen that both regulate the DC-link at its reference value. However, the proposed IFO-PID shows superior performances in terms of the steady-state error and the convergence criterion.

Fig. 20 shows that the proposed energy management control transmits a constant power to the loads, about 8300 watts. Fig. 21 clearly indicate that the proposed IFO-PID regulate the output voltage at its reference (220V).

A comparative analysis with previous works has been performed in the present section to highlight the advantages of the proposed IFO-PID. The comparative analysis is shown by Table 2. Extensive comparative analysis with
TABLE 3. Results comparison of the proposed strategy with that of ref. [27], FO-PID and PID.

| Controller                  | Proposed IFO-PID | Super Twisting Fractional Order [27] | FO-PID | PID   |
|-----------------------------|------------------|--------------------------------------|--------|-------|
| Wind power (W)              | 9800 (+3.15%)    | 9500                                 | 9800   | 9400  |
| PV power (W)                | 3000 (+50%)      | 2000                                 | 3000   | 1900  |
| SSCs power (W)              | 13000 (+4%)      | 12500                                | 13000  | 12300 |
| BSS power stored (W)        | 2500 (+13.64%)   | 2200                                 | 2500   | 2100  |
| BSS power supplied (W)      | 4500 (+12.5%)    | 4000                                 | 4500   | 4000  |
| Load power (W)              | 8300 (+2.5%)     | 8100                                 | 8300   | 8000  |
| Complexity                  | Low              | High                                 | Low    | Very Low |
| Robustness                  | High (Zero fixed gains) | Poor (more than 7 fixed gains) | Low (more than 5 fixed gains) | Very poor (more than 10 fixed gains) |
| Performance                 | Very High        | High                                 | High   | Low   |

ref. [27], FO-PID and PID is demonstrated in Table 3, where it can be seen that the proposed strategy generates more power and show high performance over the compared control strategies. From the present comparative analysis, the proposed controller produces +3.15% wind power, +50% PV power, +2.5% load power over the super twisting fractional-order and more when compared to the PID control.

In summary, the proposed control strategy has well managed the hybrid energy, and well achieved the objectives of the present work, and shows higher performances when compared to the other methods.

To test the robustness of the proposed energy management strategy, a random variation of the wind speed and solar radiance is used as shown by Fig. 22 and Fig. 23 respectively. Fig. 24 shows the wind power generated under random wind profile. The wind system appears to work at MPPT based on the reported results. Figure 25 clearly demonstrates how
FIGURE 23. Wind power under random wind speed.

FIGURE 24. Solar radiance.

FIGURE 25. Solar power under random solar radiance.

FIGURE 26. SSCs power under random variations.

the MPPT control (see Fig. 5) forces the PV panel to extract the maximum power regardless of solar radiation variations. Fig. 26 shows the power generated from both PV and wind sources. From the given results, it can be seen that the power generated is maintained between 5000-13000W which is the same as in the first test (see Fig. 16). Fig. 27 shows the BSS power under the random variations which is varying between 5000 and −5000W. The BSS works perfectly in charge/discharge mode. Fig. 28 depict that the proposed energy management control transmits a constant power to the load, about 8300W, here also it’s the same as in the first case (see Fig. 20). Finally, Fig. 29 shows the DC-link voltage response. It is clear from the reported response that the proposed technique effectively regulates the DC voltage at its reference. Thus, the proposed energy management strategy well validates the objectives even under random variations, ensures smooth output power and service continuity.

V. CONCLUSION

In this paper, a novel intelligent fractional order PID controller is proposed for the Energy management of hybrid energy sources contacted to a smart grid through a DC-link voltage. The hybrid energy sources integrated to the DC-microgrid are constituted by a battery bank, wind energy, and photovoltaic (PV) energy source. The source side converters (SCCs) are controller by the new intelligent fractional order PID strategy to extract the maximum power from the renewable energy sources (wind and PV) and
improve the power quality supplied to the DC-microgrid. To make the microgrid as cost-effective, the (Wind and PV) energy sources are prioritized. The proposed controller ensures smooth output power and service continuity. Simulation results of the proposed control schema under Matlab/Simulink are presented and compared with the other nonlinear controls. Extensive comparative analysis with super twisting fractional order control, FO-PID and PID is demonstrated in Table 3, where it can be seen that the proposed strategy generates more power and shows high performance over the proposed control strategies. From the present comparative analysis, the proposed controller produces +3.15% wind power, +50% PV power, +2.5% load power over the super twisting fractional-order and more when compared to the PID control. Future works will be focused on the experimental validation of the proposed control with a real test bench.

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