Research Article

Modeling of an Electrical Energy Switching System in Multisource Power Plants: The Case of Grid Connected Photovoltaic and Wind Power Systems

Theodore Louossi,1 Fabrice Kwefeu Mbakop1, Abdouramani Dadje,2 and Noel Djongyang1

1Department of Renewable Energy, National Advanced School of Engineering of Maroua, University of Maroua, Maroua, Cameroon
2School of Geology and Mining Engineering, University of Ngaoundéré, Ngaoundéré, Cameroon

Correspondence should be addressed to Fabrice Kwefeu Mbakop; mbakop.fabrice@yahoo.fr

Received 15 March 2022; Revised 26 October 2022; Accepted 3 November 2022; Published 28 November 2022

Academic Editor: Jedrzej Szmytkowski

This paper proposes a multisource power plant management strategy for the proposed structure. This power plant consists of photovoltaic, wind, and grid. The principle of this management strategy is based on the reference currents and defines two components of the current namely a harmonic component related to the harmonics contained in the load current and current called fundamental related to the fundamental of the load current. This proposed strategy allows the different renewable sources to supply the load partially or totally. The harmonic component performs the power quality function while the fundamental component feeds the load and injects the surplus production into the grid. The power management is done according to the established scenarios and responds to the demand of the load. The simulations were carried out with Matlab software, and these results show the performance of this strategy for this structure studied to fulfill the following functions: power supply to the load, power factor (PF) correction, harmonic elimination, reactive energy compensation, and injection in the network of a current with a low rate of harmonic distortion lower than 1% in accordance with the IEEE Std 519-2014 standard.

1. Introduction

Renewable energy production is a current area of research in many developed and even developing countries. Indeed, in recent years, in addition to the ever-increasing demand for energy and the depletion of fossil fuel reserves, the scientific community has focused on the allegedly most worrying threat to the future of the planet: global warming [1]. This phenomenon is the consequence of the increase in greenhouse gas emissions linked to human activity. However, the greenhouse gas emissions produced in the global energy sector are estimated at 75% and 85%[2]. In response to this situation, two strategies have been put in place to combat this problem. The first strategy is to save energy by implementing consumption reduction programmes and focusing on energy efficiency in the industrial and tertiary sectors. The second strategy is to use the potential of renewable energy sources (RES) [3]. The rapid development of the renewable energy sector (solar, wind, biomass, etc.) has led researchers to look beyond the threat of climate change to other alternative uses, such as supplying electricity to remote sites (rural areas not connected to the electricity grid) and reducing household electricity consumption in urban areas (areas connected to the electricity grid).

Among these RES, solar photovoltaic energy has great potential as an alternative energy resource to fossil fuels and is one of the most promising due to energy free, clean, inexhaustible, easy conversion process, free-noise, sustainable, and global availability [4–6]. However, their dependence on weather conditions leads to their coupling
with other renewable or nonrenewable sources to ensure a continuous supply of electricity. The most common combination in the field of renewable energy is that of solar photovoltaics and wind power, due to their complementary nature of using the strengths of one source to overcome the weaknesses of the other [7]. Nowadays, it is usual practice to connect RES to the grid. In this case, the electricity produced by the RES is used directly, and the surplus energy is injected into the grid during the day. In bad weather, the grid supports RES when it is unable to provide the electricity required by the load [8]. The interconnection of the RES to the grid must meet the requirements of the standard in terms of voltage magnitude, frequency, and current harmonics. A synchronization method is used for the control of grid-connected inverter in order to synchronize both sources in such way that the RES is a phase with the grid, and the currents injected into the grid have low total harmonic distortion (THD) [9]. Furthermore, one of the major problems of the harmonic currents injected by the RES is due to the proliferation of nonlinear loads which do not absorb sinusoidal current and which are connected to the network. This affects the quality of the energy [10]. These harmonics cause serious problems for loads connected to the grid, such as heating problems, unexpected resonances, disturbances in electronic equipment, “logic” faults in digital circuits, degradation of power factor, electromagnetic interference, and motor malfunctions [11–13]. Therefore, it is crucial to mitigate the harmonics level on the grid side. Several solutions for harmonic depollution of power systems have been proposed in the literature and can be grouped into traditional and modern solutions. Traditional solutions mainly include shunt passive filters. Modern solutions mainly include series active filters, shunt active filters, and hybrid filters have been proposed [14].

With the technological and scientific developments in the fields of renewable energies and their interconnection to the grid, the resolution of power quality problems has taken a major step forward. Indeed, in order to optimise the utilisation of the RES, in addition to its function of supplying AC loads, it can perform the function of power quality management [15–17]. The idea is to combine the RES and active power filters. In this topology, RES can also provide power factor (PF) correction, load balancing, harmonic elimination, and reactive power compensation and simultaneously inject the maximum available power of the RES into the grid [14, 18]. The three main functions of this system configuration are power quality, load supply, and low-THD current injection into the grid. This paper deals with this approach. In this paper, a new management strategy for a hybrid multisource PV, wind, and grid plant is proposed. This proposed management strategy allows the RES to perform the functions of load supply, harmonic elimination, PF correction, reactive energy compensation, and low-THD current injection into the grid.

The remaining part of this paper is organized as follows: in Section 2, the description of the studied system is done. Then, the management strategy proposed is described in Section 3. The performance of the management strategy proposed is illustrated by numerical simulations in MATLAB/Simulink software is presented in Section 4. Finally, Section 5 concludes the paper.

2. System Description and Modelling

The system proposed in this work is a hybrid multisource PV, wind, and grid plant based on a shunt active power filter. In this configuration, the PV system and wind turbine are connected to the grid through a SAPF. The grid-connected inverters are controlled to allow the PV system and wind turbine to perform the functions of power quality, load supply, and grid injection of low-THD current. In Figure 1, the functional components are presented. This system is composed of a PV system interfaced with the grid via a DC/AC converter, a wind turbine interfaced with the grid via an AC/DC converter and a DC/AC converter, the nonlinear and linear loads. The nonlinear loads consist of a rectified bridge supplying a resistance in series with an inductance. The reference currents of the grid-connected inverter are provided by the proposed management strategy.

2.1. Modelling of PV System. The solar cell is the basic unit of a PV panel, and it is the element in charge of transforming the sun rays or photons directly into electric power by a process called the “photovoltaic effect” [8]. Figure 2 shows the equivalent circuit of solar cell, and equation (1) shows the expression of output current of solar cell [5].

\[
I_{pv} = I_{ph} - I_s \left( \exp \left( \frac{q(V_{pv} + R_sI_{pv})}{nK_bT} \right) - 1 \right) - \frac{V_{pv} + R_sI_{pv}}{R_{sh}},
\]

We have

\[
I_{ph} = \left( \frac{G}{G_r} \right) (I_{scr} + K_i(T - T_i)),
\]

\[
I_s = I_n \left( \frac{T}{T_r} \right)^3 \exp \left( \frac{qE_g}{nK_b} \left( \frac{1}{T_r} - \frac{1}{T} \right) \right),
\]

\[
I_n = \frac{I_{scr}}{\exp \left( qV_{oc}/nK_bT \right) - 1},
\]

where \( I_{pv} \) is output current of PV cell; \( I_{ph} \) is photovoltaic current source; \( I_s \) is diode saturation current; \( I_n \) is diode saturation current at \( T_r \); \( I_{scr} \) is short-circuit current of PV module at standard test condition; \( V_{pv} \) is output voltage of PV cell; \( V_{oc} \) is open-circuit voltage; \( E_g \) is silicon gap energy of semiconductor; \( T \) is cell temperature; \( T_r \) is reference temperature; \( G \) is solar irradiation; \( G_r \) is reference solar irradiation; \( q \) is electron’s charge; \( n \) is diode ideality; \( K_b \) is Boltzmann’s constant; \( K_i \) is temperature coefficient of short-circuit; \( R_s \) is series resistance; \( R_{sh} \) is shunt resistance. For \( N_s \) cells in series and \( N_p \) cells in parallel, the characteristic equation of a PV module is delivered as follows [1]:

\[
I = I_{pv} \left( 1 - \exp \left( -\frac{V}{V_{mpv}} \right) \right),
\]
2.2. Modelling of Wind turbine. The wind turbine consists of a turbine coupled with a permanent magnet synchronous generator (PMSG) with a transistor rectified bridge [19]. The wind turbine model consists of three important blocks, namely the aerodynamic block, the mechanical block, and the electrical block. Figure 3 shows the interaction between the different blocks of the wind turbine model [20].

The turbine transforms the kinetic energy of the wind captured by the blades of the wind turbine into mechanical energy available on its shaft. The output mechanical power extracted by the wind turbine is given by [21]

\[ P_m = \frac{1}{2} C_p (\lambda, \beta) \rho S \nu^3. \]  

This power is function of air density \( \rho \), of the area covered by the blade \( S \), of wind speed \( \nu \), and of the power coefficient \( C_p (\lambda, \beta) \). For a known wind turbine, \( C_p (\lambda, \beta) \) can be determined by measurement, but in some restrictive conditions, it can be approximated as follows [22]:

\[ C_p (\lambda, \beta) = c_1\left(\frac{c_2 - c_3 x \beta - c_4 x \beta - c_5}{\lambda_i}\right) \exp\left(-\frac{c_6}{\lambda_i}\right). \]  

With \( c_1 - c_6 \), the aerodynamic coefficients are given, respectively, by 0.5176; 116; 0.4; 5; 21; and 0.0068 [22].

\[ \lambda_i = \left(\frac{1}{\lambda - 0.02\beta - \frac{0.003}{\beta^2 + 1}}\right)^{-1}, \]  

\[ \lambda = \frac{R \omega_T}{\nu}, \]  

where \( \lambda \) is the tip speed ratio; \( \beta \) is the blade pitch angle; \( R \) is the blade radius; \( \omega_T \) is the mechanical turbine speed.

The output of the turbine is the mechanical torque. The wind turbine torque may be written as follows [21]:

\[ T_A = \frac{P}{\omega_T}. \]  

Adding equations (4) and (6) into equation (7) we get:

\[ T_A = \frac{1}{2} \rho n \frac{R^2 \nu^2}{\lambda} C_p (\lambda, \beta). \]  

The wind turbine mechanical subsystem as known as the drive train consists of the rotor shaft, the generator shaft, and a gearbox. The simplified model of drive train is shown in Figure 4 [21].
In Figure 4, $T_A$ is the wind turbine torque, $T_s$ is the shaft torque, $T_m$ is the mechanical driving torque, $T_{\text{fric}}$ is the torque losses due to friction, $T_e$ is the electromagnetic torque, $J_r$ is the turbine inertia constant, $J_g$ is the generator inertia constant, $\omega_g$ is the mechanical generators speed, and $n$ is the gearbox transmission report.

The equation of motion of the drive train shaft is given by [21]
$$J_r \frac{d\omega_r}{dt} = T_A - T_s.$$ (9)

The relationship between the mechanical driving torque and shaft torque is given by [21]
$$T_m = \frac{T_s}{n}.$$ (10)

The equation of motion of the generator is given by [21]
$$J_g \frac{d\omega_g}{dt} = T_m - T_e - T_{\text{fric}}.$$ (11)

By taking into account the relationship between mechanical generator and turbine speeds given in equation (11) and equations (7)–(9), the mechanical subsystem is represented by the following equation:
$$\left( J_g + J_r \frac{1}{n^2} \right) \frac{d\omega_g}{dt} = \frac{1}{n} T_A - T_e - T_{\text{fric}}.$$ (12)

We have
$$\omega_g = n \omega_T.$$ (13)

In sum, the model of wind turbine mechanical block is a model with wind turbine torque and electromagnetic torque as inputs, and mechanical generator speed and mechanical turbine speed as outputs.

The electrical block consists of a permanent magnet synchronous generator, having as input the mechanical generator speed and electromagnetic torque and as output the power. The electrical model of PMSG in synchronous reference rotating frame is given by [23]

$$\begin{bmatrix}
id_t \\
i_q_t \\
u_d \\
u_q \\
\phi_m \\
\phi_s 
\end{bmatrix} = \begin{bmatrix}
R_s L_d & P \omega_p L_d & L_d i_d & 0 & 0 & 1/L_d \\
0 & R_s L_d & 0 & L_d i_q & 0 & 0 \\
-L_d i_d & -L_d i_q & R_s & P \omega_p L_d & 1/L_d & 0 \\
0 & -L_d i_d & -L_d i_q & R_s & P \omega_p L_d & 1/L_d \\
0 & 0 & 0 & 0 & 0 & \frac{1}{L_d} \\
0 & 0 & 0 & 0 & 0 & \frac{1}{L_d} 
\end{bmatrix} \begin{bmatrix}
\frac{d}{dt} i_d \\
\frac{d}{dt} i_q \\
\frac{d}{dt} u_d \\
\frac{d}{dt} u_q \\
\phi_m \\
\phi_s 
\end{bmatrix},$$ (14)

where $L_d, L_q$ are direct and quadratic components of the stator winding inductances; $R_s$ is stator winding resistance; $p$ is the number of pole pairs; $i_d, i_q$ are direct and quadratic components of the stator currents; $u_d, u_q$ are direct and quadratic components of the stator voltages; $\phi_m$ is the permanent magnetic rotor flux;

The following equation gives the expression of electromagnetic torque [23]:
$$T_e = \frac{3}{2} P \left( L_d i_d i_q^* + \phi_m i_q^* \right).$$ (15)
2.3. DC/AC Converter. The DC/AC converter is a voltage source inverter (VSI). Figure 5 presents the structure of DC/AC converter used. It is a two-level three-phase inverter with 6 bidirectional power switches in current. The inverter is connected to the PCC through a coupling filter. The DC part of the VSI is ensured by the RES connected through a capacitor. The grid-connected inverter control strategy is designed to allow the PV system to perform its functions of power quality, load supply, and low-THD current injection into the grid [24].

3. Management Strategy Proposed

This section presents the principle of the proposed management strategy and its application with PQ theory.

3.1. Principle. The proposed management strategy is based on the calculation of the reference currents of the grid-connected inverters. The idea is to produce a reference current with two components, one, the harmonic component linked to the harmonics contained in the load current, and the other, the fundamental component linked to the fundamental of the load current. The reference currents are deduced from their harmonic and fundamental components according to the following equation:

\[ i^* = K_h i_{harm} + K_f i_{fund} \]  

(16)

where \( i^* \) is the reference current, \( i_{harm} \) is the harmonic component of reference current, \( i_{fund} \) is the fundamental component of reference current, \( K_h \) is the modulation coefficient of harmonic component, and \( K_f \) is the modulation coefficient of fundamental component.

The harmonic component of the reference current is the sum of the harmonic components of the load current. It is extracted from the load current using a harmonic identification technique. This component is reinjected in phase opposition to the load current at the PCC to eliminate the harmonics generated by the load and thus enables the RES to perform with power quality function. The modulation coefficient of the harmonic component is set to either 0 or 1, depending on whether the renewable energy source is to provide the power quality function or not.

The fundamental component of the reference currents is the fundamental component of the load current. This component is reinjected in phase to the load current at the PCC to perform with load supply, low-THD current injection into the grid functions, or both function.

PV system performs with power quality function, the wind generator can perform with load supply, low-THD current injection into the grid functions, or both function and vice versa.

3.2. Implementation with Instantaneous PQ Theory. The instantaneous PQ theory introduced by Akagi et al. in 1983 is a time-based method, which is used to avoid difficulties due to the high number of calculations when implementing frequency-based methods. It transforms the fundamental component of the signal into a DC component and the harmonic components into AC component. Figure 6 shows the implementation with the instantaneous PQ theory of the proposed management strategy. The \((a, b, c)\) components of the three-phase load current and the three-phase grid voltage are converted to their \((\alpha, \beta)\) equivalents in the Concordia reference frame according to the following equations:

\[
\begin{bmatrix}
V_{\text{Grid}_a} \\
V_{\text{Grid}_b} \\
V_{\text{Grid}_c}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
1 & -1/2 & 1/2 \\
0 & \sqrt{3}/2 & -
\end{bmatrix} \begin{bmatrix}
V_{\text{Grid}_a} \\
V_{\text{Grid}_b} \\
V_{\text{Grid}_c}
\end{bmatrix},
\]

(17)

\[
\begin{bmatrix}
i_{L_a} \\
i_{L_b} \\
i_{L_c}
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
1 & 0 & 0 \\
0 & \sqrt{3}/2 & \sqrt{3}/2 \\
\sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2
\end{bmatrix} \begin{bmatrix}
i_{L_a} \\
i_{L_b} \\
i_{L_c}
\end{bmatrix},
\]

(18)

The instantaneous active and reactive powers are given by

\[
\begin{align*}
  P &= V_{\text{Grid}_a}i_{L_a} + V_{\text{Grid}_b}i_{L_b} + V_{\text{Grid}_c}i_{L_c}, \\
  Q &= V_{\text{Grid}_a}i_{L_b} + V_{\text{Grid}_b}i_{L_c} + V_{\text{Grid}_c}i_{L_a}.
\end{align*}
\]

(19)

The separation between the DC components linked to the fundamental and the AC components linked to the harmonics, of the powers, is done by means of low-pass filter (LPF). The AC components \(\bar{p}\) and \(\bar{q}\) are used to calculate the harmonic components of the reference currents according to the following equation:

\[
\begin{align*}
  i_{L_a} &= \frac{1}{\sqrt{3}} \left( V_{\text{Grid}_a} - \frac{2}{\sqrt{3}} V_{\text{Grid}_b} \right), \\
  i_{L_b} &= \frac{1}{\sqrt{3}} \left( V_{\text{Grid}_a} + \frac{2}{\sqrt{3}} V_{\text{Grid}_c} \right), \\
  i_{L_c} &= \frac{1}{\sqrt{3}} \left( V_{\text{Grid}_b} - V_{\text{Grid}_c} \right).
\end{align*}
\]
Figure 6: Block diagram of proposed management strategy with PQ theory.

\[
\begin{bmatrix}
i_{\text{harm}a}^* \\ i_{\text{harm}b}^* \\ i_{\text{harm}c}^*
\end{bmatrix} = \frac{1}{V_{\text{Grid}a}^2 + V_{\text{Grid}b}^2}
\begin{bmatrix}
V_{\text{Grid}a} & V_{\text{Grid}b} \\
V_{\text{Grid}b} & -V_{\text{Grid}a}
\end{bmatrix}
\begin{bmatrix}
\bar{P} \\ \bar{q}
\end{bmatrix}.
\]

The DC components \( \bar{P} \) and \( \bar{q} \) are used to calculate the fundamental components of the reference currents according to the following equation:

\[
\begin{bmatrix}
i_{\text{fund}a}^* \\ i_{\text{fund}b}^* \\ i_{\text{fund}c}^*
\end{bmatrix} = \frac{1}{V_{\text{Grid}a}^2 + V_{\text{Grid}b}^2}
\begin{bmatrix}
V_{\text{Grid}a} & V_{\text{Grid}b} \\
V_{\text{Grid}b} & -V_{\text{Grid}a}
\end{bmatrix}
\begin{bmatrix}
P \\ q
\end{bmatrix}.
\]

The (\( a, b, c \)) components of the harmonic and fundamental components of the reference currents are given by

\[
\begin{bmatrix}
i_{\text{harm}a}^* \\ i_{\text{harm}b}^* \\ i_{\text{harm}c}^*
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 \\ -\frac{1}{2} \sqrt{3} \\ -\frac{1}{2} \sqrt{3}
\end{bmatrix}
\begin{bmatrix}
i_{\text{harm}a}^* \\ i_{\text{harm}b}^* \\ i_{\text{harm}c}^*
\end{bmatrix},
\]

\[
\begin{bmatrix}
i_{\text{fund}a}^* \\ i_{\text{fund}b}^* \\ i_{\text{fund}c}^*
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
1 \\ -\frac{1}{2} \sqrt{3} \\ -\frac{1}{2} \sqrt{3}
\end{bmatrix}
\begin{bmatrix}
i_{\text{fund}a}^* \\ i_{\text{fund}b}^* \\ i_{\text{fund}c}^*
\end{bmatrix}.
\]

The reference currents are deduced from their harmonic and fundamental components according to the following equation:

\[
i_a^* = K_{ha} i_{\text{harm}a}^* + K_{fa} i_{\text{fund}a}^*,
i_b^* = K_{hb} i_{\text{harm}b}^* + K_{fb} i_{\text{fund}b}^*,
i_c^* = K_{hc} i_{\text{harm}c}^* + K_{fc} i_{\text{fund}c}^*.
\]

where \( K_{ha,b,c} \) and \( K_{fa,b,c} \) are the modulated coefficients generated by the supervisor.

3.3. Supervisor. The role of the supervisor in the proposed management strategy is to set the modulation coefficients of the harmonic and fundamental components of the reference currents. The modulation coefficients of the harmonic component are set according to the power produced by the PV system and the power produced by the wind turbine. The renewable energy source producing the most ensures the power quality function. The modulation coefficients of the fundamental component are set according to the power produced by the PV system, the power produced by the wind turbine, the power required by the load, the THD of the grid current, the THD of the current injected by the PV system, and the THD of the current injected by the wind turbine.

4. Results and Discussion

The effectiveness of the proposed control strategy is evaluated in this section by numerical simulations in Matlab/Simulink software, using the fixed-step time ODE3 (Bogacki-Shampine) solver and the SimPower system toolbox. The simulation parameters of the grid and the grid-connected inverters are given in Table 1, and those of the wind turbine are given in Table 2, and PV system is given in Table 3.

4.1. Performance under Operating Scenario 1. In this section, the performance of the proposed management strategy is verified under the conditions of operating scenario 1. In this
operating scenario, the power produced by the PV system and that produced by the wind turbine are greater than the power required by the load throughout the simulation. During the first phase, i.e., between 0 s and 0.5 s, the power produced by the PV system is higher than that produced by the wind turbine and during the second phase; i.e., between 0.5 s and 1 s, the power produced by the wind turbine is higher than that produced by the PV system. The simulation parameters of the nonlinear load are $R = 100 \, \Omega$ and $L = 2.6 \, \text{mH}$. The temperature and wind speed are fixed at 25°C and 12 m/s, respectively. The solar irradiation profile is given in Figure 7.

Figures 8–11 show the waveforms and THD of the load current, the filter current injected by the PV system, the filter current injected by the wind turbine, and the grid current, respectively. Figure 12 shows the modulation coefficients fixed by the supervisor, and Figure 13 shows the power factor of the grid. As the load is fixed throughout the simulation, its waveform does not change and stays distorted with a THD of 27% (see Figure 8). During the first phase (0 s to 5 s), the power produced by the PV system is higher than the power produced by the wind turbine and the power required by the load. For the grid-connected inverter to the PV system, the supervisor sets the modulation coefficient of the harmonic component to 1 and that of the fundamental component to 2.3. This means that the PV system eliminates the harmonics, supplies the load, and injects into the grid a current. The filter current injected by the PV system is less distorted than that of the load (see Figure 9(a)) because, in addition to the currents needed to eliminate the harmonics generated by the load, it contains a sinusoidal component to supply the load and another that is injected into the grid. This is verified in Figure 9(b) by the THD value which is about around 12%. For the grid-connected inverter to the wind turbine, the supervisor sets the modulation coefficient of the harmonic component to 0 and that of the fundamental component to 1.8. This means that the wind turbine supplies the load and injects into the grid a current. The filter current injected by the wind turbine is sinusoidal with a THD of 0.5%. The current injected by the two renewable sources into the grid has a THD of less than 1%.

During the second phase, the solar irradiation decreases and induces a decrease in the power produced by the PV system, which becomes lower than that produced by the wind turbine but remains higher than the power required by the load. The components are set to 0 for the harmonic component and 1.8 for the fundamental component. This means that in this phase, the harmonics are eliminated by the wind turbine, the load is supplied by the renewable energy sources, and the surplus renewable energy produced is injected into the grid. Indeed, in this phase, the filter current injected by the PV system is sinusoidal with a THD lower than 1%, the filter current injected by the wind turbine is distorted with a THD close to 20%, and the current injected into the grid is sinusoidal with a THD lower than 1%. The different power flows in the two phases of this scenario can also be seen in Figure 13 where the PF changes from a positive value before the RES connection to a negative value close to −1. The value of −1 means that during the whole scenario, a current with low THD in phase opposition with the voltage is injected into the grid.

4.2. Performances under Operating Scenario 2. In this section, the performance of the proposed management strategy is verified under the conditions of operating scenario 2. In this scenario, the power produced by the PV system and that produced by the wind turbine are lower than the power
required by the load throughout the simulation. The simulation parameters of the nonlinear load are $R = 2.5\, \Omega$ and $L = 0.1\, \text{mH}$. The temperature and wind speed are fixed at 25°C and 8 m/s, respectively. The solar irradiation profile is given Figure 14.

Figure 15–18 show the waveforms and THD of the load current, the filter current injected by the PV system, filter current injected by wind turbine, and the grid current, respectively. Figure 19 shows the modulation coefficients fixed by the supervisor. As the load is fixed throughout the
simulation, its waveform does not change and stays distorted with a THD of 20% (see Figure 15). During the first phase, the power required by the load is higher than the power produced by the PV system and the power produced by the wind turbine, but it is still lower than the sum of the power produced by the renewable energy sources. As the power produced by the PV system is higher than the power produced by the wind turbine, the modulation coefficients of the reference currents of the grid-connected inverter to the PV system are set to 1 for the harmonic component and 0.8 for the fundamental component. For the grid-connected inverter to the wind turbine, these components are set to 0 for the harmonic component and 0.4 for the fundamental component. This means that in this phase, the harmonics are eliminated by the PV system, the load is supplied by renewable energy sources, and the surplus renewable energy produced is injected into the grid. Indeed, in this phase, the filter current injected by the wind turbine is sinusoidal with a THD lower than 1% (see Figure 17), the filter current injected by the PV system is distorted with a THD close to 25%, and the current injected into the grid is sinusoidal with a THD lower than 1%.
During the second phase, the power required by the load is higher than the power produced by the PV system, the power produced by the wind turbine, and the sum of the power produced by renewable energy sources. As the power produced by the wind turbine is higher than the power produced by the PV system, the modulation coefficients of the reference currents of the grid-connected inverter to the wind turbine are set to 1 for the harmonic component and 0.4 for the fundamental component. For the grid-connected inverter to the PV system, these components are set to 0 for the harmonic component and 0.3 for the fundamental component. This means that in this phase, the harmonics are eliminated by the wind turbine, the load is partially supplied by renewable energy sources, and the power deficit is

\[
\begin{align*}
\text{Current (A)} & \quad \text{Time (s)} \\
0 & \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \\
-150 & \quad -100 & \quad 0 & \quad 100 & \quad 150 & \quad 200 & \quad 250
\end{align*}
\]

(a) Load current and its THD.

\[
\begin{align*}
\text{Current (A)} & \quad \text{Time (s)} \\
0 & \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \\
-120 & \quad -100 & \quad -80 & \quad -60 & \quad -40 & \quad -20 & \quad 0 & \quad 20 & \quad 40 & \quad 60 & \quad 80 & \quad 100 & \quad 120
\end{align*}
\]

(b) Filter current injected by PV system and its THD.
provided by the grid. Indeed, in this phase, the filter current injected by the PV system is sinusoidal with a THD lower than 1%, the filter current injected by the wind turbine is distorted with a THD close to 50%, and the current drawn by the load from the grid is made sinusoidal by the action of the filter current injected by wind turbine. The THD of the grid current is always less than 1%.

The different power flows in the two phases of this scenario can also be seen in Figure 20, where the PF changes from a negative value close to −1 to a positive value close to 1. This means that during the first phase, a current with a low THD and in phase opposition with the voltage is injected into the grid. During the second phase, the grid supplies the power deficit required by the load. Due to the power quality function of the wind turbine, the current drawn from the grid by the nonlinear load is sinusoidal and harmonic-free.

4.3. Performances under Operating Scenario 3. In this section, the performance of the proposed management strategy is verified under the conditions of operating scenario 3. During the first phase, i.e., between 0 s and 0.5 s, the power required by the load is lower than the power produced by the PV system

Figure 18: Grid current (a) and its THD (b).

Figure 19: Modulation coefficients of reference currents of the grid-connected inverter of the PV system (a) and wind generator (b).

Figure 20: Modulation coefficients of reference.

Figure 21: Solar irradiation profile.
but greater than the power produced by the wind turbine. During the second phase, i.e., between 0.5 s and 1 s, the power required by the load is greater than the power produced by the PV system but lower than the power produced by the wind turbine. The simulation parameters of the nonlinear load are $R = 6.5 \Omega$ and $L = 2.6 \text{mH}$. The temperature is fixed at 25°C. The solar irradiation profile is given in Figure 21.

Figure 22–25 show the waveforms and THD of the load current, the filter current injected by PV system, filter current injected by wind turbine, and the grid current, respectively. Figure 26 shows the modulation coefficients fixed by supervisor. As the load is fixed throughout the simulation, its waveform does not change and stays distorted with a THD of 25% (see Figure 22). During the first
phase, as the power required by the load is lower than the power produced by the PV system but greater than the power produced by the wind turbine, the modulation coefficients of the reference currents of the grid-connected inverter to the PV system are set to 1 for the harmonic component and 1.6 for the fundamental component. For the grid-connected inverter to the wind turbine, these components are set to 0 for the harmonic component and 0.8 for the fundamental component. This means that in this phase, the harmonics are eliminated by the wind turbine, the load is supplied by renewable energy sources, and the surplus renewable energy produced is injected into the grid. Indeed, in this phase, the filter current injected by the PV system is sinusoidal with a THD lower than 1%, the filter current injected by the wind turbine is distorted with a THD close to 20%, and the current injected into the grid is sinusoidal with a THD lower than 1%.

During the second phase, as the power required by the load is lower than the power produced by the wind turbine but greater than the power produced by the PV system, the modulation coefficients of the reference currents of the grid-connected inverter to the wind turbine are set to 1 for the harmonic component and 1.6 for the fundamental component. For the grid-connected inverter to the PV system, these components are set to 0 for the harmonic component and 0.8 for the fundamental component. This means that in this phase, the harmonics are eliminated by the PV system, the load is supplied by the renewable energy sources, and the surplus renewable energy produced is injected into the grid. Indeed, in this phase, the filter current injected by the PV system is sinusoidal with a THD lower than 1%, the filter current injected by the PV system is distorted with a THD close to 20%, and the current injected into the grid is sinusoidal with a THD lower than 1%. 

Figure 25: Grid current (a) and its THD (b).

Figure 26: Modulation coefficients of reference currents of the grid-connected inverter of PV system (a) and wind generator (b).

Figure 27: Modulation coefficients of reference.
The different power flows in the two phases of this scenario can also be seen in Figure 27 where the PF changes from a positive value before the RES connection to a negative value close to −1. The value of −1 means that during the whole scenario, a current with low THD in phase opposition with the voltage is injected into the grid.

5. Conclusion

In this paper, a new management strategy for a hybrid multisource PV, wind, and grid plant is proposed. This management strategy allows the renewable energy sources, depending on the weather conditions, to perform the functions of partial or full load supply, power quality, and low-THD current injection into the grid. The principle of this strategy is to provide a reference current with two components, one, the harmonic component linked to the harmonics contained in the load current, and the fundamental component linked to the fundamental of the load current. The harmonic component is used for the power quality function and the fundamental component for the load supply and grid injection functions. The combinations of these two components allow the RES to perform the functions of load supply, harmonic elimination, PF correction, reactive energy compensation, and low-THD current injection into the grid. In order to facilitate the management of the multisource plant while allowing the renewable energy sources to perform their functions, a new structure of hybrid multisource plant based on a shunt active power filter is proposed. This structure consists of two separate power conversion chains. Each chain is equipped with an grid-connected inverter, which is controlled in such a way that one and only one of the renewable sources provide the power quality function. This is achieved by modulating the amplitudes of the harmonic and fundamental components of the reference currents. Different operating scenarios were simulated using Matlab/Simulink software, and from the results obtained, the following contributions can be noted:

(i) In case of overproduction of RES, they supply the load alone and inject into the grid a current with a THD value lower than 1%

(ii) In case of underproduction, the RES partially contributes to supplying the load and eliminates harmonics at the network level. Main current THD values must be less than 1%.

All these results, although promising, were obtained for a balanced three-phase load and for a perfect grid. A study for an unbalanced three-phase load is an interesting perspective to test the performances of the proposed management strategy.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author hereby declares no conflicts of interest with the work under consideration.

References

[1] F. Martins, C. Felgueiras, and M. Smitková, “Fossil fuel energy consumption in European countries,” Energy Procedia, vol. 153, pp. 107–111, 2018.
[2] Y. Mi, B. Chen, P. Cai, X. He, R. Liu, and X. Yang, “Frequency control of a wind-diesel system based on hybrid energy storage,” Prot Control Mod Power Syst, vol. 7, no. 1, p. 31, 2022.
[3] A. S. Aziz, M. F. N. Tajuddin, M. K. Hussain et al., “A new optimization strategy for wind/diesel/battery hybrid energy system,” Energy, vol. 239, Article ID 122458, 2022.
[4] T. Louossi, N. Djongyang, O. T. Sosso Mayi, and A. Nanfak, “Perturb and Observe maximum power point tracking method for photovoltaic systems using duty-cycle modulation,” IREEN, vol. 23, pp. 159–175, 2020.
[5] A. Ouai, L. Mokrani, M. Machmoum, and A. Houari, “Control and energy management of a large scale grid-connected PV system for power quality improvement,” Solar Energy, vol. 171, pp. 893–906, 2018.
[6] H. Zhai, F. Zhuo, C. Zhu et al., “An optimal compensation method of shunt active power filters for system-wide voltage quality improvement,” IEEE Transactions on Industrial Electronics, vol. 67, no. 2, pp. 1270–1281, 2020.
[7] F. E. Tahiri, K. Chikh, and M. Khaflah, “Optimal management energy system and control strategies for isolated hybrid solar-wind-battery-diesel power system,” Emerging Science Journal, vol. 5, no. 2, pp. 111–124, 2021.
[8] S. A. Kalogirou, “Chapter 9 - photovoltaic systems,” in Kalogirou SA Solar Energy Engineering, pp. 481–540, Academic Press, Boston, Second Edition, 2009.
[9] M. Parvez, M. F. M. Elias, N. A. Rahim, and N. Osman, “Current control techniques for three-phase grid interconnection of renewable power generation systems: a review,” Solar Energy, vol. 135, pp. 29–42, 2016.
[10] C. Li, “Comparative performance analysis of grid-connected PV power systems with different PV technologies in the hot summer and cold winter zone,” International Journal of Photoenergy, vol. 2018, Article ID 8307563, 9 pages, 2018.
[11] G. A. Patel and M. Krishna Talari, “Power quality issues mitigation in Grid connected solar- wind hybrid system,” Journal of Xi’an University of Architecture and Technology, 2021.
[12] S. Torabi Jafrodi, M. Ghanbari, and M. Mahmoudian, “A Novel control strategy to active power filter with load voltage support considering current harmonic compensation,” Applied Sciences, vol. 10, no. 5, p. 1664, 2020.
[13] Y. Hoon, M. A. Mohd Radzi, M. A. A. Mohd Zainuri, and M. A. M. Zawawi, “Shunt active power filter: a review on phase synchronization control techniques,” Electronics, vol. 8, no. 7, p. 791, 2019.
[14] S. R. Das, P. K. Ray, A. K. Sahoo et al., “A Comprehensive Survey on different control strategies and applications of active power filters for power quality improvement,” Energies, vol. 14, no. 15, p. 4589, 2021.
[15] S. Kim, G. Yoo, and J. Song, "A bifunctional utility connected photovoltaic system with power factor correction and UPS facility," in Proceedings of the Conference Record of the Twenty Fifth IEEE Photovoltaic Specialists Conference - 1996, pp. 1363–1368, IEEE, Washington, DC, USA, May 1996.

[16] C. Ghanjati, Power control and Energy Flow Optimisation in Multi-Source Renewable Energy Systems, University of Poitiers, France, 2021, https://tel.archives-ouvertes.fr/tel-03474790.

[17] R. N. Beres, X. Wang, M. Liserre, F. Blaabjerg, and C. L. Bak, "A review of passive power filters for three-phase grid-connected voltage-source converters," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 1, pp. 54–69, 2016.

[18] B. Srikan Goud and B. Loveswara Rao, "Power quality improvement in hybrid renewable source grid-connected system with Grey Wolf Optimization," International Journal of Religious Education, vol. 10, no. 3, 2020.

[19] P. S. Kumar, R. P. S. Chandra, V. Ramu, G. N. Srinivas, and K. V. S. M. Babu, "Energy management system for Small scale hybrid wind solar battery based Microgrid," IEEE Access, vol. 8, pp. 8336–8345, 2020.

[20] M. Kouali, M. Mankour, K. Negadi, and A. Mezouar, "Energy management of hybrid power system PV wind and battery based three level converter," TECNICA ITALIANA-Italian Journal of Engineering Science, vol. 63, no. 2-4, pp. 297–304, 2019.

[21] L. Arturo Soriano, W. Yu, and J. D. J. Rubio, “Modeling and control of wind turbine,” Mathematical Problems in Engineering, vol. 2013, Article ID 982597, 13 pages, 2013.

[22] Md. Hazari, M. Mannan, S. Muyeen, A. Umemura, R. Takahashi, and J. Tamura, “Stability Augmentation of a grid-connected wind Farm by Fuzzy-logic-controlled DFIG-based wind turbines,” Applied Sciences, vol. 8, pp. 20–24, 2017.

[23] A. Rolan, A. Luna, G. Vazquez, D. Aguilar, and G. Azevedo, "Modeling of a variable speed wind turbine with a permanent magnet synchronous generator," in Proceedings of the IEEE International Symposium on Industrial Electronics, pp. 734–739, IEEE, Seoul, Korea, August 2009.

[24] F. Yonga, C. Welba, T. Louossi, and N. Djongyang, "A new control Approach of a three-phase inverter two levels," Open Journal of Energy Efficiency, vol. 11, no. 3, pp. 55–70, 2022.