A micro-grid ensuring multi-objective control strategy of a power electrical system for quality improvement

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A B S T R A C T

The increasing integration of fluctuating and NL (non-linear) loads in the main grid can introduce problems to the distribution power system quality. This study was interested in a MG (micro-grid) based on RDG (renewable distributed generator) to participate in system services and to improve the efficiency of the power electrical system. The purpose of this paper is to investigate a multi-objective control strategy for the integration of an MG into electrical network in order to ensure simultaneously active power supply, reactive power compensation, harmonic current damping and grid frequency regulation. This control is mainly composed of two parts: the first one is the “NL Loads currents identification system” used to extract the fundamental active current from the disruptive one in order to provide the required harmonic and reactive currents to the considered NL loads. The second one is the “active power transfer and frequency control algorithm” used to manage the MG in six operation modes in order to control the fundamental active power flow exchange between the MG and the electrical network making the grid frequency in an allowable range of stability.

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1. Introduction

Recently, the integration of distributed generation systems based on renewable energy resources like photovoltaic system, wind power conversion system, biomass and geothermal resources, in the future distribution grid, has represented an area of growing interest. In fact, electricity generation based on renewable resources is a reliable, efficient, clean and environmentally friendly compared to the traditional centralized energy system [1,2]. However, their exploitation was mostly employed for autonomous application or for reducing electrical network power generation by feeding local consumers [3–5].

The need for more flexible power electric systems with good quality generation, leads to the development of the RDG (renewable distributed generator) applications, that are predicted to play an increasing role in the future power systems quality improvement. New concepts have been elaborated to enhance the visibility of RDG to participate in system services and guarantee a satisfactory operation of the future main grid. From these new concepts, particular interest focuses on the MG (micro-grid), which is defined as a local energy system containing various microsources, and loads, and it can operate either connected or disconnected from the main grid [6].

The application of this concept provides an opportunity to RDG for improving the stability, the reliability of supply and the power quality indices of the future utility grid by controlling different aspects of the electrical system such as harmonic and reactive power distortions, low power factor, voltage and frequency fluctuations, imbalance voltage, flicker, etc. These aspects can cause critical and sometimes several power quality problems such as malfunction protection systems, overheating of conductors and electrical equipment, additional losses in power systems and reduction in equipment lifetime [7]. And due to the significant increase of electricity consumption and to the growth integration of sensitive and NL (non-linear) loads in the electric main grid, conventional techniques are today insufficient to guarantee the power electrical system quality in different buses [8]. For that, many recent works are done for system services using MG based on RDG. In Ref. [9], a control technique to minimize distribution networks nodal voltages deviations by supervising the reactive power generated by photovoltaic plants inverters has been proposed. Authors in Ref. [10] have presented a control technique for distributed generators and single phase distribution static compensator in an MG. This control has been proposed with the
objective of reactive power compensation. An energy management strategy for a hybrid distributed generators composed by photovoltaic, diesel and battery systems has been proposed in Ref. [11]. This strategy focuses on the optimization of the grid frequency profile by acting on the active power produced by the whole system inverters. A study in Ref. [12] has developed a hierarchical method that enables photovoltaic power inverters to adjust its active power outputs in order to ensure the frequency regulation service to power systems without association of energy storage systems. In Ref. [13] authors were interested in the harmonic compensation service. They have proposed a harmonic impedance synthesis method based on band-pass filter and resonant integrators for voltage-controlled RDG interfacing converters to ensure harmonic voltage damping on the distribution network. For the same objective, the idea of using photovoltaic inverters as virtual harmonic resistances to perform residential system harmonics damping is investigated in Ref. [14]. Similarly, a strategy based on integer-order and fractional-order controllers for WT (wind turbine) system with different power converter topologies to compensate the harmonic current injected into the electrical network is explored in Ref. [15]. All these methods have proposed good solutions to ensure power electrical system quality using MG based on RDG. However, each of them focuses on a specific objective task and they don't take into account various problems in power systems.

In this paper, a multi-objective control strategy for connection of an MG including RDG resources to the main grid to participate in the system services and to ensure power electrical system quality improvement is proposed. Compared to present compensation techniques, the proposed MG control technique favors application of different types of renewable energy resources, e.g., WF (wind farm) generation and photovoltaic panels, to solve various problems in the electrical network. In fact, the main contribution of this control is to monitor the MG in six operation modes in order to make it able to ensure, simultaneously, at the PCC (point of common coupling) the harmonic current damping, the reactive power compensation, the load active power and the grid frequency regulation.

The description and the modeling of the studied MG are developed in Section 2. In Section 3, the control strategy applied to the studied MG was described. An “NL loads currents identification system” based on the instantaneous powers theory is implemented to calculate the reference currents involved in each RDG inverter control to ensure harmonic and reactive power compensation. Then, an “active power transfer and frequency control algorithm” is proposed to supervise the NL loads fundamental active power, to control the fundamental active power transfer between the MG and the main grid and to provide the grid frequency service. The simulation results and the conclusion of this paper are given in Section 4 and Section 5, respectively.

2. System description and modeling

The system under analysis is composed of an electrical network and an MG including RDG and NL loads. The type of RDG may be AC sources like WT generators which may be connected to DC bus through AC/DC converters, or DC power sources like photovoltaic panels with their DC/DC converters. In any case, the power electronics converters (DC/DC or AC/DC) are employed to maximize the generated power from renewable sources and the DC/AC converters are focused to improve the AC grid power quality.

In this work, the RDG source is considered as a WF (wind farm) (WF) power generation as it is sketched in Fig. 1. This WF is made up of \( n_{T} \) VSWT (variable speed wind turbines). Each one includes two power electronic converters AC/DC and DC/AC. The first converter is used to regulate the DC bus voltage and to extract the maximum power from the renewable energy source and the second is needed for loads supplying and system services participating. The considered NL loads are full-wave thyristor converters which supply RL loads, and these NL loads draw harmonic currents from the main grid. The grid is modeled as generation station based on synchronous machine, transmission lines operating at different voltage levels and variable loads.

The functioning of this studied system is as follows. The required compensating harmonic and reactive currents are obtained by measuring the NL loads currents and passing them through the “NL loads currents identification system” to remove the fundamental frequency component. After corrective currents have been calculated, the reference compensating currents can be generated for each WT inverter command to cancel harmonic and reactive powers at the PCC point. The fundamental active power supplied to the NL loads is usually ensured from the WF. In fact, in case of wind availability, the WF which operates in the MPPT (maximum power point tracking) supplies the fundamental active power demanded by NL loads and the excess will be injected into the grid. But in case of WF lack of generation, it generates the maximum fundamental active power demanded by NL loads and the lack will be absorbed from the grid. Considering the intermittent and fluctuating behavior of wind energy and load demands, the fundamental active power exchanged between grid and WF should be assured according to well-defined standards without disturbing the grid stability and more specifically the grid frequency stability. For that, the “active power transfer and frequency control algorithm” shown in Fig. 1 is proposed. This algorithm provides as output the various operating modes of the studied WF. These modes will be integrated into the voltage-source inverter control of each WT to monitor the powers exchange at the PCC point making the grid frequency in an allowable range of stability.

2.1. WF mechanical model

In this paper, the studied WF is composed of similar WT units with a short distance between them. The wind speeds profiles applied to these units are near. In order to reduce the computation time and increase the simulation speed when simulating WF with large number of identical WT units on power system, the WF can be represented by an aggregate model that consists of one equivalent WT [16,17]. This equivalent WT receives as input the mean value of winds applied to the group of WT units as follows [18]:

\[
V_m = \frac{\sum_{i=1}^{n_{T}} V_i}{n_{T}}
\]

Such equivalent WT presents as output a rated power equal to \( n_{T} \) times the rated power of individual WT unit [18]:

\[
P_{\text{mec}} = \frac{n_{T}}{2} \rho S V_m^3 C_p
\]

2.2. Electrical network model

Currently, the majority of the electrical energy is produced by SG (synchronous generators) power stations [19]. The synchronous machine is an electromechanical converter which, from the mechanical energy supplied by a motor, injects into the grid electrical energy in three-phase forms. The studied synchronous machine was modeled in this paper in d-q frame axes as the following equations [20]:

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\[ \frac{d\phi_d}{dt} = T_e - T_m \] (4)

The electromagnetic torque \( T_e \) is given by:

\[ T_e = \frac{3}{2} n_p (\phi_d i_q - \phi_q i_d) \] (5)

with \( \phi_d \) and \( \phi_q \) are the direct and transverse stator. The following relationships can be written [21]:

\[ \begin{bmatrix} V_d \\ V_q \\ V_f \\ 0 \\
0 \end{bmatrix} = \begin{bmatrix} -r_s & l_q l_{6qep} & 0 & 0 & -M_{D6qep} \\
l_{4qep} & -r_s & M_{D6qep} & 0 & 0 \\
0 & 0 & r_f & 0 & 0 \\
0 & 0 & 0 & r_D & 0 \\
0 & 0 & 0 & 0 & r_Q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{bmatrix} + \begin{bmatrix} -l_q & 0 & M_{4qep} & M_{D4qep} & 0 \\
0 & -l_q & 0 & 0 & M_{4qep} \\
-M_{f} & 0 & l_f & 0 & M_{D4qep} \\
0 & -M_{f} & 0 & M_{D4qep} & 0 \\
0 & 0 & 0 & M_{f} & 0 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \\ i_f \\ i_D \\ i_Q \end{bmatrix} \] (3)

2.3. NL loads model

Modeling and characterization of harmonic sources are important steps in THD and harmonics studies. Different NL loads are modeled as a harmonic current source in parallel with the fundamental component as follows [22]:

\[ I_{NL} = \sum_{h} I_h \sin(h \omega t + \phi_h) \] (7)

The harmonic currents created by balanced NL loads typically have orders of \( h = -5, 7, -11, 13 \ldots \) with \( h = 1 \) corresponding to the fundamental frequency.

3. Grid control and ancillary services

In this work, the RDG system based on WF distributed generation is introduced to the grid in order to ensure the following services:

- Compensation of NL loads harmonic currents,
- Compensation of loads reactive power,
- Capture of maximum energy from wind to provide active power,
- Grid frequency regulation to make it at an allowable range of stability.

3.1. NL loads currents identification system

As shown in the lower part of Fig. 1, the harmonic and reactive compensation is ensured through proper control of each WT interface converter. In fact, these inverters are controlled to inject at PCC, equal but opposite harmonic component of NL loads in addition to the reactive component current to cancel the original harmonic distortion and to eliminate the reactive power flow to the grid that are responsible for power network pollution.
For each WT inverter reference currents computation, the “NL loads currents identification system” presented in Fig. 2 is employed. The operation of this block system is based on the instantaneous powers theory which has the advantage of selecting the disturbance compensation with precision, rapidity and ease of implementation [23]. In fact, as it can be seen in Fig. 2, the source voltages at PCC \( V_{1,d}, V_{1,q} \) and the NL loads currents \( I_{NL,d}, I_{NL,q} \) data are extracted by this block system on the d-q reference frame.

The conventional instantaneous active and reactive powers \( P_{NL}, Q_{NL} \) absorbed by the NL loads are written in matrix form as shown in this relation.

\[
\begin{bmatrix}
P_{NL} \\
Q_{NL}
\end{bmatrix} = \begin{bmatrix}
V_{1,d} & V_{1,q} \\
V_{1,q} & -V_{1,d}
\end{bmatrix} \begin{bmatrix}
I_{NL,d} \\
I_{NL,q}
\end{bmatrix}
\] (8)

Each of \( P_{NL} \) and \( Q_{NL} \) powers can be split into continuous (DC) and alternative (AC) components as illustrated below:

\[
P_{NL} = P + \tilde{P}
\]
\[
Q_{NL} = Q + \tilde{Q}
\] (9)

where: \( P \) and \( Q \) are the active and reactive DC powers related to the fundamental frequency of the NL loads current and voltage. \( \tilde{P} \) and \( \tilde{Q} \) are the active and reactive AC powers related to the harmonic components of the NL loads current and voltage.

The objective of the “NL loads currents identification system” is to separate alternative and constant components. For this purpose, 2 s-order low pass filters are used. Second-order filters are more employed than other filters because they provide good performance and can filter the oscillations properly [24,25]. So the AC power components \( \tilde{P}, \tilde{Q} \) can be obtained simply as shown in Fig. 2 by the difference between the input signal and the filtered one.

Considering Equation (9), the NL loads currents in the d-q reference frame can be divided into four components: active current at the fundamental frequency \( I_{NL,d,0} \), reactive current at the fundamental frequency \( I_{NL,q,0} \), active harmonic current \( I_{NL,d,h} \) and reactive harmonic current \( I_{NL,q,h} \). So we can write in matrix form:

\[
\begin{bmatrix}
I_{NL,d} \\
I_{NL,q}
\end{bmatrix} = \frac{1}{V^2} \begin{bmatrix}
V_{1,d} & V_{1,q} \\
V_{1,q} & -V_{1,d}
\end{bmatrix} \begin{bmatrix}
P \\
Q
\end{bmatrix} + \frac{1}{\sqrt{2}} \begin{bmatrix}
V_{1,d} & V_{1,q} \\
V_{1,q} & -V_{1,d}
\end{bmatrix} \begin{bmatrix}
\tilde{P} \\
\tilde{Q}
\end{bmatrix}
\]

with \( V^2 = V_d^2 + V_q^2 \)

After NL loads currents identification at d and q-axis, to use the studied WF as an active power filter, harmonic and reactive components of NL loads currents should be shared and supplied by the inverters of the WT power generations. For this purpose, as shown in the lower part of Fig. 1, it is sufficient to set d and q-components of reference currents involved in each WT inverter control to ensure harmonic and reactive compensation \( I_{comp,d}, I_{comp,q} \) equal to the alternative d and q-components \( I_{NL,d,0}, I_{NL,q,0} \) and to the DC q-component \( I_{NL,q,0} \) of the NL loads currents divided by the number of wind power inverters as follows:

\[
I_{comp,d} = \frac{I_{NL,d,0}}{n_T}
\]
\[
I_{comp,q} = \frac{I_{NL,q,0} + I_{NL,q,h}}{n_T}
\] (11)

In this paper, the studied WF is used not only as an active power filter to compensate harmonic and reactive power, but also, to capture the maximum of energy from the wind in order to provide the total or a portion of NL loads fundamental active power. The excess or lack of fundamental active power generated by the WF will be injected or absorbed into or from the grid, respectively. However, the uncontrollable exchange of active power between WF and electrical power system may disrupt the stability of electrical network frequency [6,26]. In fact, it can create derivation which can exceed the normalized frequency variations mentioned in standards. Therefore, in order to ensure an active power transfer with the electrical power system and to make the grid frequency within an allowable range of stability, the “active power transfer and frequency control” algorithm is proposed in this work.

3.2. Active power transfer and frequency control algorithm

The consequence of a mismatch between the grid supply (generation) and demand (load and network losses) for active power is a change in the rotational energy stored in the rotating mass of the synchronous electricity generators, and hence, a drift in the system frequency. As shown in the top part of Fig. 3, the change of the demanded power \( P_{D,req} \) to that of the frequency \( f' \) is as follows: A surplus in demand creates a frequency decrease, and a lack in demand leads to an increase in the frequency. Because when there are more loads, it becomes harder to turn the generators at the nominal frequency and vice versa [27]. All the generating equipment in an electric system is designed to operate within very strict frequency margins. Grid codes specify that all generating plants should be able to operate continuously between a frequency range around the nominal frequency of the grid, usually between 49.5 Hz and 50.5 Hz in Europe [28]. Operation outside these limits would damage the generating plants, so even very short duration deviations from the nominal frequency values would trip load shedding relays and generation capacity would be lost. Maintaining the frequency at its target value requires that the active power produced and/or consumed be controlled to keep the
Fig. 3. Description of different selected modes by the “active power transfer and frequency control algorithm”.

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loads and grid generation in equilibrium [29]. This equilibrium must be preserved in the face of fluctuations in loads and uncontrolled generations. Recently, there has been motivation for RDG to provide grid frequency regulation service by controlling its real power output in order to assist in balancing total power generated on the grid with total power consumed [30,31]. In this paper, the studied WF also focuses on frequency regulation for the utility grid. It measures simultaneously the frequency of the utility \( f \) and the fundamental active power \( \Delta P \) to be transferred between it and the grid. This power is calculated by subtracting the fundamental active power demanded by NL loads \( P_{NL-f} \) from the maximum fundamental active power \( P_{WF-MPPT} \) generated by the WF. And it is considered as excess or lack of the studied WF active power generation that will be injected or absorbed into or from the grid respectively. The exchange of \( \Delta P \) between grid and WF should be assured according to well-defined standards without disturbing the grid stability and to keep the frequency in the standards range. For that, the studied WF can operate, according to the transfer power \( \Delta P \) and the frequency variations \( \Delta f \) in six operating modes. To monitor the different operating modes of the studied WF, the “active power transfer and frequency control algorithm” presented in Fig. 4 is proposed. This algorithm ensures the following roles:

- Supervision of NL loads fundamental active power.

The operation of this algorithm is well described in Fig. 3 and Fig. 4. Indeed, at each instant, the sign of \( \Delta P \) (positive or negative)

**Fig. 4. Active power transfer and frequency control algorithm.**
and the frequency variation $|\Delta f|$ (included or excluded from the desired margin) are detected simultaneously. It is noticed that $|\Delta P_{49.8}|$ and $|\Delta P_{50.2}|$ are fundamental active powers corresponding to the 49.8 Hz and 50.2 Hz frequency, respectively. In fact, when these powers are injected or absorbed into or from the grid, we will get the limits of the desired frequency range. These powers are calculated as shown in these relations:

\[
|\Delta P_{49.8}| = |P_{D_{PCC}} - P_{D_{max}}| \\
|\Delta P_{50.2}| = |P_{D_{PCC}} - P_{D_{min}}|
\]  

(12)

This algorithm works as below:

When $|\Delta P|>0$, meaning that there is an excess of WF fundamental active power production and $|\Delta f| \leq 0.2$ Hz meaning that the frequency variation is included in the desired area. In this case, $|\Delta P|$ should be injected into the grid. The injection of active power into the electrical network causes a reduction of demanded power $P_{D_{PCC}}$ and hence an increase of frequency [27,32]. The problem here is when injecting $|\Delta P|$ into the grid, the frequency can be increased without leaving its desired margin $f \leq 50.2$ Hz as it can exceed it $f > 50.2$ Hz. For this, it is necessary to compare the power $|\Delta P|$ injected into the grid with the power $|\Delta P_{50.2}|$ corresponding to the 50.2 Hz. When $|\Delta P| \leq |\Delta P_{50.2}|$, the WF can inject $|\Delta P|$ into the grid without excluding the frequency from its required margins. This is the first case of mode 2 (mode 2.1). Otherwise, when $|\Delta P| > |\Delta P_{50.2}|$, the WF will operate without MPPT mode. It will supply the NL loads and it will inject into the network another fundamental active power $|\Delta P| < |\Delta P|$ with $|\Delta P| = |\Delta P_{50.2}|$. In this situation, the utility frequency never leaves the optimal margins (the frequency will be equal to 50.2 Hz). This is the first case of mode 3 (mode 3.1).

When $|\Delta P|>0$ and $|\Delta f|>0.2$ and $|\Delta f|>0$, meaning that there is an excess of WF power generation with the case of under frequency 49.5 Hz $< f < 49.8$ Hz. In this condition, the injection of $|\Delta P|$ into the grid will increase the frequency. Three levels of increasing frequency can be sensed according to $|\Delta f|$ states: When $|\Delta P| < |\Delta P_{49.8}|$, the WF injects $|\Delta P|$ into the network and the frequency rises, but it does not achieve its optimal range. This is the second case of mode 2 (mode 2.2) that allows the injection of power with partial frequency regulation. When $|\Delta P_{49.8}| < |\Delta P| < |\Delta P_{50.2}|$, the WF will inject $|\Delta P|$ into the grid, but in this situation, the frequency will achieve its optimal margin 49.8 Hz $< f < 50.2$ Hz. This is the third case of mode 2 (mode 2.3) where we will get a total frequency regulation. When $|\Delta P| > |\Delta P_{50.2}|$, the WF will operate without MPPT. It will meet the demands of NL loads and will inject into the network $|\Delta P| < |\Delta P|$ for the grid frequency does not exceed 50.2 Hz. This is the second case of mode 3 (mode 3.2).

Now, when $|\Delta P|>0$ and $|\Delta f|>0.2$ and $|\Delta f|<0$ meaning there is an excess of production with the case of over frequency 50.2 Hz $< f < 50.5$ Hz. Under this condition, the injection of $|\Delta P|$ into the grid increases the frequency more, which can lead to adverse damages in the electrical power and the electrical equipment stabilities. This is mode 5, in which the WF stops feeding power to the grid. It operates without MPPT to satisfy only the NL loads demands.

Now treating the case of WF lack of generation under different states of frequency variation $|\Delta f|$:

When $|\Delta P| \leq 0$ and the frequency variation is in its optimal margins $|\Delta f| \leq 0.2$ Hz, the power $|\Delta P|$ should be absorbed from the network to meet the fundamental active power required by NL loads. The absorption of active power from the electrical network causes an increase in power required $P_{D_{PCC}}$ and hence a drop in grid frequency $f$ [27,32]. Therefore, it is necessary to compare the absorbed power $|\Delta P|$ with $|\Delta P_{49.8}|$. Because unsupervised absorption of $|\Delta P|$ from the network may drop the frequency without leaving its desired margin $f \geq 49.8$ Hz is the first case of mode 1 (mode 1.1), as it can exceed it $f < 49.8$ Hz on the first case of mode 4.

### Table 1

<table>
<thead>
<tr>
<th>Wind turbine</th>
<th>Number of blades</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>blade radius</td>
<td>41 m</td>
</tr>
<tr>
<td></td>
<td>$\rho$</td>
<td>1.225 kg/m$^3$</td>
</tr>
<tr>
<td>PMSG</td>
<td>Nominal power</td>
<td>2 MW</td>
</tr>
<tr>
<td></td>
<td>$L_s$</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>$\phi_m$</td>
<td>1.285 mF</td>
</tr>
<tr>
<td></td>
<td>$C_{bus}$</td>
<td>4813 mF</td>
</tr>
<tr>
<td>DC bus</td>
<td></td>
<td>2200 µF</td>
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</tbody>
</table>

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In this last mode, the minor priority NL loads will be disconnected in order to alleviate the demands on the network. Consequently, the absorbed power from the grid becomes
\[ P_{\text{absorbed}} = \frac{P_0}{C_{12}} \]
and the grid frequency never leaves its optimal margins (the frequency will be equal to 49.8 Hz).

When \(|\Delta P| \leq 0\) and \(|\Delta f| > 0.2\) and \(|\Delta f| < 0\), meaning that there is a lack of WF power generation and a rise in grid frequency \(50.2\) Hz, the absorption of \(|\Delta P|\) from the grid will decrease the frequency that can reach 3 levels according to \(|\Delta P|\) statements indeed: When \(|\Delta P| < |\Delta P_{50.2}|\) the frequency decreases but does not reach 50.2 Hz. This is the second case of mode 1 (mode 1.2), which allows NL loads to absorb \(|\Delta P|\) from the network with partial frequency regulation. When \(|\Delta P_{49.8}| \leq |\Delta P| \leq |\Delta P_{50.2}|\) in this situation the frequency decreases and reaches its optimal margins \([49.8, 50.2]\) Hz, it is the third case of mode 1 (mode 1.3). The third level is attained when \(|\Delta P| > |\Delta P_{49.8}|\). This is the second case of mode 4 (mode 4.2) which allows disconnection of the minor priority NL loads for the frequency drop does not exceed 49.8 Hz.

Now, when \(|\Delta P| < 0\) and \(|\Delta f| > 0.2\) and \(|\Delta f| > 0\) meaning that there is a lack of WF power generation with the case of under frequency \(49.5 < f < 49.8\) Hz, the absorption of \(|\Delta P|\) from the network will further reduce the frequency level which can disrupt the grid and the electrical equipments stabilities. This is mode 6, which disconnects the minor priority NL loads until the cancellation of the lack and consequently the absorption of fundamental active power from the network is shut down.

### 3.3. Wind turbine control side

As shown in Fig. 1, each WT is controlled by its own control block. The control strategy used in each WT is divided into 2 parts. The first one illustrates the “DC/AC converter control” and the second represents the “DC Bus and AC/DC converter control” as shown in Fig. 5 and Fig. 6, respectively.

The objective of “AC/DC converter control” is to get each WT to give harmonic and reactive power compensation. In addition, each WT must deliver an appropriate fundamental active power \(P_{\text{ref}}\), MPPT or without MPPT according to the selective operating mode, to meet NL loads fundamental active power and to participate in system services. In fact, the WT reference currents applied on each WT DC/AC converter on d-q reference frame \(i_{\text{ref, WT}}\) is

\[ i_{\text{ref, WT}} = \begin{bmatrix} I_{\text{ref, WT}} \end{bmatrix} \]

![Fig. 8. Electrical network state after NL loads and before WF integration: Demanded power in PCC (a) - Grid frequency (b) and grid currents (c).](image)

![Fig. 9. NL loads active and reactive powers.](image)

![Fig. 10. NL active and reactive load powers identification.](image)
deduced by adding the compensating reference currents \( I_{\text{comp_ref}} \) calculated by the "NL Loads currents identification system" to the fundamental WT reference currents \( I_{\text{WT_ref}} \) corresponding to the WF operating mode that is selected by the "active power transfer and frequency control algorithm". Then, the reference currents are expressed in a-b-c reference frame through the inverse Park transformation. These currents are compared with the injected inverter currents \( I_{\text{WT}} \) using PI control loops. The differences between both currents are then compared to a triangular PWM signal to provide the control command of WT voltage source inverter switches.

Fig. 6 illustrates the control applied to the "DC Bus and AC/DC converter control". The role of this control is to regulate the DC bus voltage \( U_{\text{Bus}} \) at a fixed value and to extract the necessary power to supply NL loads and to participate in system services. The principle of this control is based on the vector control applied to permanent magnet synchronous generator (PMSG), which consists in imposing a reference direct current \( I_{\text{sd_ref}} \) equal to zero. This allows the electromagnetic torque to behave in a similar way as in the quadratic component of the stator current \( I_{\text{sq_ref}} \) so:

\[
I_{\text{sq_ref}} = \frac{T_{\text{em_ref}}}{\rho_{\text{m}}} \tag{13}
\]

The adjustment of the DC bus voltage is assured by applying a reference torque \( T_{\text{em_ref}} \) at the terminal of PMSG equivalent to the required torques needed to supply NL loads and to participate in system services. In fact, the "DC Bus and AC/DC converter control" system receives instantaneous information about the required modulated current \( I_{\text{sq_ref}} \). The imposed reference torque on WT control generator is obtained by dividing the required WT power \( P_{\text{WT}} \) by the rotor mechanical speed \( \Omega_{\text{m}} \) of the WT PMSG. In such situations the wind generator debits only a torque similar to the asked torque \( T_{\text{em_ref}} \) to ensure the balance between production and consumption and hence a continued voltage at DC bus.

4. Simulation results

In order to evaluate the performance of the proposed approach, a model of the AC grid, NL loads and WF generators have been performed. The simulated WF is made up of fifteen WT generators \( n_{\text{T}} = 15 \) of a 2 MW variable-speed PMSG, with a total installed capacity of 30 MW. The parameters of the proposed control strategy used in the simulation conditions are provided in Table 1. The following subsections present the process of simulation before and after integration of the variable NL loads and the studied multi-objective WF in the electrical power system.

4.1. Initial electrical network state

Initially, neither the NL loads nor the studied WF is connected to the network. In fact, the electrical network is considered just to feed the constant and the variable balanced linear loads presented in Fig. 1. In normal and stable conditions, the network produces 215 MW in order to supply the demands; in this case, the frequency is equal to 50 Hz. But, variations in active power required by the loads generate an electrical network over or under production and therefore frequency levels variations. Indeed, if the demands are greater than the stable network generation (215 MW in this paper), a drop in frequency will be obtained and vice versa. Fig. 7 describes the network state before NL loads and studied WF integration. According to Fig. 7a and b, the impact of the active power demand...
\(P_{D-PCC}\) variations in PCC point at the network frequency is remarkable. During the intervals \([0, 55\, s]\) and \([300, 350\, s]\) the frequency is equal to 50 Hz because there is equilibrium between production and consumption \(P_{D-PCC} = 215\, MW\). In \([55, 175\, s]\) the demand is less than the production, which will lead to an increase in frequency. Whereas, during \([175, 300\, s]\) demand exceeds production and hence we will get a frequency drop. It is also notable as shown in Fig. 7a and Fig. 7b, that when an instantaneous active power demand \(P_{D-PCC}\) variation is carried, the frequency needs a period of time to change from a level to another. This period depends on the amplitude of \(P_{D-PCC}\) variations. In fact, as shown in Fig. 7b, active power demand \(P_{D-PCC}\) variation at \(t_1 = 119\, s\) is more important than at \(t_2 = 300\, s\) for that, \(\Delta t_1 > \Delta t_2\). Fig. 7c represents the requested network currents in PCC point. It is noticeable that these required currents are well sinusoidal, but they present variations due to loads power changes in PCC point.

4.2. Electrical network state after NL loads connection and before WF integration

In this section, NL loads were connected and supplied by the studied electrical power system. So the power required from the network \(P_{D-PCC}\) becomes as presented in Fig. 8a. It is noticeable that these NL loads have negative influences on the grid quality and stability. They disrupt the network frequency on the one hand. In fact, as discussed in Fig. 8b, frequency exceeds its normalized margins \([49.5, 50.5\, Hz]\). And they pollute the utility currents (THD very strong) as mentioned in Fig. 8c on the other hand which can cause several power quality problems such as malfunction protection systems, reduction in equipment lifetime and additional losses in power systems. For this, in the next section, a multi-objective WF will be integrated in the electrical network to address these issues.

4.3. Electrical network state after NL loads connection and WF integration

In this paper, the studied WF is added for the following objectives:

- To compensate NL loads harmonic power,
- To compensate NL loads reactive power,
- To provide active power,
- To make the grid frequency in an allowable range of stability.

To validate the capabilities of the proposed control strategy applied on the multi-objective WF, we began by simulating the behavior of the NL loads. In fact, Fig. 9a and Fig. 9b illustrate the active and the reactive powers demanded by the NL loads, respectively. Using “NL Loads currents identification system” block, these powers are composed of two components as shown in Fig. 10. The curves in red illustrate the continuous active and reactive powers components related to the fundamental NL loads current and voltage and the curves in blue represent the alternative active and reactive powers component related to the sum of the NL loads currents and voltages disturbances.

After power identification, the compensating reference currents that will be shared among different WT inverters is determined by adding the NL loads harmonic currents presented in Fig. 11c with NL loads fundamental reactive currents presented in Fig. 11b. The NL loads fundamental active currents presented in Fig. 11a will be usually supplied by the WF. But in case of generation lack, the WF satisfies the maximum of NL loads fundamental active currents and the lack will be absorbed from the grid.

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The excess or lack of WF fundamental active power $\Delta P$ is controlled and supervised by the "active power transfer and frequency control algorithm" to be injected or absorbed into or from the grid, respectively, without disturbing the grid frequency and to make it the most possible in the optimum range of stability [49.8, 50.2 Hz]. This algorithm receives as input the grid frequency states shown in Fig. 12b, and the power $\Delta P$ that will be exchanged between the WF and the grid as shown in Fig. 12c. This power depends mainly on the NL loads fundamental active power $P_{NL,f}$ shown in Fig. 11a and on the maximum WF active power $P_{WF,MPPT}$ generated according to the average applied wind speed presented in Fig. 12a.

The operation of this algorithm is well explained in Section 3.2. Indeed, at every moment, it senses on the one hand the frequency status (included or excluded from [49.8, 50.2 Hz]) and it compares on the other the power exchanged $\Delta P$ with the powers limits $\Delta P_{50.2}$ and $\Delta P_{49.8}$ which are shown in Fig. 12c. Then, it presents as an output the various operating modes of the studied WF. These modes will be integrated into each WT inverter control to monitor the powers exchange at the PCC point without disturbing the grid frequency. Fig. 13 shows the transitions between the six modes during the whole sequence. Some modes of operation are obtained from different cases. For example mode 1 will be activated when one of these cases: mode 1.1 or mode 1.2 or mode 1.3 is selected. It is noticed that only one case and only one mode is active at each moment.

From Fig. 14a, it is observable that both power $\Delta P$ before and after regulations are equal in mode 1 and mode 2 for two reasons: because injection or absorption of $\Delta P$ does not exceed the frequency from its optimal margin, or else, because the transfer of $\Delta P$ regulates the frequency level to be close to its desired margin (mode 1.2 and mode 2.2). However, in specific modes, the powers transferred $\Delta P$ before and after regulation are not the same. In fact, $\Delta P$ after regulation is equal to zero in both modes 5 and 6, and hence, no change will be accrued in the frequency. Because, when both $\Delta P$ before and after regulation are equal in these modes, the frequency can submit strange derivations of maximum levels [49.5, 50.5 Hz] which can damage the electrical equipment and the personnel. Moreover, $\Delta P$ after regulation is equal to one of these limitations powers $\Delta P_{49.8}$ or $\Delta P_{50.2}$ in modes 3 or 4, respectively because the injection or the absorption of $\Delta P$ before regulation exceeds the grid frequency from its desired margin [49.8, 50.2 Hz]. But, $\Delta P$ after regulation limits the frequency variability to 49.8 Hz or 50.2 Hz.
Fig. 7b, Fig. 8b and Fig. 14b show respectively the grid frequency in these different situations: Before NL loads and WF integration, after NL loads connection and before WF integration, and finally, after NL loads and WF integration. It is observable that in the first situation the frequency exceeds its desired margin during long periods of time. Moreover, in the second situation the frequency variation becomes more important and harmful which can damage the electrical equipment and the personnel. But in the last situation, the frequency variations are well minimized which proves the effectiveness of this control strategy.

Fig. 15 illustrates the behaviors of the grid and the WF conversion chain after application of the proposed control strategy. Fig. 16, Fig. 17 and Fig. 18 are zooms of Fig. 15 under the respective following cases: In case of WF excess of generation, in case of WF lack of generation and in case of the transition between them. According to these figures, it is observable that the grid currents are well sinusoidal without any disturbance which proves the capability of the studied WF to ensure its objectives successfully.

Fig. 19 shows the performance of the studied WF to compensate reactive power. In fact, as depicted in this figure, the grid voltage and the current injected into the grid at PCC, in case of WF excess of generation, are perfectly on phase. But in case of WF lack of generation, the grid voltage and the current absorbed from the grid at PCC are perfectly opposite. To evaluate the capabilities of studied WF to compensate harmonic currents, the spectra of currents before and after connection of WF are shown in Fig. 20. Fig. 20a shows that the THD after connection of the variable NL loads to the distribution network is 62.45%. Fig. 20b shows that the THD of grid currents after connection of the studied WF is drastically decreased to 2.81% which demonstrates capabilities of the proposed system to compensate loads harmonic currents with presented control strategy.

5. Conclusion

A multi-objective control strategy for the integration of RDG system to the distribution grid to eliminate the harmonic distortion, to ensure the reactive power compensation and to provide active power in addition to the grid frequency service has been proposed in this paper. This control has two main structures. The first one is the “NL Loads currents identification system” which is used to calculate the reference currents applied for each renewable source inverter control to ensure harmonic and reactive power damping. The second one is the “active power transfer and frequency control algorithm” which is implemented to control the fundamental active power exchange between the RDG and the electrical power system and to provide the grid frequency service. The proposed method in different operation modes of the studied RDG has been tested through simulation results. The obtained results proves that the electrical network does not need to generate harmonic and reactive currents for NL loads. Similarly, the utility frequency variation is well minimized into desired range of stability. This shows that the studied RDG can be considered simultaneously as active power filters, reactive power corrector devices, active power generator and frequency regulator.

References


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