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Frequency Participation by Using Virtual Inertia in Wind Turbines Including Energy Storage

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Abstract—With the increase of wind generation penetration, power fluctuations and weak inertia may attempt to the power system frequency stability. In this paper, in order to solve this problem, a hierarchical control strategy is proposed for permanent magnet synchronous generator (PMSG) based wind turbine (WT) and battery unit (BU). A central controller forecasts wind speed and determines system operation states to be sent to the local controllers. These local controllers include MPPT, virtual inertia, and pitch control for the WT; and power control loops for the BU. The proposed approach achieve at the same time both output power smoothing and frequency participation. Simulation results confirm the effectiveness of the proposed control strategy in different scenarios.

Keywords—Wind power, virtual inertia control, frequency regulation, microgrids, automatic generation control (AGC)

I. INTRODUCTION

The penetration of the wind power installed is increasing worldwide, however impacting seriously the grid performances [1]-[4]. Wind power fluctuations may result in frequency instabilities, especially in weak-grid situations. Recently, more permanent magnet synchronous generator (PMSG) based wind turbines (WT) are becoming more popular in wind farms due to the higher performances required in new grid code. In contrast to the conventional synchronous generators, PMSG, because of the use of back-to-back converters, disturbances in the wind generator little affect the main grid. However, the WT rotor speed is decoupled from the grid frequency, which may result in a lack of inertia, i.e. frequency changes will not produce power variations, as it is desired in a power system [5]-[6].

Further, placing energy storage systems in wind power systems can effectively smooth wind power fluctuations, and can improve the output controllability of the wind power generation, which has great significance to the frequency regulation [7]-[8]. Relevant research has been done on wind generation frequency regulation [9]-[10]. In order to make WTs to participate in frequency regulation, we can use power reserve and rotor inertia controllers. A method to do that consist on reserving some amount of power, so that the power generation is out from the optimal value. Another way to achieve it is to reduce the output active power by using pitch control, thus when the frequency drops, reserved power may be used to support the system frequency. However, the abovementioned methods are at the expenses of reducing wind power efficiency.

Alternatively, rotor inertia control can be also used providing a short time power support for DFIG-based WTs [9]. In [10], frequency-rotor speed coordinated control strategy is adopted to reduce sudden WT torque changes, and to adjust rotor speed when the frequency changes. However, in [11] was pointed out that rotor speed recovery may cause the secondary frequency drop down.

To solve this problem, in [12] by introducing energy storage may help wind power systems in frequency regulation. In this work, a flywheel is used in combination with a DFIG for these purposes. In [13], BU is connected to the ac bus of the stationary synchronous compensator, while in [14] a super capacitor is be connected to the dc bus of PMSG wind power generator. Although the abovementioned methods may be used to make wind power participating in frequency regulation, they present complex implementation and control.

In order to solve wind power and frequency fluctuations, this paper uses a method to calculate the expected interchanged power flow of the wind power system tie-line, according to the predicted wind speed inside a determined time period. The designed WT-BU structure connects the BU to the ac part through an inverter. A power-frequency loop is added PMSG side converter, so that the system inertia is effectively increased. When the system frequency exceeds specified range, the wind power generation system ensures the MPPT performances, while the WT-BU
active power output is rapidly changed according to the automatic generation control (AGC) instructions. A hierarchical control structure is presented to implement those functionalities. Simulation results and analysis are given showing the performances of the proposed approach.
Fig. 1. Structure of WT-BU system.

II. HYBRID STRUCTURE OF WT-BU SYSTEM

Fig. 1 shows the hybrid WT-BU system, including the power stage and the control architecture. In this case the BU is connected to the AC side to facilitate the retrofitting. Note that adding batteries in the DC side may be more effective, but in practice it may not be suitable since it may require cooperation between WT and BU producers companies, which may not be easy in many cases. Since in our case, the hardware control between the WT and the energy storage system is completely decoupled from each other, it is more feasible in practice.

Regarding the controllers, the easiest way is to have WT-BU locally controlled and to add a central controller that can be placed in a SCADA system that may control the hybrid power system. The central controller includes wind forecasting, power calculations, system operation mode selections, battery charge/discharge management, and the real-time grid frequency detection.

Through the coordinated control of WT-BU, when the frequency of the system is nominal, the power supplies smoothed power to the main grid. Furthermore, when the frequency of the system is outside the normal range, the WT-BU power system participates in the frequency regulation.

III. FREQUENCY PARTICIPATION

A. Kinetic Energy of the Wind Turbine

The kinetic energy stored in the rotor blade of a WT can be expressed as:

$$E = \frac{1}{2} J \omega^2$$  \hspace{1cm} (1)

where $J$ is the inertia of the wind turbine and its generator and $\omega$ is the rotor speed. When the rotor speed is ranged from $\omega_0$ to $\omega_1$, the difference of the kinetic energy of the wind turbine is:

$$\Delta E = \frac{1}{2} J \omega_0^2 - \frac{1}{2} J \omega_1^2$$  \hspace{1cm} (2)

From (2), we can conclude that the wind power system has a certain rotational kinetic energy. Conventional variable-speed WT, in order to achieve maximum wind energy capture, uses back-to-back converters in order to decouple rotor speed and grid frequency. Therefore, a frequency-dependent power command $P_f$ can be imposed on the active power reference value of the rotor side converter controller.

Hence when the system frequency is nominal, $P_f$ will be zero, otherwise $P_f$ will change accordingly. This way, the kinetic energy stored in the wind power system can be converted into electrical energy in order to support the grid frequency.
B. Battery participation in power grid frequency regulation

The proposed WT-BU hybrid power system is able to follow AGC power scheduling $P_{AGC}$ to restore the grid frequency, see Fig. 2. For instance, when the grid frequency is out from the nominal range, the WT-BU hybrid system will react according to the AGC scheduling instructions in order to quickly change its active power output thus achieving frequency restoration. The system reacts according to the following strategy to control the frequency. If the grid frequency is high, BU is charging, thus reducing the output power of the tie-line. Otherwise, if the grid frequency is low, BU is discharging, thus increasing the output power of the tie-line.

\[
P^* = \begin{cases} 
  P_L - P_G, & \text{if } f > f_{nom} \\
  f_{nom}, & \text{if } f = f_{nom} \\
  P_L - P_G, & \text{if } f < f_{nom}
\end{cases}
\]

Fig. 2. Block diagram of the automatic generation control (AGC).

IV. CENTRAL CONTROLLER

The central controller takes care of the BU management and the different operation modes of the WT-BU power system.

A. Output power reference of BU inverter

The wind energy generated $W_w$ during the scheduling period $T$ can be expressed as follows:

\[
W_w = \int_0^T p_w dt
\]

being $P_w$ the forecast wind power generation.

Thus, during this scheduling period $T$, the average wind power, $P_L$, takes the form:

\[
P_L = \frac{w_c}{T}
\]

If the grid frequency is nominal, the expected total active power output during the scheduling period $T$ is the output power average over this period. At this time, the reference output power of the BU inverter can be expressed as:

\[
P_{ref} = P_L - P_G
\]

where $P_G$ is the actual output power of WT.

If the main grid requires all WTs to participate in the frequency regulation, the expected total active power output during the scheduling period $T$ is the output power average plus the active power of frequency regulation $P_{AGC}$ over this period. The reference output power of the BU inverter can be expressed as:

\[
P_{ref} = P_L + P_{AGC} - P_G
\]

Notice that the output power of BU, $P_B$, should track $P_{ref}$.

B. Operation modes and transition conditions

The central controller takes care of managing the different operation modes. Notice that $V$ is the actual wind speed, while $V_n$ is the rated nominal wind speed; $f$ is the actual grid frequency, $f_{min}$ and $f_{max}$ are the minimum and maximum grid frequency. Battery maximum power charge and discharge are noted as $P_{BC}$ and $P_{BD}$.

- **Mode 1:** If $V \leq V_n$, the frequency will be nominal, WT operates in the MPPT mode, and the tie-line active power of is regulated to a constant value. The reference value of the active power of the energy storage inverter is: $P_{ref} = P_L - P_G$.

- **Mode 2:** If $V > V_n$, the frequency of the power grid is nominal, the pitch control of wind generation system starts working, to limit the output power of wind power the active power output of wind-energy storage system tie-line stays a constant value. The reference value of the active power of the energy storage inverter is: $P_{ref} = P_L - P_G$.

- **Mode 3:** When $f > f_{max}$ and $\Delta P + P_{AGC} \geq P_{BC}$ ($\Delta P = P_G - P_L$), the energy storage starts participating in the frequency regulation, $P_{ref} = P_L - P_G + P_{AGC}$.

- **Mode 4:** When $f < f_{min}$ and $\Delta P + P_{AGC} < P_{BD}$ ($\Delta P = P_G - P_L$), and at this time rotor speed of wind turbine $\omega \leq 0.8\omega^*$, $\omega^*$ is rated speed of wind turbine, the energy storage start to adjust the frequency, $P_{ref} = P_L - P_G + P_{AGC}$.

- **Mode 5:** When $f < f_{min}$ and $\Delta P + P_{AGC} < P_{BD}$, and at the same time rotor speed of wind turbine $\omega > 0.8\omega^*$, virtual inertia starts operating. When rotor speed dropped to 0.7$\omega^*$, the frequency is not restored to the nominal value, and at the same time BU starts participating in the frequency regulation $P_{ref} = P_L - P_G + P_{AGC}$.

It should be noted that when the frequency of the power grid is too high or too low, the $P_{AGC}$ is greater than the BU charge/discharge maximum output power, and the hybrid WT-BU system is disconnected from the power grid, running in islanded mode. Tables I present the operation modes and transition conditions of the WT-BU system.

<table>
<thead>
<tr>
<th>Mode</th>
<th>State transition condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$V \leq V_n$</td>
</tr>
<tr>
<td></td>
<td>$f_{min} \leq f \leq f_{max}$</td>
</tr>
</tbody>
</table>

**Table I. Operation modes and transition conditions**
\[
\frac{k}{2} = \frac{1}{2} \rho R^2 C_p \frac{\omega^3}{\lambda^2}
\]

The PMSG rotor-side control block diagram is shown in Fig. 3. The generator side converter is designed to achieve maximum power tracking for wind energy by using stator flux linkage vector control. By using the synchronous reference frame transformation in \( dq \) axis, the stator voltage equation can be expressed as:

\[
\begin{align*}
\begin{cases}
    u_{sd} &= -R_s i_{sd} - L_s \frac{di_{sd}}{dt} - \omega_e L_s i_{sq} \\
    u_{sq} &= -R_s i_{sq} - L_s \frac{di_{sq}}{dt} - \omega_e L_s i_{sd} + \omega \phi
\end{cases}
\end{align*}
\]

The electromagnetic torque can be obtained as:

\[
T_e = \frac{3}{2} p [\varphi i_{sq} + (L_{sd} - L_{sq}) i_{sq} i_{sd}]
\]

where \( R_s \) is the stator resistance, \( L_{sd} \) and \( L_{sq} \) is the stator inductance, \( i_{sd} \) and \( i_{sq} \) is the stator current, \( u_{sd} \) and \( u_{sq} \) is the stator voltage, \( \omega_e \) is synchronous angular velocity, \( \varphi \) is permanent magnet flux linkage and \( p \) is the number of pole pairs. Considering that the current \( d \)-axis component is always fixed to 0, then the electromagnetic torque can be expressed as

\[
T_e = \frac{3}{2} p \varphi i_{sq}
\]

2) Grid Side Control

The aim of the grid side controller is to stabilize DC bus voltage and to achieve \( P/Q \) decoupling control. Grid side controller block diagram is shown in Fig. 4.

\[
\begin{align*}
\begin{cases}
    u_{gd} &= -R_g i_{gd} - L_g \frac{di_{gd}}{dt} + \omega_g L_g i_{gq} + e_{gd} \\
    u_{gq} &= -R_g i_{gq} - L_g \frac{di_{gq}}{dt} - \omega_g L_g i_{gd}
\end{cases}
\end{align*}
\]

where \( e_{gd} \) and \( e_{gq} \) is the grid voltage, \( i_{gd} \) and \( i_{gq} \) is the grid voltage, \( R_g \) and \( L_g \) is the resistance and inductance of grid-side converter, and \( \omega_g \) is grid angular frequency.

![Fig. 3. Block diagram of generator side control](image)

![Fig. 4. Wind power grid side control](image)
The grid side controller uses grid P/Q calculation as:

\[
\begin{align*}
P_g &= e_g d_i d_a + e_g q i q_a = e_g d i d_a \\
Q_g &= e_g d i q_a - e_g q i d_a = e_g q i d_a
\end{align*}
\]  
(14)

From (13), \( i_{sd} \) and \( i_{sq} \) references can be achieved by independent controlling \( P \) and \( Q \).

3) Pitch control

When wind speed exceeds the rated wind speed, active power output of the WT needs to be limited by changing the wind turbine pitch angle \( \beta \), hence reducing the wind energy capture coefficient. The output power \( P_w \) of the current generator is compared with the reference power \( P_w^* \). The error is processed by the PI controller to produce the required \( \beta' \) (see Fig. 5). Thus the pitch angle is changed accordingly, so that the WT output power is kept at reference \( P_w^* \).

![Fig. 5. Pitch control.](image)

4) Virtual inertia and rotor speed control

Fig. 6 shows the block diagram of the virtual inertia and the rotor speed control. The virtual inertia controller detects when the grid frequency drop down, making the rotor speed decreasing, thus the rotating kinetic energy is released to prevent further decreasing the grid frequency.

![Fig. 6. Rotor inertia control and speed recovery control.](image)

When starting the virtual inertia loop, the controller will connect \( \Delta P \) to switch 1 (see Fig. 6), and the power reference will change according to the frequency deviation that will go through a P controller that will added over the MPPT output (\( P_{MPPT} \)). In order to prevent WT losing too much kinetic energy, when the rotor speed dropped down to 0.7 times of the rated value, the virtual inertia loop is disconnected, and \( \Delta P \) will be connected to switch 0. If the grid frequency is nominal, the speed recovery control will start, connecting \( \Delta P \) to switch 2.

Then, the rotor speed control will generate the power reference, which will be obtained by using the rotor speed deviation through a PI controller that will be subtracted from \( P_{MPPT} \).

B. BU Inverter Power Control

The BU inverter power controller structure is shown in Fig. 7. The grid voltage \( u_{abc} \) and inverter grid current \( i_{abc} \) are used to calculate \( P/Q \), controlling those to follow \( P_{ref}/Q_{ref} \), and then control \( I_d/I_q \) through internal current loops.

![Fig. 7. Energy storage inverter power control.](image)

VI. MICROGRID CASE STUDY

The model of a hybrid WT-BU system connected through a tie-line to a microgrid system was developed by using Matlab/Simulink. The selection and switching of the operating modes of the WT-BU system embedded in the central controller is realized based on the stateflow toolbox. The main parameters of the system are shown in Table II. The rated capacity of the microgrid is 10MW, and the unit regulation power of the wind storage system is 1MW/Hz. The nominal grid frequency is \( f_n = 50 \) Hz, with +/-1% of error, so that the maximum and minimum frequencies where \( f_{min} = 50.5 \) Hz and \( f_{max} = 49.5 \) Hz. The microgrid control includes a secondary control based on AGC to restore the frequency.

Wind speed curve, as shown in Fig. 8, cut the wind speed at 6m/s, and the rated wind speed is 12m/s. According to the above mentioned, according to the wind speed curve, the calculation of the tie-line power is \( P_L = 940 \) kW.

![Table II: Simulation Parameters](image)

<table>
<thead>
<tr>
<th>Wind turbine parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbine radius /m</td>
<td>27.5</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Rated wind speed m/s</td>
<td>12</td>
</tr>
<tr>
<td>Air density kg/m³</td>
<td>1.225</td>
</tr>
<tr>
<td>Rated power /MW</td>
<td>1.1</td>
</tr>
<tr>
<td>Best tip speed ratio</td>
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<tr>
<td>Wind energy maximum utilization factor</td>
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</tr>
<tr>
<td>Pitch control proportional coefficient</td>
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</tr>
<tr>
<td>Permanent magnet wind turbine parameters</td>
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<tr>
<td>Rated power /kW</td>
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</tr>
<tr>
<td>Flux linkage</td>
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<td>Inertia /Joules</td>
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<td>Pole pairs</td>
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<td>Stator resistance /Ω</td>
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<tr>
<td>d-axis inductance /mH</td>
<td>1.216</td>
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<td>Grid side converter parameters</td>
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<td>Line inductance /mH</td>
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<td>DC side voltage /V</td>
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<td>Rotor side converter parameters</td>
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<tr>
<td>Rotor side q-axis current inner loop k₄₁, k₄₁</td>
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<tr>
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<td>Rotor inertial control loop k₆₀, k₆₀</td>
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<td>Speed recovery loop k₇₁, k₇₁</td>
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</tr>
<tr>
<td>Energy storage system parameters</td>
<td></td>
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<td>Battery capacity /Ah</td>
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<tr>
<td>Battery maximum discharge current</td>
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<tr>
<td>Maximum charge power P_BDC</td>
<td>-160 kW</td>
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<td>PQ controls d-axis current inner loop k₉₁, k₉₁</td>
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</tr>
<tr>
<td>PQ controls q-axis current inner loop k₉₂, k₉₂</td>
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<tr>
<td>PQ control reactive power outer loop k₁₁₁, k₁₁₁</td>
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</tr>
</tbody>
</table>

Fig. 8. Wind speed curve

The simulation results of the wind storage system in different operating modes are shown in Fig 9. F and f are frequency of the wind-energy storage system before and after the participation in the frequency regulation in Fig. 9 (a). Fig. 9 (b) is the wind generation output power; Fig. 9 (c) is the generator rotor speed; Fig. 9 (d) is DC voltage of wind power.
VII. CONCLUSION

This paper proposed a grid-connected wind generation system retrofitted with a battery energy storage unit. The proposal includes inertia emulation by linking the rotor speed with the frequency, taking into account speed constraints and coordinating the actions between WT and BU. The paper introduces a control architecture in order to achieve a good integration of the WT-BU system with the power system, thus achieving the following salient features:

- Output power smoothing
- AGC power schedule following
- Frequency regulation and participation

Simulation results shown the hybrid WT-BU power system with the proposed control architecture operates properly in the context of a small weak grid.

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