Control of a wind farm based on synchronous generators with a central HVDC-VSC converter

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Abstract—A control scheme for wind farms based on synchronous generators connected to a single power converter is presented. The scheme is applicable to HVDC interfaced offshore or remote wind farms. The proposed control scheme is based on computing the optimal wind farm electrical frequency depending on the different incoming wind speeds. The power converter regulates the system frequency by adjusting the power injected to the HVDC circuit. Fault ride-through is also possible by reducing rapidly the injected active power. The proposed scheme is validated by means of simulations with a wind farm composed of four wind turbines.

Index Terms—Wind power generation, High voltage direct current (HVDC), Variable frequency wind farm, Offshore wind power.

I. INTRODUCTION

Onshore wind farms are nowadays capable of not only generating power, but provide support to the grid where they are connected providing ancillary services [1] or contributing to power system stability [2] while riding through faults in the grid [3], [4]. Onshore wind farms can actually be considered as wind power plants as they can be operated as conventional power plants [5].

Remote and offshore wind farms need HVDC or HVAC lines to interface them to the main grid [6]. Above a certain critical distance, HVDC technology stands as the appropriate solution, which can be based on Line Commutated Converters HVDC-LCC [7]–[9] or Voltage Source Converters HVDC-VSC [10]–[12]. In both cases, HVDC systems require a power converter at the connection point of the wind farms, allowing a centralized control for the whole wind farm. Some offshore wind farms employ only this central power converter with squirrel cage induction generators [13] or synchronous generators [14], [15], while others combine a central power converter with individual converters and doubly fed induction generators [12] in each wind turbine.

Jovic [14], [15] proposed a variable frequency wind farm grid to maximize power generation, based on the approach of [16], which is well demonstrated for a single wind turbine: applying a power reference $P^* = K\omega^3$ or the equivalent

torque reference $T^* = K\omega^2$ [17], [18] with the appropriate constant K , the wind turbine generation is maximized. This approach is broadly used for maximum power point tracking of a single wind turbine controlled by a dedicated power converter. However, the performance of this approach is not demonstrated for a wind farm with multiple wind turbines and a single power converter, when the different wind turbines are generating at different wind speeds. Other authors [13] proposed methods to dynamically search the maximum generation by changing frequency and observing power changes, but these methods present the drawback of possible operation at local maximums, that may generate much less power than an absolute maximum in certain cases. Therefore, the mentioned approaches do not guarantee maximum power generation for all wind speeds in the case of a wind farm connected to a single power converter. The present work proposes a technique to assure maximum power extraction in an offshore wind farm based on synchronous generators connected to a single power converter. Maximum generation power is obtained by computing the optimal wind farm grid electrical frequency depending on the measured wind speeds in all the wind turbines. A frequency controller is implemented to obtain the optimal frequency by adjusting the power converter power. It is important to stress that the term *maximum generation power*, used throughout the paper, means maximum generation for the chosen topology, i.e. wind farm connected to a single power converter. It is clear that the only possible way of getting all the available power is using dedicated converters for each machine.

Offshore wind farms connected by means of HVDC have to reduce power rapidly when faults onshore occur in order to prevent overvoltages in HVDC circuits. Moreover, this has to be done without using fast communication systems to assure system reliability. Several solutions have been proposed recently [19], [20], including the use of braking resistors to dissipate the power, wind farm frequency increase to reduce power generation letting the wind turbines accelerate, wind farm voltage reduction or directly reducing the power in the converter. Although, the last method is usually not convenient to avoid current and voltage transients in the operation mode switching, the present work achieves fault ride-through by reducing directly the power in main HVDC-VSC converter. This is possible without important transients because the proposed control scheme is based on controlling directly the power in the HVDC-VSC and therefore no operation mode change is required to reduce the power injected in the HVDC circuit.

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The present work presents a control scheme for wind farms (or clusters or wind turbines inside a wind farm) with wind turbines based on synchronous generators connected to a single HVDC-VSC converter. The configuration can be used for HVDC connections (with an already existing HVDC-VSC converter) and also with full power back to back power converters. The main advantage of the proposed configuration is that no power converters are required in the individual wind turbines and therefore cost is reduced and reliability is increased. The drawbacks include the lost of part of the wind energy when wind speeds are different (discussed in Section II), the need for auxiliary power converters to supply auxiliary equipment in the wind turbines and the more reduced control capability over the wind turbine mechanical system, compared to the use of individual power converters.

The proposed control scheme can be used both with permanent magnet synchronous generators (PMSG) and wound rotor synchronous generators (WRSG). For PMSG, the generator flux is created by a rotating magnet and therefore individual wind turbines are not capable of controlling it. For WRSG, the flux can be controlled adjusting the rotor current, however for the present work a constant rotor current is assumed and therefore the behavior of both PMSG and WRSG wind farms would be equivalent. The control scheme operates the wind farm to maximize power generation in normal conditions and reduces the power injection when a fault onshore occurs. The proposed scheme has been validated by means of simulations.

The paper is organized as follows. In Section II the convenience of the wind farm grid with a single power converter is discussed considering wind speed variability in wind farms. In Section III the optimum electrical frequency search procedure is described. Section IV analyzes electrically the proposed scheme. The proposed control scheme is introduced in Section V and simulated in Section VI. The conclusions are summarized in Section VII.

II. COMPARISON OF THE POWER EXTRACTED BY A WIND FARM WITH A SINGLE CENTRAL POWER CONVERTER AND INDIVIDUAL CONVERTERS IN EACH WIND TURBINE

Wind variability in wind farms is difficult to analyze in a general way, since it depends heavily on wind turbine locations and incoming wind directions. However, it is possible to undergo a statistical analysis in order to evaluate the effect of wind variation in terms of maximum available power considering the use of a single converter for the whole wind farm or dedicated converters for each wind turbine.

The present section uses an evaluation methodology to evaluate the wind power generated using the three following concepts:

- A Wind farm with a single power converter and variable frequency
- B Wind farm with constant frequency (50 Hz)
- C Wind farm with individual power converters in each wind turbine

The evaluation methodology consists in a massive analysis of different scenarios in order to extract conclusions about the amount of power generated by the different concepts. The methodology is based on a two-level approach:

- In the first level a set of wind speeds is generated. According to the data provided by means of Weibull distribution parameters, the average wind farm wind speed is generated randomly. With this average value and the typical deviation the individual wind turbines speeds are generated randomly using a Normal distribution. The different wind speeds sets are generated N_{sim} times for different N_{sd} standard deviations values to be analyzed. Therefore a total number of $N_{sim} \times N_{sd}$ wind speeds sets are generated.
- In the second level, the generated power for the different configurations is analyzed. Each wind speeds set is analyzed for different electrical frequencies: for a given wind speeds set, a sweep of N_{freq} electrical frequencies is undergone, calculating for each of them the equilibrium point and the electrical power generated. As a result of the analysis the following total powers are computed: maximum available power P_{cp} (only obtained using individual power converters in each wind turbine), maximum power using a single power converter with variable frequency P_{pc} and power generated with a constant frequency grid (50 Hz) P_{50} . Summing the powers obtained for the N_{sim} simulations, the ratios $\alpha_{pc} = \sum P_{pc} / \sum P_{cp}$ and $\alpha_{50} = \sum P_{50} / \sum P_{cp}$ are calculated for each different standard deviation.

The methodology has been applied to the wind farm described in the Appendix, considering a Weibull distribution data from [21], [22] ($a = 9.02$, $b = 2.26$) and different standard deviations between 0.5 and 10 m/s ($N_{sd} = 20$). The simulations have been performed with $N_{freq} = 100$ and $N_{sim} = 200$. The results are shown in Fig. 1. Initially, for a standard deviation of 0.5 m/s, α_{pc} is 0.9979 and α_{50} is 0.802. Therefore for low standard deviations (similar wind speeds throughout the wind farm), the performance of the single power converter with variable frequency is excellent. When the standard deviation is increased the performance of both single power converter based methods is decreased due to the larger wind speed variability, however the single power converter with variable frequency concept maintains α_{pc} above 0.95 until the standard deviation is larger than 2.5 m/s, which is larger than typical values of less than 1 m/s [23]. Even for a huge standard deviation of 10 m/s, the value of α_{pc} 0.7827 is acceptable. In all the cases, the performance of the single power converter with variable frequency is between 0.19 and 0.38 better than the constant frequency grid.

Similar analysis for wind farms with different number of wind turbines shows similar results. For 10 wind turbines, with standard deviation of 2 m/s, α_{50} is 0.75 and α_{pc} 0.95. With standard deviation of 5 m/s, α_{50} is 0.57 and α_{pc} 0.82. For 20 wind turbines, with standard deviation of 2 m/s, α_{50} is 0.71 and α_{pc} 0.94. With standard deviation of 5 m/s, α_{50} is 0.55 and α_{pc} 0.8. For larger number of wind turbines the results are very similar to the 20 wind turbine wind farm. It can be seen that a larger number of wind turbines reduces the generated power. This effect can be overcome by appropriately clustering the wind turbines.

Fig. 1. Dependence of the ratios α_{pc} and α_{50} on the standard deviation of the wind speeds inside the wind farm

III. OPTIMUM ELECTRICAL FREQUENCY SEARCH

A. Wind turbine power generation

The power P_{wti} generated by a wind turbine can be written as $P_{wti} = C_p P_{wind} = \frac{1}{2} C_p \rho A v_w^3$ where P_{wind} is the air stream kinetic power, ρ is the air density, $A = \pi R^2$ is the surface covered by the wind wheel of radius R , v_w is the average wind speed and C_p is the power coefficient, which can be written as [24]:

$$C_p(\lambda, \theta_{pitch}) = c_1 \left(c_2 \frac{1}{\lambda} - c_3 \theta_{pitch} - c_4 \theta_{pitch}^{c_5} - c_6 \right) e^{-c_7 \frac{1}{\lambda}} \quad (1)$$

where θ_{pitch} is the pitch angle and λ is the so called tip speed ratio defined as $\lambda = \frac{\omega_t R}{v_w}$ where ω_t is the wind turbine speed and $\frac{1}{\lambda} = \frac{1}{\lambda + c_8 \theta_{pitch}} - \frac{c_9}{1 + \theta_{pitch}^3}$ where $[c_1 \dots c_9]$ are characteristic constants for each wind turbine.

A typical $C_p - \lambda$ curve is sketched in Fig. 2. The $C_p - \lambda$ curve has a maximum value which corresponds to the optimum operating point of the wind turbine as long as the wind speed does not overcome the maximum threshold.

In a single wind turbine, the maximum C_p is obtained [17], [18] when $T_{wti} = K \omega_t^2$ (K depends on the coefficients c_i) which guarantees maximum power generation for a single wind turbine, but it cannot be directly applied to a whole wind farm with different wind speeds.

B. Wind farm generation analysis

The total power generated by a wind farm composed of N_{wt} wind turbines can be expressed as $P_{wf} = \sum_{i=1}^{N_{wt}} P_{wti}$. Without loss of generality, all the wind turbines can be considered identical and therefore all the wind turbine constants will keep the same values for all the wind farm. In this case, the total power generated $P_{wf} = \frac{1}{2} \rho A \sum_{i=1}^{N_{wt}} C_{Pi} v_{wi}^3$, where it can be noted that C_{Pi} and v_{wi} can be different for the different wind turbines and therefore it is not possible to operate all the machines at the optimum operating point except when they are all working with the same wind speed.

A typical example of a multi wind turbine wind farm is shown in Fig. 2. Four operation points for four wind turbines

Fig. 2. $C_p - \lambda$ curve for different wind turbines generating with different wind speeds with electrical frequency of 50 Hz. The wind turbine parameters of Appendix are used.

with different wind speeds are shown. The different wind speeds imply different λ and C_p and therefore it can be seen clearly that it is not possible to operate all the wind turbines at the maximum C_p . The four different wind turbine operating points correspond to the following data: **1** $v_w=5$ m/s, $C_p=0.189$, $P_{elec}=0.0409$ MW, **2** $v_w=13$ m/s, $C_p=0.381$, $P_{elec}=1.52$ MW, **3** $v_w=9.7$ m/s, $C_p=0.485$, $P_{elec}=0.767$ MW, **4** $v_w=6.2$ m/s, $C_p=0.368$, $P_{elec}=0.152$ MW.

C. Optimum electrical frequency search

In order to generate the maximum possible energy in a wind farm, it is proposed to modify the electrical wind farm frequency and consequently the wind turbines speed. To find the electrical frequency that maximizes the total power of the wind farm (circular marker of Fig. 3), it is proposed to express the C_p expression (1) as a polynomial of degree N_{pol} and coefficients a_j

$$C_p(\lambda) = \sum_{j=0}^{N_{pol}} a_j \lambda^j = \sum_{j=0}^{N_{pol}} a_j \frac{(\omega_t R)^j}{v_{wi}^j} \quad (2)$$

where θ_{pitch} has been assumed to be the minimum value (zero) as the maximum power is to be extracted. The power generated by each turbine i can be expressed as

$$P_{wt-i} = \frac{1}{2} \rho A v_{wi}^3 \sum_{j=0}^{N_{pol}} a_j \frac{(\omega_t R)^j}{v_{wi}^j} \quad (3)$$

For each synchronous generator, the wind turbine speed in steady state conditions can be written as $\omega_t = \frac{\omega_e}{P N_{mult}}$ where ω_e is the grid electrical angular speed, P is the pole pairs number and N_{mult} is the multiplier factor. Substituting it in expression (3), rearranging and summing all the wind turbine power, the total wind farm power yields

$$P_{wf} = \frac{1}{2} \rho A \sum_{i=1}^{N_{wt}} \sum_{j=0}^{N_{pol}} a_j \left(\frac{R}{P N_{mult}} \right)^j \omega_e^j v_{wi}^{3-j} \quad (4)$$

To determine the electrical angular speed ω_e that maximizes the total generated power, one can evaluate $\frac{dP_{wf}}{d\omega_e} = 0$ which

can also be expressed as

$$\sum_{j=1}^{N_{pol}} b_j \omega_e^{j-1} = 0, \quad b_j = \frac{1}{2} \rho A j a_j \left(\frac{R}{P N_{mult}} \right)^j \sum_{i=1}^{N_{wt}} v_{wi}^{3-j} \quad (5)$$

Solving (5), $N_{pol} - 1$ solutions are found, the obtained real solutions can be substituted in the total power equation (4) in order to determine which is the optimal solution.

It is important to note that the computational time needed to solve (5) can be expressed as the sum of the time T_{com-bj} needed to calculate the parameters b_j and the time T_{com-eq} needed to solve the equation. T_{com-bj} can be expressed as $T_{com-bj} = N_{pol} T_b$ where T_b is proportional to the number of wind turbines N_{wt} . On the other hand, since the equation is a polynomial of degree $N_{pol} - 1$ with a single unknown ω_e , T_{com-eq} depends only on the degree of the polynomial and not in the number of wind turbines. Using a common computer, and considering $N_{pol} = 5$, the optimal frequency of a wind farm of 198 wind turbines can be calculated in approximately 100 ms and a wind farm of 1998 wind turbines in 1 second.

D. Application example

A wind farm composed of four wind turbines is analyzed, considering the parameters described in the Appendix.

The $C_p - \lambda$ curve has been approximated to the fifth degree polynomial $-8.08 \times 10^{-6} \lambda^5 + 0.00042 \lambda^4 - 0.0078 \lambda^3 + 0.053 \lambda^2 - 0.024 \lambda - 0.176$.

Wind speeds of 11.1 m/s, 13 m/s, 9.6 m/s and 8.2 m/s have been considered. Fig. 3 shows the power generated in the wind farm depending on the electrical grid frequency. The bold black line shows the power generated for different grid electrical frequencies, whose maximum is illustrated by a circular marker.

In order to determine the optimum electrical frequency, the parameters b_i have been computed according to (5) as functions of the wind turbines parameters and the incoming wind speeds. The optimal electrical frequency can be computed solving the equation $-3.6570 + 0.4930 \omega_e - 0.0035 \omega_e^2 + 8.1861 \times 10^{-6} \omega_e^3 - 6.6126 \times 10^{-9} \omega_e^4 = 0$ whose solutions yield 467.95+j143.87, 467.95-j143.87, 294.21 and 7.84. Among these four solutions it is clear that the optimum ω_e is 294.21 rad/s (which corresponds to 47.05 Hz), since two of the other roots are complex numbers and the other one corresponds to the minimum power. In a real time control system, the Newton iteration method can be used to rapidly compute the solution by choosing appropriate initial solutions such as $2\pi 50 \approx 314.16$ rad/s.

IV. WIND FARM GRID CONNECTED TO A SINGLE POWER CONVERTER

The proposed electrical scheme is sketched in Fig. 4. The wind farm is composed of wind turbines coupled to synchronous generators. Each generator is connected to the medium voltage farm grid by means of a transformer. A single power converter receives the power from all the turbines in order to rectify it and let the power flow through the HVDC link. Onshore, a HVDC-VSC inverter interfaces the HVDC link to the main AC grid.

Fig. 3. Generated power depending on the electrical frequency in a wind farm with four wind turbines with different wind speeds

Fig. 4. Offshore wind farm connected to the main grid by means of HVDC

A. Wind farm and power converter analysis

The wind farm grid voltage and current is controlled by a single power converter which also is in charge of rectifying all the generated power and injecting it in the HVDC circuit. This power converter will also control the system frequency and generated active power. The considered power converter is a two-level boost rectifier equipped with an AC filter and a transformer for the wind farm grid.

Referring all the quantities to the generator low voltage grid and considering all the voltages and currents in the synchronous reference frame, the wind farm grid voltage equations can be written as:

$$\begin{bmatrix} v_{sq} - v_{cq} \\ v_{sd} - v_{cd} \end{bmatrix} = \begin{bmatrix} R_l & -L_l \omega_e \\ L_l \omega_e & R_l \end{bmatrix} \begin{bmatrix} i_{sq} \\ i_{sd} \end{bmatrix} + \begin{bmatrix} L_l & 0 \\ 0 & L_l \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{sq} \\ i_{sd} \end{bmatrix} \quad (6)$$

where v_c is the converter side voltage, v_s is the wind farm voltage and i_s is the total wind farm current. The power converter transformer is simplified as a RL branch with resistance R_l and inductance L_l . Subindexes q, d stand for quadrature and direct quantities in the synchronous reference frame.

Active and reactive power provided by the power converter can be written using instantaneous power theory as $P_c = \frac{3}{2} (v_{sq} i_{sq} + v_{sd} i_{sd})$ and $Q_c = \frac{3}{2} (v_{sq} i_{sd} - v_{sd} i_{sq})$.

B. Synchronous generator wind turbines

Each wind turbine is based on a synchronous generator, attached to the wind wheel by means of a multiplier. The wind turbine has a pitch system to limit power, which is activated when the turbine speed overcomes a given threshold. The generator is connected to the wind farm grid by means of a transformer.

In the present Section steady-state analysis is conducted with the system sketched in Fig. 5. The transient simulation analysis is developed in Section VI with complete transient models.

The power converter is represented in the steady state analysis as a voltage source with its voltage referred to the generator voltage. The synchronous generators are modelled as voltage sources with a series resistance and inductance.

Fig. 5. Analyzed simplified system

For the case of permanent magnet synchronous generators (PMSG), the generator voltage equations in the synchronous reference frame ($\mathbf{V}_{gqd} = v_{gq} + 0j$) for each wind turbine i can be written as:

$$\mathbf{V}_{gqd} = \begin{bmatrix} r_s & P\omega_{ri}L_q \\ -P\omega_{ri}L_d & r_s \end{bmatrix} \mathbf{I}_{gqd-i} + \begin{bmatrix} L_q & 0 \\ 0 & L_d \end{bmatrix} \frac{d}{dt} \mathbf{I}_{gqd-i} + \mathbf{E}_{pmqd-i} \quad (7)$$

where ω_{ri} is the generator i mechanical speed, $\mathbf{I}_{gqd-i}$ is the generator i current, $\mathbf{V}_{gqd}$ is the wind farm voltage which is assumed constant for all the generators, r_s is the generator stator winding resistance, and L_q and L_d the generator inductances. The voltage $\mathbf{E}_{pmqd-i}$ generated by the permanent magnet flux yields

$$\mathbf{E}_{pmqd-i} = \lambda_m P \omega_{ri} \begin{bmatrix} \cos \theta_i \\ -\sin \theta_i \end{bmatrix} \quad (8)$$

where λ_m is the flux due to the rotor magnet, P is the number of pairs of poles of the generator and θ_i is the angle between the rotor and the synchronous reference frame.

The generator torque yields $\Gamma_{e-i} = \frac{3}{2}P \left(\lambda_m i_{gq-i}^r + (L_d - L_q) i_{gq-i}^r i_{gd-i}^r \right)$ where the currents $\mathbf{I}_{gqd-i}^r = i_{gq-i}^r + j i_{gd-i}^r$ are orientated with the generator rotor. For a surface mounted PMSG, $L_{qd} = L_q = L_d$ and the torque expression can be simplified $\Gamma_{e-i} = \frac{3}{2}P \lambda_m i_{gq-i}^r$. Considering the currents in the converter synchronous reference frame, the torque can be expressed as $\Gamma_{e-i} = \frac{3}{2}P \lambda_m (i_{gq-i} \cos \theta_i - i_{gd-i} \sin \theta_i)$. The steady state equations of the system can be written using (7), assuming that all the generators speeds are equal $\omega_{ri} = \omega_e / P$ and considering $d\mathbf{I}_{gqd-i} / dt \approx 0$

$$v_{gq} + 0j = \begin{bmatrix} r_s & \omega_e L_{qd} \\ -\omega_e L_{qd} & r_s \end{bmatrix} \mathbf{I}_{gqd-i} + \lambda_m \omega_e \begin{bmatrix} \cos \theta_i \\ -\sin \theta_i \end{bmatrix} \quad (9)$$

where there are $3N_{wt}$ equations and the $3N_{wt}$ unknown quantities are N_{wt} angles θ_i , N_{wt} currents i_{gq-i} and N_{wt} currents i_{gd-i} .

Fig. 6. Phasor representation of a two generator system

A phasor diagram with two generators is illustrated in Fig. 6. It can be seen that the angle θ_i is adjusted to accommodate the different power generation between the different wind turbines; the larger the angle, the larger the generated power. The module of the vectors $\mathbf{E}_{pmqd-i}$ is kept constant since all the generators rotate at identical mechanical speed.

V. CONTROL SCHEME

The system is controlled separately by two non-communicating systems. Onshore, the power converter controls the HVDC voltage by injecting all the incoming power to the main AC grid. Offshore, the power converter seeks the maximum power generation in normal conditions and maintains HVDC voltage reducing the generated power if the onshore converter cannot extract all the available power, for example in the event of a voltage sag in the main AC grid.

A. Onshore converter

The onshore converter is responsible for the HVDC voltage control and the support to the main AC grid. The VSC converter can control independently active and reactive power. Active power is adjusted to control the HVDC voltage while reactive power is usually used to provide voltage support to the grid. When a fault in the AC grid occurs, the power converter can continue operating but its power injection capability is

Fig. 7. Proposed control scheme

dramatically reduced. In this case, it switches its operating mode and enters a current control mode (to protect the power converter) instead of HVDC voltage control mode, implying a HVDC voltage increase until the offshore power converter can take over the voltage control and maintain system stability.

B. Offshore converter

The proposed system control scheme is illustrated in Fig. 7. The control structure is composed of two different levels: the frequency controller and the current controller. The frequency controller is slower than the lower level fast current controller.

1) *Frequency controller*: The higher level controller is responsible for the wind farm electrical frequency control and HVDC voltage control in the event of faults. It has three operation modes:

- Normal operation mode: The HVDC voltage is controlled by the onshore power converter. Offshore, the wind speed is measured in each wind turbine. The central frequency controller receives the measurements from all wind turbines and computes the optimum electrical frequency according to (5). A controller regulates the system electrical frequency to the reference value by adjusting the power converter i_{sq}^* current, which is proportional to the extracted active power. The frequency controller is adjusted to be a slow loop in order to guarantee system stability. The wind turbine pitch angle is maintained in the minimum angle in this operation mode.
- Maximum frequency mode: There is a maximum electrical frequency which corresponds to the maximum mechanical wind turbines speed. When this frequency is reached, the electrical frequency will be kept constant, and the wind turbines will locally limit their injected power adjusting the pitch angle.
- Power limiting mode: When there is a fault in the main AC grid, the onshore power converter can dramatically reduce its extraction power capability. In this case, the onshore power converter cannot control the HVDC voltage and the offshore power converter deals with this task. Since there are no communications between the two power converters, the only way of detecting the abnormal situation is with the HVDC voltage E . When E overcomes a given threshold $E_{L-pow-red}$, the computed i_{sq}^* reference current is modified with the factor $\alpha_{pow-red}$, which is expressed as

$$\alpha_{pow-red} = 1 - k_{pow-red} (E - E_{L-pow-red}) \quad (10)$$

where $\alpha_{pow-red}$ is limited between 0 and 1.

The frequency PI controller can be designed as the control of the rotation speed of an aggregated wind turbine which accumulates the inertia and mechanical torque of the whole wind farm. Using [25], the PI controller can be expressed as $K_n + \frac{K_n}{s\tau_n}$, where $K_n = \frac{J_{ag}}{2\tau}$ and $\tau_n = 20\tau$, where $J_{ag} = \frac{N_{wt}J}{(PN_{mult})^2}$ is the aggregated equivalent inertia of all the turbines considered and τ is the time constant of the current loops.

2) *Current controller*: The power converter voltage and current are measured in the medium voltage grid. A phase-locked loop (PLL) is employed to generate the synchronous reference frame angle θ_e and determine the electrical angular speed ω_e and voltages v_{sq} (note that $v_{sd} = 0$).

Using the instantaneous power theory [26] with the selected rotating reference frame ($v_{sd} = 0$) the current reference can be calculated

$$i_{sq}^* = \frac{2P_c^*}{3v_{sq}}, i_{sd}^* = \frac{2Q_c^*}{3v_{sq}} \quad (11)$$

where Q_c^* will usually be 0 in order to minimize the wind farm current. It can be seen in Fig. 7 that the higher level control supplies directly the current reference i_{sq}^* which is equivalent to supplying the power reference P_c^* .

The current control is done by the following state linearization feedback [3]:

$$\begin{bmatrix} v_{cq} \\ v_{cd} \end{bmatrix} = \begin{bmatrix} -\hat{v}_{cq} + v_{sq} - L_l \omega_e i_{sd} \\ -\hat{v}_{cd} + L_l \omega_e i_{sq} \end{bmatrix} \quad (12)$$

where the $\hat{v}_{cq}$ and $\hat{v}_{cd}$ are the output voltages of the PI current controller.

The PI controllers have been designed using the so-called internal model control (IMC) methodology detailed in [27]. The parameters of a PI controller to obtain a desired time constant τ are obtained as $K_p = \frac{L}{\tau}$ and $K_i = \frac{R}{\tau}$. The currents and voltages have been limited according to the converter operating limits. PI controllers have been designed with anti-windup in order to prevent control instabilities when the controller exceed the limit values.

VI. SIMULATION RESULTS

The proposed control scheme has been tested with a four 2 MW wind turbine wind farm by means of simulations using Matlab Simulink®. The wind farm is connected to a HVDC circuit with a full power HVDC-VSC converter. Onshore, another HVDC-VSC interfaces the HVDC circuit to the main grid. Wind turbine, generator, gearbox and grid parameters from typical wind turbine components [24] have been employed. Simulation parameters are shown in the Appendix.

A. Normal operation with different wind speeds

Simulations with four different varying winds for each wind turbine have been performed. The different wind speeds are illustrated in Fig. 8. The system has been simulated with different winds for each machine in order to evaluate the system performance with a single power converter.

The optimal calculated electrical frequency is shown in Fig. 8, where it can be seen that it is changing depending on the different wind speed measurements. The frequency controller regulates smoothly the system to the desired value by modifying the power converter current i_{sq}^* . The electrical frequency evolution is slow in order to guarantee system stability. The power converter current loops are illustrated in Fig. 8, a good tracking of both i_{sq}^* and i_{sd}^* can be observed.

The generators electrical power and torque are shown in Fig. 8. After an initial transient, both torque and power change according to the overall power converter power. It can be noted

Fig. 8. Simulation results for normal operation with different wind speeds

that each wind turbine generates a different amount of torque and power depending on the incoming wind.

The generator speeds and C_p coefficients are shown in Fig. 8. After small oscillations in the initial transient, all the generator speeds are equal. It can be noted that C_p values are maintained at high values, although it is not possible with a single converter to have the four wind turbines at maximum C_p value.

B. Operation with maximum frequency

Simulations with a wind abrupt changes for each wind turbine have been performed. The wind speed of the four wind turbines is increased in order to test the operation of the system for high winds. The different wind speeds are illustrated in Fig. 9.

The optimal calculated electrical frequency and the current loops are shown in Fig. 9, where it can be seen that the system responds smoothly to the wind speed increase. The generators electrical power, torque and speed are shown in Fig. 9. It can be seen, that after a transient, stable steady state points are obtained.

The simulation shows that the system is operated at constant maximum frequency. The individual wind turbines reduce the power injected by employing the pitch system.

C. Fault ride-through

A fault in the main AC grid has been simulated in order to check the overall system behavior. The fault is produced at the time instant 5 s and lasts 500 ms, implying a three phase voltage sag of 20 % of the nominal voltage. It can be seen in Fig. 10 that once the HVDC voltage overcomes the threshold $E_{L-pow-red}$, the offshore power converter takes over the HVDC voltage control and maintains it stable by reducing the active power generation. This reduction implies the turbines speed increase and electrical frequency increase. Once the fault is cleared, the power converter returns to the electrical frequency control mode, and increases the generated power. A delay of about 33 ms can be observed between the fault and the reaction of the power converter. This delay occurs because the power reduction is triggered when the HVDC voltage overcomes the threshold $E_{L-pow-red}$ and this occurs 33 milliseconds after the fault.

In the case that the turbine speed would reach the maximum allowed value, the pitch system would respond incrementing the pitch angle and reducing generated power.

VII. CONCLUSIONS

A control scheme for wind farms based on synchronous generators connected to a single power converter has been presented. The proposed control system can be applied to wind farms interfaced to the main AC grid by means of HVDC-VSC technology.

Depending on the different wind speeds in the wind turbines, an optimum electrical frequency is calculated. The power converter regulates the measured electrical frequency to this reference value by modifying the active power injected

Fig. 9. Simulation results for wind speeds increase

Fig. 10. Simulation results under a fault in the main AC grid

in the HVDC circuit. Fault ride-through capability is achieved with the reduction of the injected active power when a fault onshore occurs.

The proposed scheme has been validated with dynamic simulations, considering different wind speed operation and faults in the main AC grid.

APPENDIX

A wind farm composed of four wind turbines is considered. The employed wind turbine has a radius of 30 meters and a multiplier with $N_{mult} = 45$. Air density is assumed 1.225 kg m^{-3} . The power coefficient C_p is computed for all the turbines with $c_1 = 0.44$, $c_2 = 125$, $c_6 = 6.94$, $c_7 = 16.5$ and $c_9 = -0.003$. A virtual resistance [28] has been added to the HVDC cable to model the losses in the power converter. The HVDC system has capacitors of $20 \mu\text{F}$ in each side and voltage of 150 kV. A wind farm with four wind turbines rated to 2 MW is considered. The base voltages are 110 kV in the power converter AC side, 25 kV in the medium voltage wind farm grid and 1000 V in the generators. The generators are permanent magnet synchronous generators with parameters are $R_s = 0.01 \Omega$, $L_{qd} = 1.65 \times 10^{-4} \text{ H}$, $\lambda = 2.5 \text{ Wb}$ and 2 pairs of poles. The controller parameters are $K_n = 246.91$ and $\tau_n = 4$ for the frequency controller, and $k_p = 0.125$ $k_i = 6.25$ for the current loops. The simulations have been performed with Matlab Simulink® using the ode15s solver.

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