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Maximum generation power evaluation of variable frequency offshore wind farms when connected to a single power converter

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ABSTRACT

The paper deals with the evaluation of power generated by variable and constant frequency offshore wind farms connected to a single large power converter. A methodology to analyze different wind speed scenarios and system electrical frequencies is presented and applied to a case study, where it is shown that he variable frequency wind farm concept (VF) with a single power converter obtains 92% of the total available power, obtained with individual power converters in each wind turbine (PC). The PC scheme needs multiple power converters implying drawbacks in terms of cost, maintenance and reliability. The VF scheme is also compared to a constant frequency scheme CF, and it is shown that a significant power increase of more than 20% can be obtained with VF. The case study considers a wind farm composed of four wind turbines based on synchronous generators.

1. Introduction

Wind energy conversion systems [1] are proliferating worldwide both for stand alone [2,3] and grid connected systems [4]. Power converters have acted as an enabling technology to change the conception of wind farms to start thinking about wind power plants, able not only to generate active power, but to support the grid. Modern onshore wind power plants are based on doubly fed induction generators (DFIG) or synchronous generators with full power converters (FPC) and they are required to provide support to the grid voltage and frequency [5–9].

Offshore wind power plants can be connected by means of HVDC technology (HVDC-LCC [10–12] or HVDC-VSC [13–15]. HVDC systems require a power converter at the entrance 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 [16] or synchronous generators [17], while others combine a central power converter with individual converters and doubly fed induction generators [15] in each wind turbine.

The present paper deals with the evaluation of the power capture increase when employing a variable frequency wind farm connected to a HVDC grid by means of large power converter, which provides the grid frequency and voltage for the wind farm. The paper focuses on the energy capture analysis, other extremely important issues related to variable frequency wind farm engineering, stability and control are out of the scope of the paper.

2. Wind farm concepts analyzed

The present work considers different wind farm alternatives:

- PC: Wind farm with a power converter in each wind turbine and another HVDC-VSC or HVDC-LCC converter for the whole wind farm (Fig. 1). This scheme guarantees independent speed control for each wind turbine and therefore allows to maximize the power generated in each wind turbine. However, the FPC scheme show the following drawbacks: higher cost due to the additional power converter in each wind turbine, higher maintenance requirements which are especially critical for offshore wind farms, lower reliability due to the higher number of components which can eventually present problems and higher losses.
- VF: Wind farm with a single power HVDC-VSC or HVDC-LCC converter and variable frequency operation (Fig. 2). This scheme cannot guarantee the maximum power generation as the PC concept, but it can search optimum operation points by adjusting the wind farm electrical frequency. The main advantage of the concept is the need for only one power converter for the whole wind farm with the associated cost, losses and mainte-

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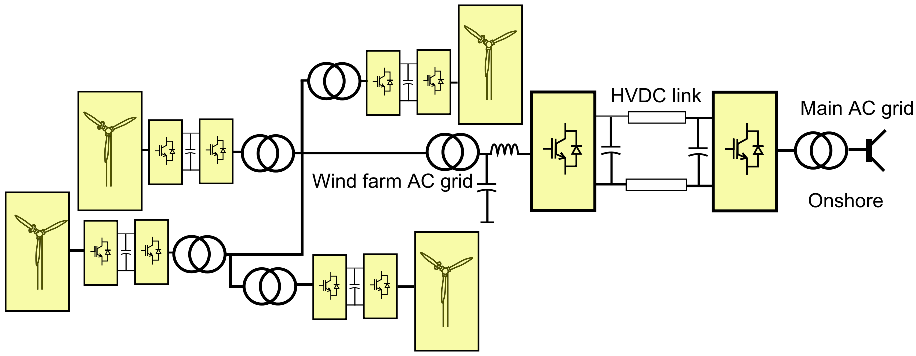

Fig. 1. Wind farm with individual power converters for each wind turbine PC. The wind farm is connected to the main grid by means of HVDC.

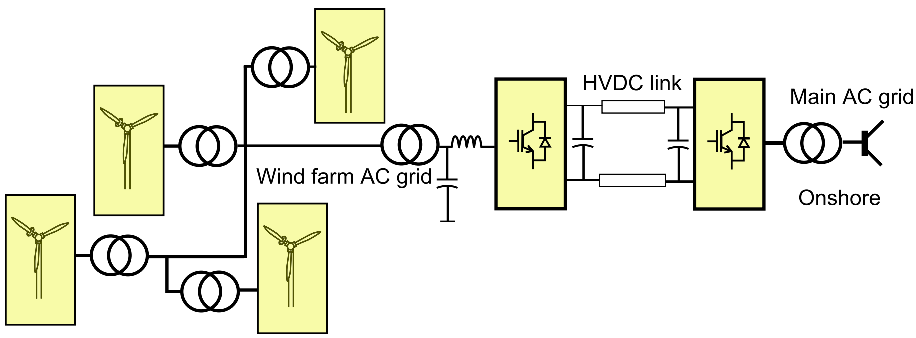

Fig. 2. Wind farm with a single power converter and variable VF or constant CF frequency operation. The wind farm is connected to the main grid by means of HVDC.

nance reduction and reliability increase. The main drawback is the impossibility of controlling independently the speed of each wind turbine.

- CF: Wind farm based on a single HVDC-VSC or HVDC-LCC converter operated with constant frequency (Fig. 2). This scheme operates the wind farm at constant frequency and therefore the optimum operation point is only obtained when the wind speed in all the wind turbines is equal to the wind speed for which the wind turbines have been designed (fixed speed concept). This scheme can be also used for HVAC, with important problems to fulfill current grid codes in terms of fault ride-through capability. The main advantage of CF scheme comparing to VF is the simplicity of the control, while the main drawback is the more reduced energy capture.

3. System analysis

3.1. Wind turbine power generation

The power P_{wti} generated in a wind turbine can be expressed as

$$P_{wti} = C_P P_{wind} = \frac{1}{2} C_P \rho A v_w^3 \tag{1}$$

where P_{wind} is the air stream kinetic power, ρ is the air density, A is the surface covered by the wind wheel, v_w is the average wind speed and C_p is the power coefficient, which can be written as [18,19]:

$$C_p(\lambda, \theta_{pitch}) = c_1 \left(c_2 \frac{1}{\Lambda} - c_3 \theta_{pitch} - c_4 \theta_{pitch}^{c_5} - c_6 \right) e^{-c_7 \frac{1}{\Lambda}} \tag{2}$$

where θ_{pitch} is the pitch angle and λ is the so called tip speed ratio defined as:

$$\lambda = \frac{\omega_t R}{v_w} \tag{3}$$

and

$$\frac{1}{\Lambda} = \frac{1}{\lambda + c_8 \theta_{pitch}} - \frac{c_9}{1 + \theta_{pitch}^3} \tag{4}$$

where $[c_1 \cdots c_9]$ are characteristic constants for each wind turbine.

3.2. Single wind turbine analysis

A typical $Cp - \lambda$ curve is sketched in Fig. 3. The $Cp - \lambda$ 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.

The maximum C_P is obtained when $d\, C_P/d\lambda = 0$

$$C_{Pmax}(\lambda_{CPmax}) = \left(\frac{c_1 c_2}{c_7} \right) e^{-\frac{c_6 c_7}{c_2} - 1} \tag{5}$$

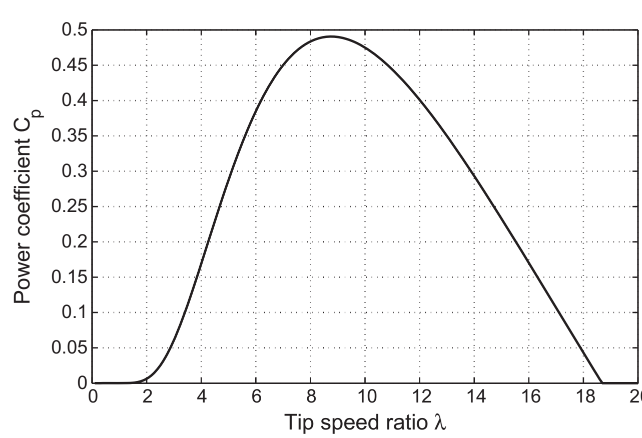

Fig. 3. Typical $C_p - \lambda$ curve.

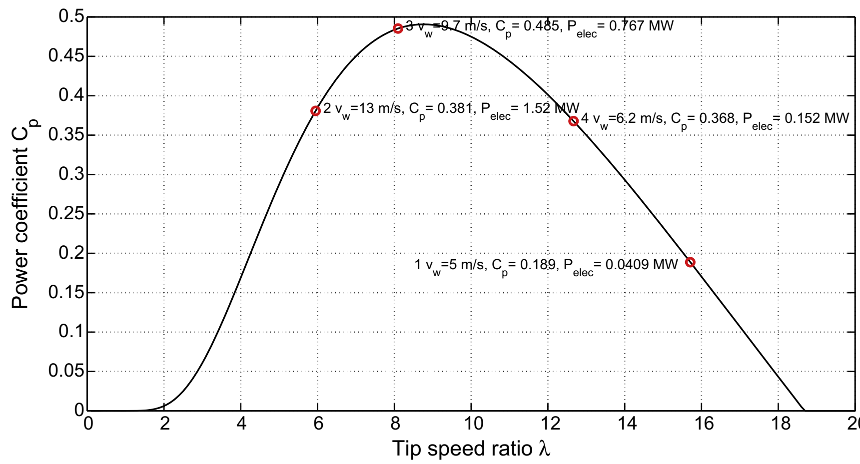

Fig. 4. $C_p - \lambda$ curve for different wind turbines generating with different wind speeds with electrical frequency of 50 Hz.

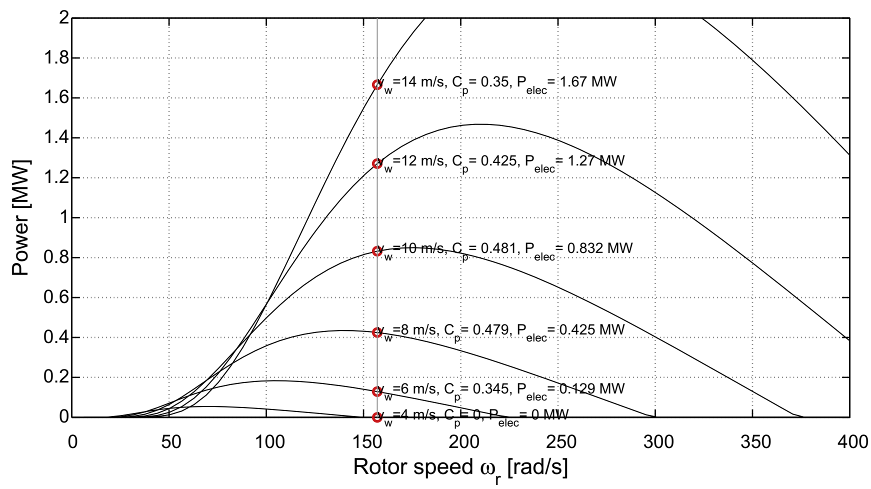

Fig. 5. Power generated by a single wind turbine for different wind speeds and constant electrical frequency.

with

$$\lambda_{CPmax} = \frac{c_2 c_7}{c_2 c_9 c_7 + c_6 c_7 + c_2} \tag{6}$$

Using $v_w = \frac{\omega_t R}{\lambda}$, expression (1) can be written as a function of the tip speed ratio as

$$P_{wti} = \frac{1}{2} C_P \rho A \frac{\omega_t^3 R^3}{\lambda^3} \tag{7}$$

The torque can be expressed as

$$T_{wti} = K\omega_t^2 \tag{8}$$

with

$$K = \frac{1}{2}\left(\frac{c_1 c_2}{c_7}\right) e^{-\frac{c_6 c_7}{c_2} - 1} \rho A \frac{R^3}{\left(\frac{c_2 c_7}{c_2 c_9 c_7 + c_6 c_7 + c_2}\right)^3} \tag{9}$$

According to [20,21], for a single wind turbine, it is enough to equal the generator electrical torque to $K\omega_t^2$ to guarantee maximum wind power capture.

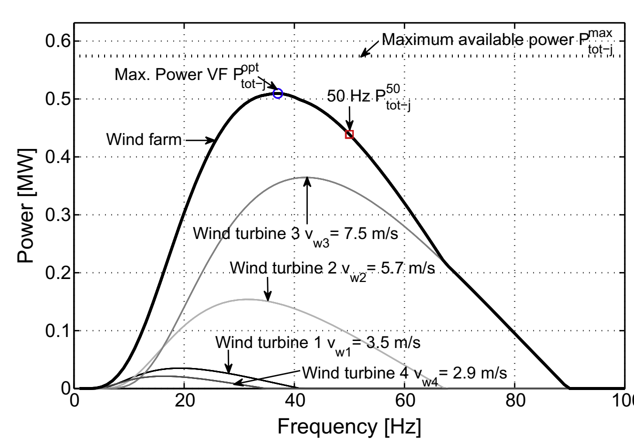

Fig. 6. Generated power comparison in a wind farm with four wind turbines with different wind speeds.

3.3. Wind farm analysis

The total power generated by a wind farm composed of N_{wt} wind turbines can be expressed as

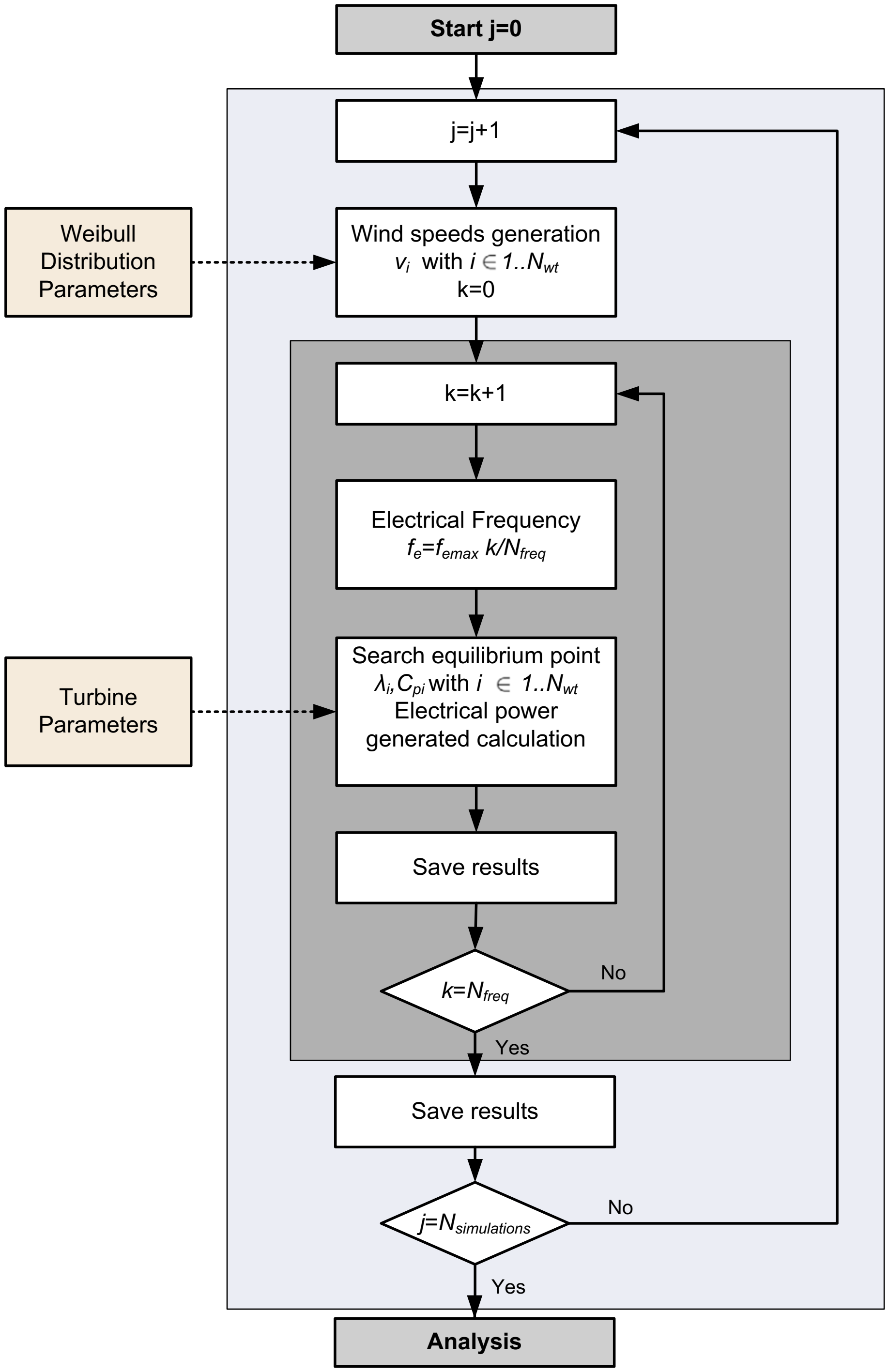

Fig. 7. Evaluation methodology.

$$P_{wf} = \sum_{i=1}^{N_{wt}} P_{wti} \tag{10}$$

Without loss of generality, all the wind turbines can be considered equal and therefore all the wind turbine constants will keep the same values for all the wind farm. In this case, the total power generated

$$P_{wf} = \frac{1}{2}\rho A \sum_{i=1}^{N_{wt}} C_{Pi} v_{wi}^3 \tag{11}$$

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 farm is shown in Fig. 4, where it can be noted that it is not possible to operate all the wind turbines at the maximum C_p.

3.4. Wind farm optimum frequency

In order to generate the maximum possible energy in a wind farm, it can be interesting to modify the electrical wind farm frequency and consequently the wind turbines speed. Fig. 5 shows the power generation for a single wind turbine for a given electrical frequency. If the vertical line is moved to the right or to the left, the power generated can be maximized depending on the wind speed.

A similar strategy can be applied to a whole wind farm. Fig. 6 shows the power generated in a wind farm composed of four wind turbines with wind speeds of 3.5 m/s, 5.7 m/s, 7.5 m/s and 2.9 m/s. The bold black line shows the power generated for different grid electrical frequencies, whose maximum is illustrated by the circular marker. The standard 50 Hz electrical grid generated power corresponds to the squared marker. The maximum available power is the upper horizontal dotted line and would be achieved only using a power converter for each wind turbine.

4. Evaluation methodology

4.1. General considerations

Depending on the kind of electrical generator employed, the equilibrium point can be slightly modified. Synchronous generators rotate at synchronous speed (as long as they are stable), and therefore for a wind farm connected to a single power converter, all the wind turbines will rotate at the same mechanical speed. Induction generators speed is always slightly above synchronous speed and therefore for an induction generator based wind farm, each generator will rotate at a different speed depending on each mechanical torque. The present work considers a wind farm based on synchronous generators. However, since equilibrium speed differences are not very important, the conclusions extracted can be applied to induction generator wind farms.

There are a number of engineering problems to be considered when designing a variable frequency offshore wind farm, ranging from stability and reactive power control to the electrical protections. These engineering problems are out of the scope of the present work, which is focused on evaluating the increase of power generation for variable frequency grids.

4.2. Evaluation procedure

The employed evaluation methodology is sketched in Fig. 7 for a wind farm of N_{wt} wind turbines. It consists in a massive analysis of different scenarios in order to extract conclusions about the amount of power generated with a variable frequency wind farm.

Two different simulations loops are executed:

- Analysis for different wind speeds: According to the data provided by means of Weibull parameters, different winds for the different wind turbines are generated randomly. The generated wind speeds are provided to the other loop to analyze the power generated for different frequencies. The loop is executed $N_{simulation}$ times. In order to get relevant results, $N_{simulation}$ should be at least 1000.
- Analysis for different frequencies: For given wind speeds, a sweep of all the electrical frequencies is undergone for N_{freq} frequencies, calculating for each of them the equilibrium point and the electrical power generated.

The equilibrium states λ_i and C_{pi} with $i \in 1, \ldots, N_{wt}$ are found:

$$C_{pi} = c_1\left(c_2\left(\frac{1}{\lambda} - c_9\right) - c_6\right)e^{-c_7\left(\frac{1}{\lambda} - c_9\right)} \tag{12}$$

$$\lambda_i = \frac{\omega_e R}{P v_w N_{mult}} \tag{13}$$

where ω_e is the electrical pulsation and P the generator pole pairs. ω_e and the wind speeds v_i are known inputs. Pitch angle θ_{pitch} is assumed to be 0. The total generated power is computed:

$$P_{total} = \frac{\rho A}{2}\sum_{i=1}^{N_{wt}} C_{pi} v_i^3 \tag{14}$$

The analysis of the whole system for given input wind speeds v_i provides an optimum electrical frequency which maximizes the power generation. For each wind scenario, an optimum frequency f_j^{opt} is found whose generated power is P_{tot-j}^{opt}. This optimum can be considered in *per unit* dividing P_{tot-j}^{opt} into the maximum possible power P_{tot-j}^{max} which corresponds to the power generated when operating all the wind turbines with the maximum power coefficient. A ratio α_{VF} can be defined as

$$\alpha_{VF} = \frac{P_{tot-j}^{opt}}{P_{tot-j}^{max}} \tag{15}$$

The 50 Hz generated power P_{tot-j}^{50} can be also expressed in *per unit* dividing by the maximum possible power P_{tot-j}^{max}. A ratio α_{CF} can be defined as

$$\alpha_{CF} = \frac{P_{tot-j}^{50}}{P_{tot-j}^{max}} \tag{16}$$

Repeating this analysis for all the wind scenarios, the average variable frequency in *per unit* can be compared to the 50 Hz in order to assess the power capture optimization when operating the wind farm at variable frequency.

5. Case study

The proposed methodology has been applied to a wind farm composed of four wind turbines with the characteristics shown in the Appendix.

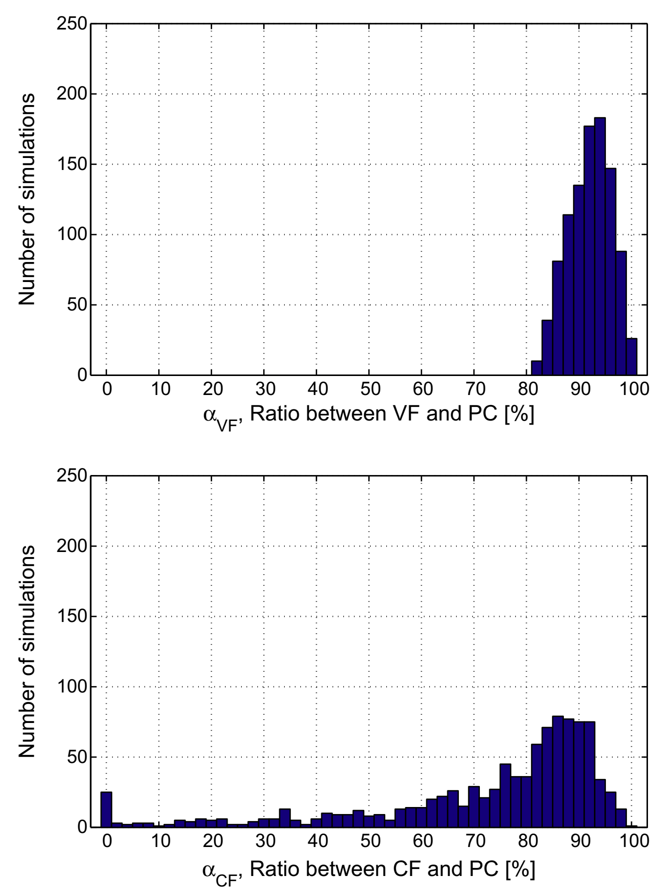

Fig. 8. Comparison of the power obtained with a 50 Hz and a variable frequency wind farm.

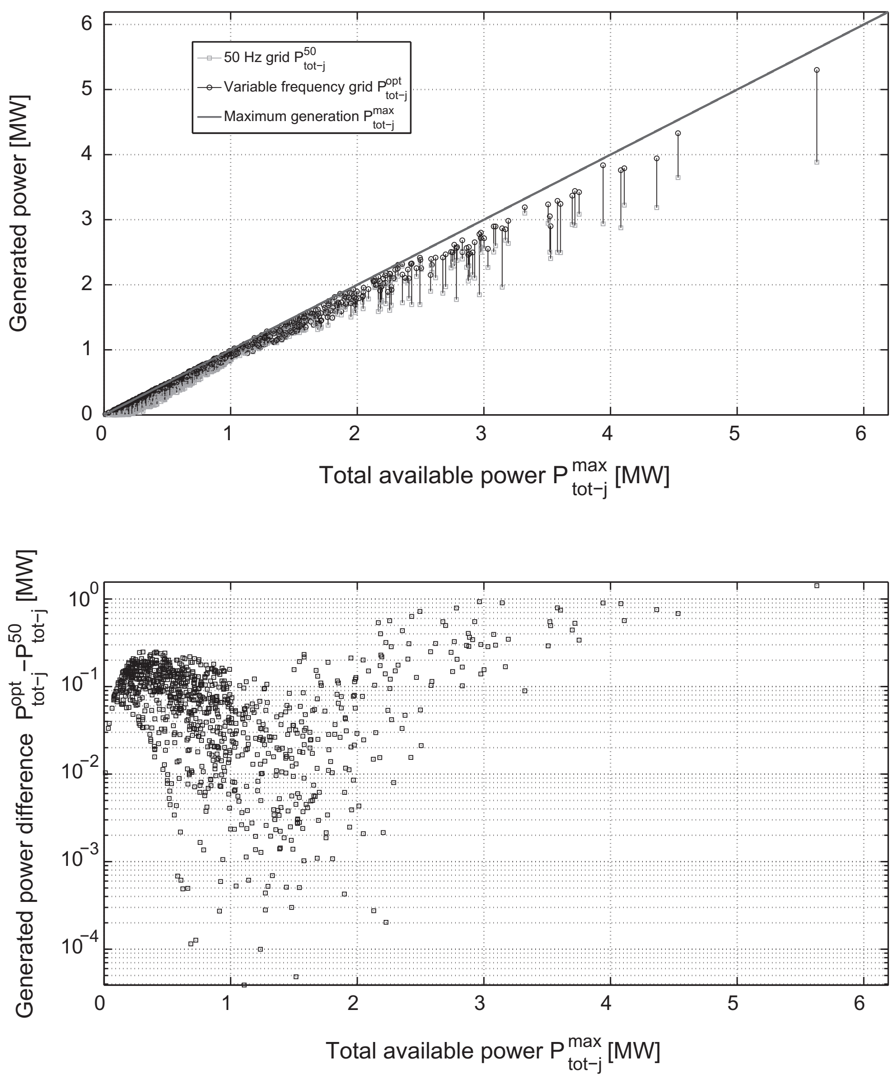

Fig. 9. Comparison of the power obtained with a 50 Hz and a variable frequency wind farm for different available power values.

One thousand different wind scenarios have been generated randomly using a Weibull distribution with typical values for offshore wind farms (scale factor of 6 and shape factor of 2).

The results allow to compare a 50 Hz conventional wind farm (CF) with a variable frequency wind farm (VF) and a wind farm with individual power converter in each wind turbine (PC). In Figs. 8 and 9 it is clearly shown how the power production is substantially incremented when varying the system frequency. The histograms of Fig. 8 show the number of simulations corresponding to each ratio α_{VF} and α_{CF}. For PC it is not necessary to illustrate it graphically, since all 1000 simulations provide the maximum available power. For VF and CF, it can be seen that while the power generated with CF is very reduced for some situations (see the bars in the left and center of the bottom figure), for variable frequency grids it is concentrated above 90% of the available power. The average value for CF is 70.6% of the available power, while for VF this figure is increased to 92.07%. For PC 100% of the available power can be obtained.

The same conclusion can be extracted from Fig. 9, where the 50 Hz grid and the variable frequency are compared for different available wind powers. It can be noted that the difference is specially significant for low and high available power, while for average values the difference is not as big in such extreme cases. This is because the 50 Hz grid is designed precisely for these average values.

Some samples of the 1000 cases studied of the power generated variation for different electrical frequencies are shown in Fig. 10, it can be noted that the shape of the curve depends importantly on the wind speeds of the different turbines. The circular marker shows the selected optimum frequency, while the squared marker shows 50 Hz.

6. Conclusions

The paper has presented an evaluation of power generated by variable and constant frequency wind farms connected to a single large power converter. A methodology has been presented, including the analysis of different wind speed cases generated randomly by a Weibull distribution and considering different electrical grid frequencies. The methodology has been applied to a case study with a wind farm composed of four synchronous generator based wind turbines.

It has been shown that a significant power increase of more than 20% (between VF and CF) can be obtained by applying the appropriate variable frequency. The variable frequency VF and constant frequency CF schemes have been compared power generated by a wind farm with individual power converters for each wind turbine PC. Results show that VF achieves 92.1% of PC power and CF 70.6% of PC power.

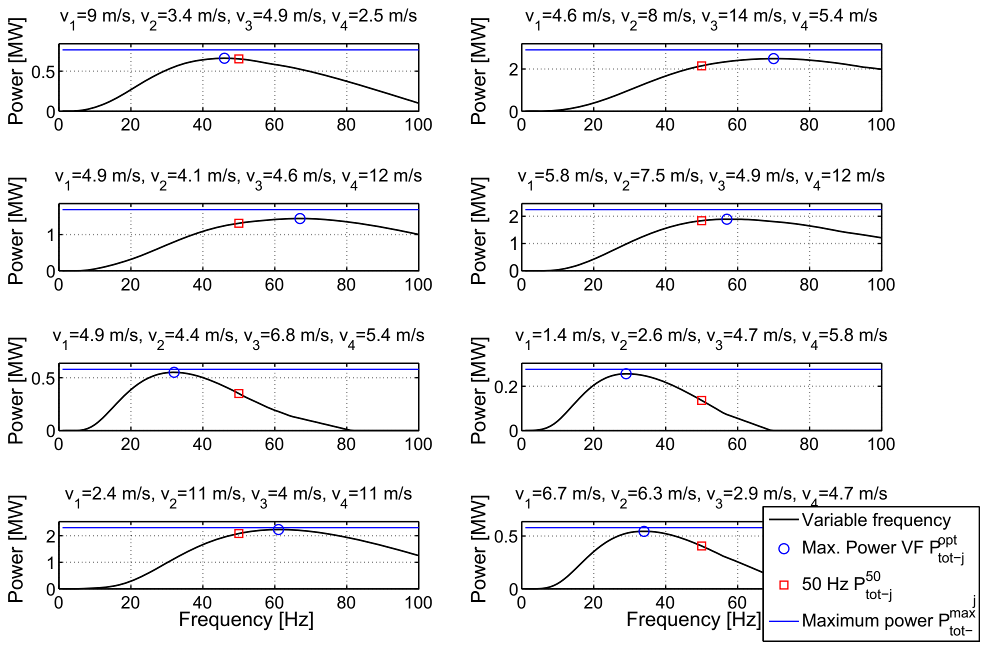

Fig. 10. Example generated power variations for different electrical frequencies.

The results suggest a good potential for VF wind farms which show more power generation than CF. Compared to PC, although power generation is 8% lower, VF shows the following advantages: lower cost, lower maintenance requirements which are especially critical for offshore wind farms, higher reliability due to the lower number of components which can eventually present problems and lower converter losses.

Acknowledgements

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Appendix A

A wind farm with four wind turbines has been considered. The pitch angle is assumed of 0, and the power coefficient C_p is computed according to (2) for all the turbines as

$$C_p = 0.44\left(125\left(\frac{1}{\lambda}+0.002\right)-6.94\right)e^{-16.5\left(\frac{1}{\lambda}+0.002\right)} \tag{17}$$

Wind speeds have been generated with a Weibull distribution with scale factor 6 and shape factor 2. The cut-in speed has been assumed 2.5 and the cut-off speed 15 m/s.

The wind turbine has a radius of 30 m. The gearbox multiplication factor is of 60. The assumed air density is of $\rho = 1.225\ \mathrm{kg\ m^{-3}}$. The considered synchronous generators have four poles, rated power of 2 MW and nominal voltage of 960 V. The wind farm voltage is of 25 kV and the HVDC voltage 150 kV. The power transformers of each wind turbine is rated to 2.5 MVA and the wind farm transformer to 10 MVA.

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