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VOLTAGE REGULATION OF DISTRIBUTION NETWORKS THROUGH REACTIVE POWER CONTROL

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Abstract: Until recent years, the connection of dispersed Independent Power Producers to electrical networks has not been a problem for utilities, due to the fact that installed power represented a small amount of the total power connected to the system. But in the last few years this scenario is changing and especially wind energy has turn out to be one of the most important and promising sources of renewable energy. Consequently, it is reasonable to think that wind generators should take part in the control of electrical variables of the network they are connected to. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Distributed energy generation is becoming one of the most important energy sources along the last few years. Even if these generation units bring important advantages for utilities and customers, the problems associated to the total amount of power connected to a distribution network are continuously increasing. As an example, problems related to the no-regulation of frequency and voltage of those units, problems related to the non-dispatchable characteristic of most the dispersed generation and those related to assets management could be mentioned.

Several types of electric power generation are emerging with different degrees of development and future prospective (co-generating units, PV cells, combustion cells, etc), but today, one type of units – wind farms- is increasing its presence in a continuous and amazing way. This can be due to several reasons: wind units are available in an useful amount of power, they are zero fuel cost, their production is environmentally clean, etc.

In order to avoid the fact that dispersed and not controlled generation adds risks to exploitation of electrical systems and decreases the quality of electrical service (electrical variables out of exploitation range, risk of outages, etc.), Spanish utilities work trying to properly locate new generation units and more recently, to control the voltage in new types of wind driven generators.

The first stage of the work presented in this paper has been tackled in order to achieve proper locations for new wind farms and to evaluate their impact on the electrical network. Consequently, an accurate wind farm model for the network analysis programs has been developed.

Then, the possibility of a voltage control (through the reactive power control) has been explored for wind farms endowed with doubly fed induction machines (the new type of generators that are used in the lately built wind farms in Spain).

2. WIND GENERATOR MODELLING

The first step of the work developed in order to obtain the wind farm model was to analyse the double fed induction generator, the most widely used generator in the Spanish wind farms. To model a double fed induction machine (DFIM) under different wind speeds, it is important to consider that this kind of wound rotor machine has to be fed both from stator and rotor sides, Fig. 1.

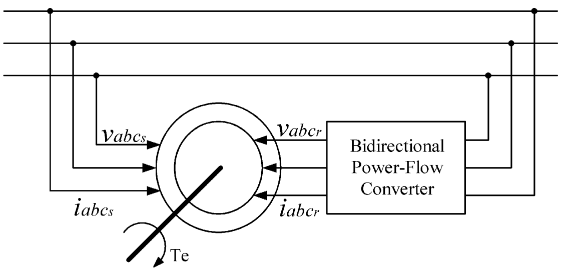

Figure 1. Double fed induction machine

Normally, the stator is directly connected to the grid and the rotor is interfaced through a variable frequency power converter. In order to cover a wide operation range from subsynchronous to supersynchronous speeds, the power converter placed on the rotor side has to be able to operate with power flowing in both directions. This is achieved by means of a back-to-back PWM inverter configuration. The operating principle of a DFIM can be analysed using the classical theory of rotating fields and the well-known d-q model, as well as both three-to-two and two-to-three axes transformations, Vas (1990).

In order to deal with the machine dynamic behaviour in the most realistic possible way, both stator and rotor variables are referred to their corresponding natural reference frames. In other words, the stator side current and voltage components are referred to a stationary reference frame, while the rotor side current and voltage components are referred to a reference frame rotating at rotor electrical speed, ω_r. When aiming to express the induction machine electrical model in the above-mentioned reference frames, it is first necessary to perform the Clarke´s transformation, Vas (1990) from the three-phase to the d-q current and voltage system.

In this way, taking the general three-phase model of the electric machine dynamic performance as a starting point, the “Quadrature-Phase Slip-Ring” model [10] for the DFIM might be expressed through the following matrix equation

$$\begin{bmatrix} u_{sD} \\ u_{sQ} \\ u_{r\alpha} \\ u_{r\beta} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m\cos\theta_r & -pL_m sin\theta_r \\ 0 & R_s + pL_s & pL_m sin\theta_r & pL_m\cos\theta_r \\ pL_m\cos\theta_r & pL_m sin\theta_r & R_r + pL_r & 0 \\ -pL_m sin\theta_r & pL_m\cos\theta_r & 0 & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{sD} \\ i_{sQ} \\ i_{r\alpha} \\ i_{r\beta} \end{bmatrix} \quad (1)$$

where, L_s and L_r are the stator and rotor side inductances, L_m is the magnetising inductance, R_r and R_s are the stator and rotor side resistances, θ_r, is the rotor angle (variable) and p corresponds to the derivative operation, p = d/dt. The roles of current and voltage components in (1) need to be interchanged so as to treat voltages as independent variables —system inputs— and currents as dependent variables —system outputs—, as corresponds to a voltage fed doubly fed induction generator (DFIG).

Fig. 2 represents a typical DFIM control structure that works with two cascaded control loops. The inner loop (stator-flux oriented vector control) task consists in controlling independently the rotor current direct - i_{rx} - and quadrature – i_{ry}- components expressed according to the reference frame fixed to the stator-flux linkage space phasor. Two identical PI controllers are typically used to implement this inner control loop. The outer one, governs both the stator side active and reactive powers.

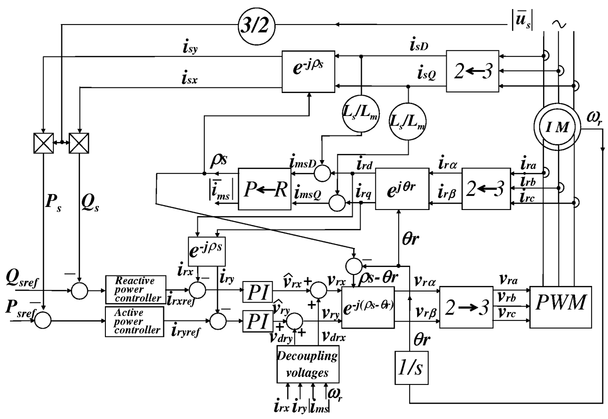

Fig. 2. Overall control structure for the DFIM

2.1 Operating conditions

In order to develop a correct model of the wind generator, some operative restrictions must be considered. Firstly, the reactive power generation/absorption capability for each generated active power of the modelled generator (a 660 kW generator) must be considered, that means, the typical P/Q curves depending on the ambient temperature.

On the other hand, the currents that can be driven by the double-sided PWM must be analysed to obtain the operative conditions. From these really performed tests, the curves appearing in Fig. 3 have been obtained.

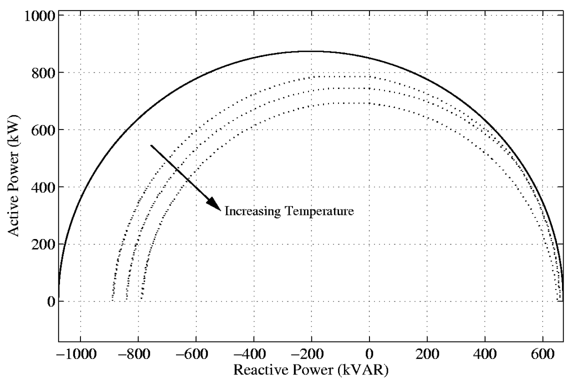

Fig. 3. P/Q curves for the generator + inverter

It can be seen that the outer curve, corresponding to the limitations imposed by the inverter are less restrictive than those fixed by the generator itself. Consequently, it must be ensured that the operation range of the generator is always maintained inside the most restrictive curve, the one obtained for the hotter ambient temperature, Fig. 4

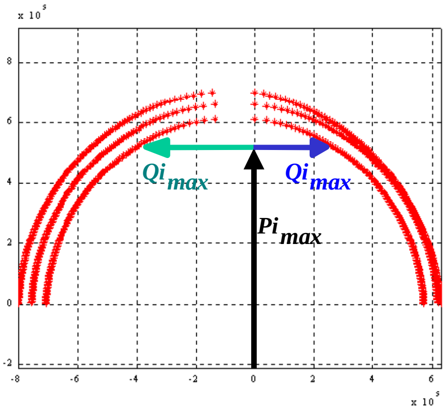

Fig. 4. Limitation for the P/Q operation in the DFIM generator

2.2 Experimental validation of the model

Prior modelling the complete wind farm, the validity of the developed DFIM model must be demonstrated. Table I presents the main parameters, referred to a 20º C ambient temperature, of a typical double fed induction machine of 660kW that is used in a wind farm deployment.

Table I. DFIG electric parameters

Parameter	Value
R_s, stator resistance per phase	0.0067 Ω
X_{sl}, stator leakage reactance per phase	0.0300 Ω
n, general turns ratio	0.3806
X_m, mutual reactance	2.3161 Ω
R_r, rotor resistance per phase	0.0399 Ω
X_{rl}, rotor leakage reactance per phase	0.3490 Ω

The model presented in section 2 has been implemented under the MATLAB/SIMULINK simulation package. Fig. 5 and Fig. 6 show respectively, the dynamic behaviour of the simulated and the real 660 kW generator dynamic performance when, generating 300 kW as a result of the wind speed with a cosφ=1, a power factor set-point change takes place. This new set point corresponds to a cosφ=0.857 capacitive power factor. Generated active and reactive powers are considered to be positive. Since wind conditions remain constant during the whole trial, it can be seen how the generated active power is not changed, while the generated reactive power varies rapidly so as to track the new power factor set point.

It can be seen from Figs. 5 and 6 that the model dynamic performance corresponds exactly with the real generator performance and so, it will be used to develop a complete wind farm model.

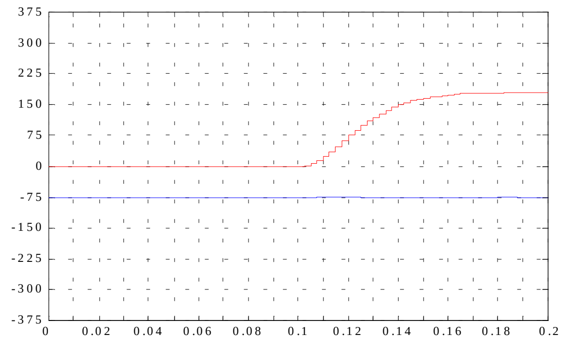

Fig. 5. Generator model performance under step changes in the power factor

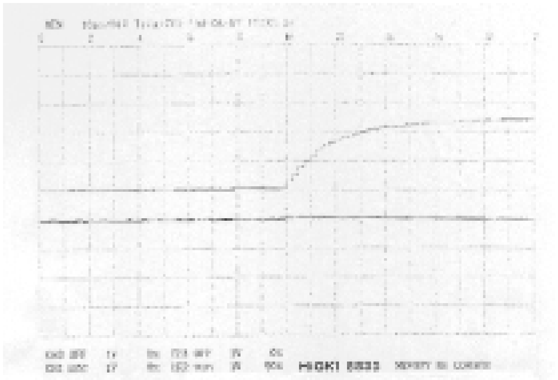

Fig. 6. Real generator performance under step changes in the power factor

3. WIND FARM MODELLING

To model a wind farm made up of doubly fed induction machines, n generators parallel connected to an infinite bus have been considered.

Even if the wind speed on each generator can be quite different (some generators can be disconnected while others are generating at their maximum level), the total active and reactive power of the farm can be represented as the sum of the active and reactive power generated by each windmill in the farm, (2).

$$\begin{aligned} P_{s\ total} &= \sum_{i=1}^{n} p_i \\ Q_{s\ total} &= \sum_{i=1}^{n} q_i \end{aligned} \qquad (2)$$

where, P_{stotal} represents the generated active power in the wind farm, Q_{stotal} represents the generated/absorbed reactive power in the wind farm, p_i represents the generated active power by each i generator and q_i, the generated/absorbed reactive power by each i generator.

Figs. 7 a) and b) present some simulation results of the performance of a wind farm, with n=37 generators, under step changes in the power factor. The simulation has been made in order to observe the wind farm performance when the power factor changes at t=0.01 from cos φ = 1 to cos φ = 0.98 in Fig. 7 a) and from cos φ = 1 to cos φ = 0.9 in Fig. 7 b). As only 0.12 seconds are represented, the wind speed has been considered constant during that period.

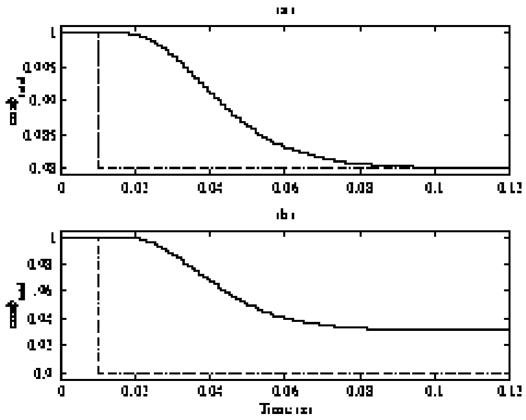

Fig. 7. Farm performance under step changes in the power factor set-point

It has to be pointed out that the wind farm performance follows a first order system response. This dynamic performance matches the response that a single generator had, with almost the same time-constant, Fig. 5. The power factor set point in Fig. 7 b) is not reached due to the safety-levels imposed on each generator. The wind speed hitting the blades of some generators can cause an important level of active power generation and consequently, because of the safety-level limitation in the PQ curves of those generators, the reference power factor (reactive power), can not be reached.

4. REACTIVE POWER CONTROL

Once the wind farm made up of doubly fed induction machines has been completely modelled, a control strategy for the reactive power control has been proposed. As it has been mentioned above, the operation limitations of the generator are quite important in order to ensure a correct dynamic performance of the generator and a sufficient security-level from the maintenance point of view.

So, the developed control algorithm tries to distribute the reactive power that the farm has to generate/absorb in a proportional way, taking always into account the instantaneous active power generation level of each generator, (3).

$$q_{eisp} = \frac{Q_{eref}}{Q_{emax}} * q_{eimax}$$
$$Q_{emax} = \sum_{i=1}^{n} q_{eimax} \qquad (3)$$

where q_{eisp} is the reactive power set point calculated for each generator, q_{eimax} is the maximum of the reactive power that each machine can generate and Q_{eref} is the reactive power reference for the farm.

The proportional distribution algorithm has to measure the working conditions (generated active power and P/Q limits) of each generator and then, obtain the reactive power generation demanded for each machine. The used algorithm is based on the control-law described by (3) and represented in Fig. 8.

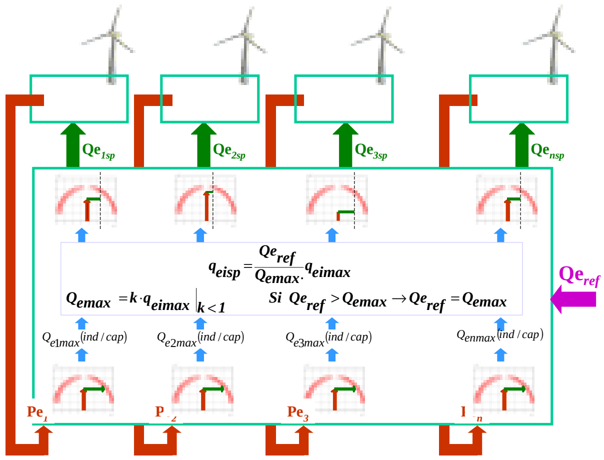

Fig. 8. Implementation of the control law.

4.1 Simulation results

Some simulations have been performed under MATLAB/SIMULINK package, for a wind farm made up of 37 generators parallel connected. The above mentioned tests were simulated under different communication conditions, but under the best ones, simultaneous measurements of P and Q for each machine and simultaneous sent of set-points to all generators, very adequate results have been obtained, Fig. 9.

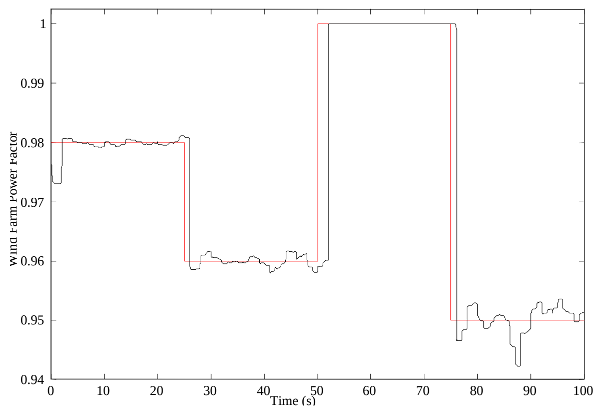

Fig. 9. Dynamic power factor performance

It has to be pointed out that for decreasing power factors, less than 0.95, some oscillations occur due to the fact that some generators can be in their saturation limits because of the wind speed changes.

Anyway, from the obtained results it can be concluded that the developed control algorithm can be perfectly implemented in the real farm with results that are expected to be adequate.

4.2 Experimental results

Several simulation tests have been performed under MATLAB/SIMULINK simulation package in order to ensure the correct performance of the developed algorithm and once the needed improvements have been completed in the real farm communication network, the reactive power control-law has been implemented in the central computer of the wind farm.

Some of the real results obtained under step changes in the power factor appear in Fig. 10.

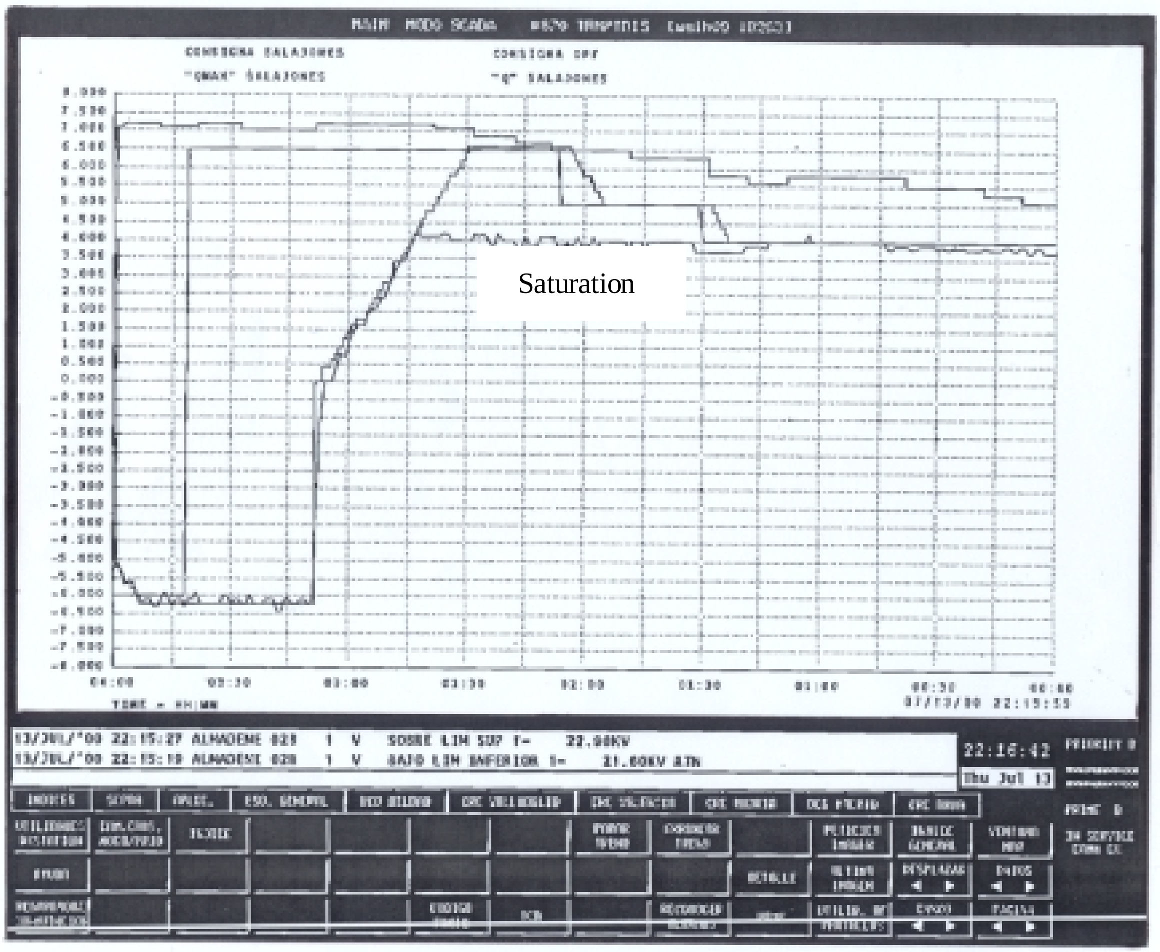

Fig. 10. Reactive power control of the farm

In the performed test, the reactive power set point for the farm is sent in 200 kVAR steps. It can be seen that there is a saturation because the instantaneous wind speed on each generator, causes some of them to work in the reactive power generation limits. Anyway, the set-point is correctly tracked along the test even if some communication faults occur during the first part of the test.

It can be seen from Fig. 10 that the first results obtained from the application of the developed control law can be used to ensure a good performance of the farm under step changes in the reactive power generation level, always maintaining the active power generation in its optimum limits.

5. VOLTAGE CONTROL

The results obtained for the reactive power regulation are satisfactory enough to enable the electric company to fix the reactive power control for each farm, with the data obtained from an OPF algorithm.

The problem that can appear in this stage of the work is that the farm tracks perfectly the required reactive power but because of sudden changes in the electric network topology, some voltage-level violations can occur. Consequently, even if a complete voltage control algorithm has not yet been developed, some security levels have been imposed in the reactive power control and the voltage-level can be always ensured.

For the security level implementation, three voltage levels have been fixed: V_{normal}, $V_{admissible}$ and V_{secure}, Fig. 11.

If $V_{min\ normal} \leq V \leq V_{max\ normal}$, the developed proportional distribution reactive power regulation can be applied, that means, the control law (3) is directly applied.

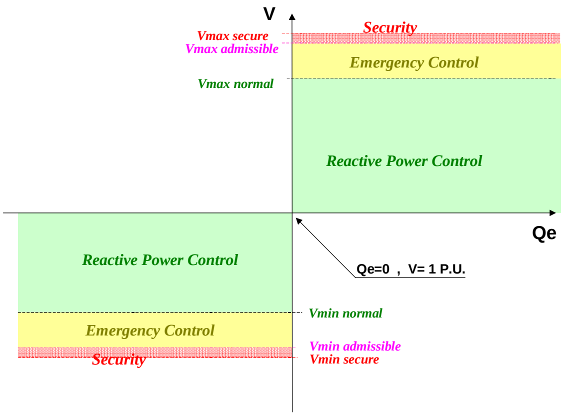

Fig. 11. Voltage levels for a secure reactive power control

If $V_{max\ normal} \leq V \leq V_{max\ admissible}$ an emergency control is developed. In this second area, the new reactive power set point (obtained from the application of the proportional control law) is accepted if it is less than the previous one. If it is greater, then the old reactive power set point will be applied. The same occurs if $V_{mim\ normal} \leq V \leq V_{mim\ admissible}$, but in the opposite sense.

Finally, if $V_{max\ admissible} \leq V \leq V_{max\ secure}$, the reactive power set point is automatically and continuously decreased in order to maintain the voltage level under security conditions. That means, that the developed control law is not applied and the reactive power set point is decreased or increased through continuous steps until the $V_{admissible}$ level is reached. As in the previous case, the same occurs for $V_{min\ admissible} \leq V \leq V_{min\ secure}$ in the opposite sense.

Anyway, if any of the previously mentioned actions is enough and the last voltage level is reached, $V=_{Vminsecure}$ or $V=_{Vmaxsecure}$ the power factor of the farm is automatically reset to $\cos\varphi = 1$.

Through all this regulation levels, the reactive power control is ensured but at the same time, the voltage level will be maintained inside the permitted limits.

6. CONCLUSIONS

From the results obtained in all the simulations and real experiments that have been performed, it can be concluded that wind farms made up with double fed induction generators constitute an important tool from the voltage regulation point of view.

Double fed induction machines have a much better dynamic performance than squirrel cage ones and do not need capacitors. They are strongly recommended for the new wind farms from the power system viewpoint, especially in areas with a large wind generation concentration.

Additionally, it is important to consider a complete voltage regulation system for the wind farms connected to the electrical network, in order to ensure the utility and effectiveness of the developed and probed reactive power control.

In order to allow the maximum power to be connected to electrical subsystems, studies for each particular situation should be the way that dictate the possibility and constraints for new wind farm connections. Moreover, to avoid problems when weaker connectivities of a subsystem with its feeding networks exist, remote tripping for selected wind-farms should be set.

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