Impact of Large Wind Power Generation on Frequency Stability

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Abstract-- **This paper explores the available control options for enabling wind power generation plants to participate on the maintenance of system frequency following a major power imbalance. Taking the currently employed control structures for wind generators as the baseline case, possible expansions and additional features have been discussed. The options include voltage or alternatively frequency dependent active power control. The responses of these control schemes vis-à-vis their frequency supporting capability in a power system contingency situation have been simulated and with one another compared. It was found out that at the conceptual level there are indeed a range of options which would place wind generating plants in a position to support system frequency in an emergency situation.**

***Index Terms*—Wind power, Wind generator control, Frequency stability, Interconnected system**

I. Introduction

THE rapid expansion of wind power generation experienced during the past decade is, in all likelihood, set to continue well into the future. Germany, maintaining its precursor role in terms of installed wind capacity, has set itself some ambitious goals. By 2010, the proportion of electricity consumption to be covered by renewable energies is envisaged to rise to at least 12.5%, and further down the line to at least 20% by 2020. Preliminary studies foresee further significant increases in the timeframe extending to the year 2050.

Wind being the only renewable energy resource capable of meeting the projected goals in the near to medium term, it is safe to conclude that most of the anticipated increases in renewable energy is going to be wind based. Consequently, in addition to the current large number of onshore sites, many offshore sites are in the planning or implementation stages. The installed capacity of the offshore plants in the North and Baltic seas is expected to reach 2-3 GW by 2010. This figure is projected to rise to 20 – 25 GW by 2030.

It is already clear that the interconnected European network (UCTE) will, for example, have to accommodate a significant wind power component in the years to come and wind, in all probability, will feature prominently in the generation mix in many parts of the world. The task at hand, therefore, is the efficient integration of both on- and offshore wind power plants into the interconnected power system by maintaining the current level of system security.

Apart from the overall share of wind power, many large off- and onshore wind farms already possess generating capabilities on a scale of conventional power plants, and the number of in-feed points into the network from such plants will continually increase in the years to come. This together with the prominence that wind power has attained in relation to the aggregate system-wide power underscores the need for wind farms to be in a position to undertake tasks necessary for maintaining system frequency within the prescribed tolerance band. This task is currently considered to be the exclusive responsibility of conventional power plants. Moreover, the performance of the wind generating plants during a contingency situation, particularly their fault ride-through capability, and the impact that the wind plants make on the rest of the system is an issue of immense interest. There is a strong need now, for example, for power system operators to carry out stability analysis of the whole power system including dynamic models of the wind farms [1].

In earlier papers, the effect of the increased share of wind power on system frequency and voltage profile was presented [2], [3]. This paper builds on those studies and aims to assess the impact of a much larger share of wind power (exceeding 50% of the overall power) on system frequency and voltage profile during a contingency situation. The paper then will dwell on possible control measures to be implemented in wind generating plants to counter the frequency sag arising from a sudden loss of generation or increase in system load. Taking the existing control systems for wind generators as the baseline case, possible expansions and additional features capable of providing frequency support are explored and their performance evaluated.

II. Description of the Test System

Before delving into the detailed discussion of the alternative control options, some background information pertaining to the test system is provided below.

A. The test network

The test network to be used for this simulation is a 137-bus system containing 16 conventional power plants, 28 transformers and 124 transmission lines. The one-line diagram of the network is given as Fig. 1. The letters A to H in the

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diagram indicate the points of connection for the wind generators replacing conventional plants. The system includes hydro, nuclear and thermal conventional power plants. The total system-wide installed capacity is 15860 MW, of which 160 MW is earmarked for primary control to be provided by only four of the conventional generating plants. The network encompasses the voltage levels 380 kV, 220 kV and 110 kV. For all network elements, including the generators and their controllers, real data from existing networks has been used. The generators are represented using their 5th order models extended by IEEE-type excitation and governor models. The frequency and voltage dependency of the loads have also been considered.

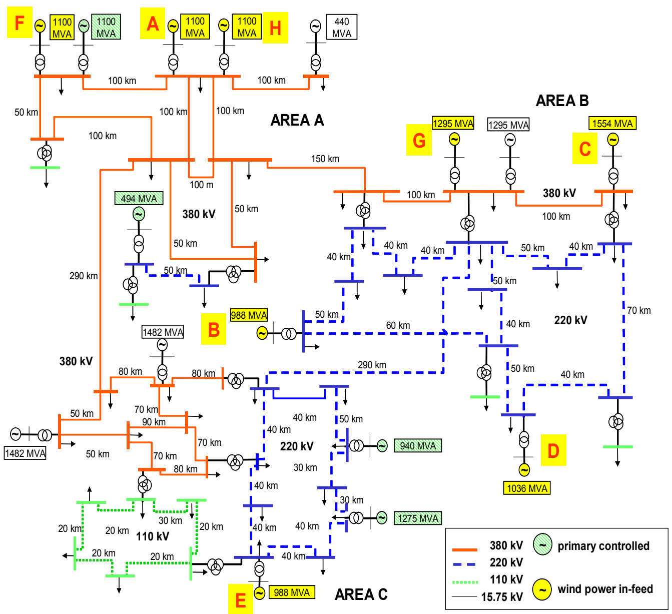

Fig. 1. One-line diagram of the test network

B. Control of the doubly-fed induction machine (DFIM)

The objective of this study, as stated above, is to assess the impact on system frequency of the increasing share of wind power in relation to the overall power during a large power unbalance within the system. For this purpose, some of the conventional plants are to be replaced by wind generation plants in stages, staggered incrementally as follows:

TABLE I
CONNECTION POINTS FOR WIND GENERATION PLANTS AND THE RESULTING WIND POWER IN RELATION TO THE OVERALL POWER

Point of connection	A	B	C	D	E	F	G	H
Overall share of wind power (%)	6.3	12	20.4	26.4	31.8	38.1	45.6	51.9

The impact of each addition, starting from A (6.3% wind power) to all others up to H (51.9%), has been studied separately. All wind generators replacing these conventional plants are assumed to be of the DFIM type.

The DFIM encompasses two control structures, the fast electrical control and the slower mechanical pitch-angle control as shown in Fig.2. Depending on the wind speed the turbine operates in full or partial load mode. Beyond a certain wind speed, the output power is limited by the pitch-angle control of the turbine blades. In part-load mode, the turbine is adjusted for the maximum available power. Therefore, the blades are turned fully into the wind. The optimum rotor speed is adjusted to follow a characteristic diagram to track the maximum power points. This maximum power is then passed on to the fast electrical converter control as the power reference through the control block with the transfer function $F_1(s)$. The speed is kept at the optimum level by the speed control denoted as $F_2(s)$ providing the reference pitch-angle to the blade drive mechanism, denoted by $F_3(s)$. The mechanical torque is then computed based on the Cp characteristic of the turbine.

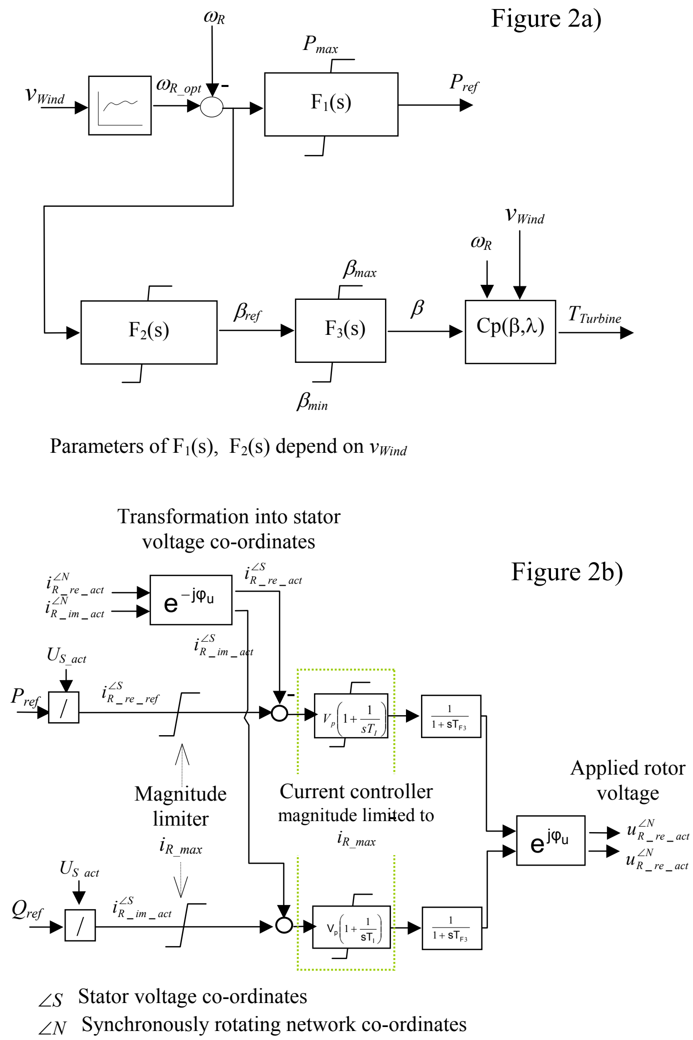

Fig. 2. Control schema of DFIM; 2a) Determination of P_{ref} and pitch angle control; 2b) Current control

The fast electrical control consists of two decoupled control channels, which act via a converter unit on the rotor circuit. The fact that the frequency and the amplitude of the rotor voltage can be varied independently from one another permits a decoupled control of P and Q. The reactive power can be set at any value within the capabilities of the machine, usually described by the active and reactive current operating chart. However, the reference value in this study is set to zero apart from the case where the voltage control prescribes a different reactive power generation (see Fig. 5). Issues related to voltage control will be discussed in more detail in the subsequent chapters in this paper.

The mechanical torque and the two components of the rotor voltage are input variables to the electromechanical DFIM model. The DFIM itself is represented by its reduced 3rd order model.

C. *Configuration of the wind farm*

As is well known, the output power of the wind plant depends strongly on the wind speed. Due to the random nature of wind speed, a wind plant replacing a conventional power plant and that is expected to deliver the same amount of power needs to have a larger size. The installed capacity of the wind farms in this case is determined to be 1.5 times larger than the capacity of the conventional power plant replacing them.

The nominal output power of one of the wind farms, for example, is 1650 MVA. This corresponds to the output of 528 pitch controlled DFIM, each with a nominal capacity of about 3 MVA. The individual units have been represented by a single equivalent model. Figure 3 shows the interconnection of the wind units to one another and then to an onshore bus.

It is necessary to ensure that the simulation with and without wind power generation has the same initial conditions so that the results can be compared with one another. This implies that during normal operation, the wind farms need to feed the same amount of active and reactive power at the same voltage as the conventional power plants they are replacing. For this purpose an optimization algorithm was implemented in the software package used, which varies the active and reactive power generated by the wind plants until the load flow (with and without wind generation) matched.

Because the study essentially focuses on frequency stability following large disturbances, it is necessary to describe voltage and frequency dependency of the loads. The corresponding model is represented by equation (1).

$$P = P_0 \cdot \left(\frac{U}{U_0}\right)^{pu} \cdot \left(\frac{f}{f_0}\right)^{pf} \qquad pu = 1.5 \quad pf = 0.7$$
$$Q = Q_0 \cdot \left(\frac{U}{U_0}\right)^{qu} \cdot \left(\frac{f}{f_0}\right)^{qf} \qquad qu = 2.7 \quad qf = -0.1 \qquad (1)$$

The numerical values for voltage and frequency dependency indices used in this study are based on the results of an extensive study carried out on the German network in the late 1980s [6]. It should be underscored at this point that the behavior of the aggregate load to change with voltage magnitude and frequency plays an important role in the discussions to follow.

III. WIND GENERATOR CONTROL OPTIONS AND THEIR IMPACT ON SYSTEM FREQUENCY DURING A DISTURBANCE

The centerpiece of this study is to characterize the impact of the loss of generation on system frequency as the share of wind power increases. During the simulation, only the generation allocation is being altered in stages in favor of wind plants, with everything else including the overall generated power remaining unchanged. The disturbance may be the loss of a major tie line carrying a large amount of power or a loss of a significant amount of generation resource. In this work this has been simulated by increasing the load by 1.3 % or alternatively by 2.5 % of the total load (at cosφ = 0.98). At t=2 s the additional load is switched on at various buses concurrently.

Four of the 16 power plants are earmarked for primary control. With the primary controlled power plants deploying all the available primary reserve, the frequency deviation for a sustained load increase of 1.3 % will be 200 mHz, which corresponds to the frequency droop in the UCTE system for a similar loss of generation.

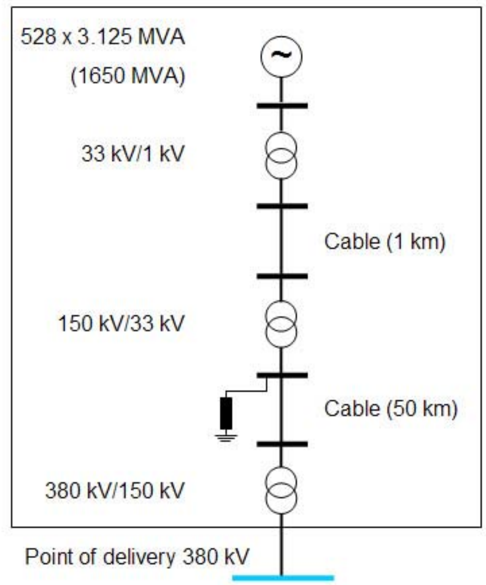

Fig. 3. Wind farm configuration

The objective now is to identify a possible control structure for wind generators that is best suited to provide frequency support during a contingency situation. Of the five control options listed below, the first two are already well-established control schemes for the DFIM. Taking these two as the baseline cases, possible improvements vis-à-vis the frequency supporting capability of the machine will be investigated. The list of the control options are:

(1) Constant P and constant Q control
(2) Constant P and constant U control
(3) Constant P and U control with superimposed static frequency dependent element
(4) Constnat P and U control with superimposed static and dynamic frequency dependent element
(5) Frequency dependent P and constant Q control

A. *Baseline case*

The basic structure for both (1) and (2) is given in Figure 2. Although the two control options are akin to one another, the response of the machine for both control approaches in terms of frequency deviation is fundamentally different. Thus, the two cases will be dealt with separately.

i. Active and reactive power control

In case of an active and reactive power control, i.e. option (1), the control structure is identical to the one in Figure 2.

Figure 4 shows the frequency characteristic, with this control option being implemented, after a loss of 2.5 % of the total generated power. The result clearly presents two contrasting pictures. In the initial phase of the disturbance, increased wind power leads to a much quicker frequency dip. However, the kink in the frequency characteristic occurs much earlier and the frequency generally settles at a higher steady state value. With the generation comprising only of conventional plants, however, the frequency drop goes on longer and a steady state deviation of 1 Hz is reached after approximately 60 s.

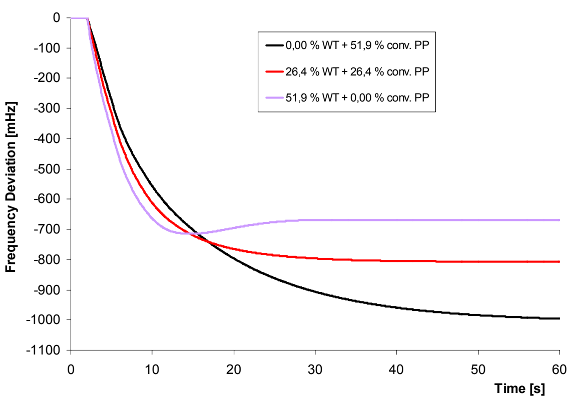

Fig. 4. Frequency deviation after a 2.5 % loss of generation, P and Q controlled DFIM

With the system containing a larger wind power, the frequency initially drops rapidly due to the fact that the DFIM is coupled indirectly to the grid via the converter. The decoupling of the machine from the grid by the converter results in the decoupling of the mechanical speed of the wind power generators from the grid frequency. In other words, the DFIM does not have significant contribution towards the overall inertia of the system, and this leads to the initial steeper drop in frequency. By contrast, synchronous generators of conventional power plants are connected directly to the grid leading to a higher inertia of the whole system. The faster transition into the steady state in the presence of larger wind power is also caused by the smaller inertia together with the fast electrical control of the DFIM (which increases the real power output quickly) as opposed to the governor control of the conventional power plants, which is much slower.

It can thus be concluded that in the later stages of the disturbance, in terms of maintaining constant frequency, the system performs better when it includes a larger wind power component. The reason for this behavior can be explained as follows. The conventional plants replaced by the wind generating plants were maintaining the voltage, and with it the load, constant by virtue of their voltage control capability, resulting in a lower frequency. The wind generation plants on the other hand are maintaining a constant reactive power output, which leads to lower voltage than what otherwise would have been with the conventional plants. This leads to the reduction of the load and thus to increase in the frequency.

ii. Active power and voltage magnitude control

In this case, each of the wind generators used in the simulation is equipped with P and U controllers of PI type. The control structure involves minor modification to Figure 2, as shown in Figure 5. The reference value (Q^*_{ref}) is now influenced by the voltage deviation. A higher voltage deviation will lead to a higher reference value Q^*_{ref}. The active power channel remains unchanged.

Figure 6 shows the frequency behavior after a loss of 2.5 % generation. The result in this case is fairly straightforward. As the share of the wind power increases, so does also the drop in frequency. For the largest wind power generation considered in this study (5%), the frequency settles below 49 Hz, which would trigger the operation of frequency relays.

The increased frequency drop observed in the immediate aftermath of the disturbance is caused by a smaller inertia support provided by wind generating plants as discussed in the previous section. The presence of voltage controllers maintains the power drawn by the load constant at nearly the pre-disturbance value. The voltage controller, by maintaining the load constant, removes the cushion that the load provides in support of the system frequency following the loss of generation.

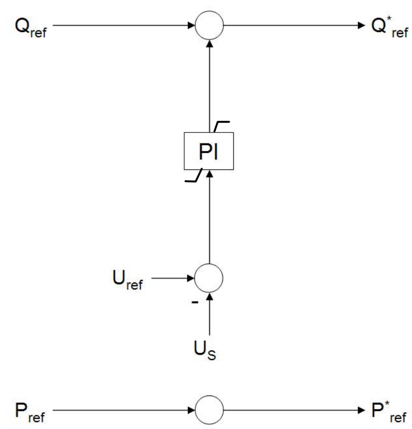

Fig. 5. Real power and voltage controller

B. *Active power and static frequency dependent voltage control*

This option involves a slight modification of the scheme discussed in the previous section (Section A(ii)). The voltage control channel is augmented by a new proportional term, whose input signal is the frequency deviation. The output is then subtracted from the voltage reference, as shown in Fig. 7. As can be seen from the signal flow chart (Fig. 7), the voltage reference is deliberately reduced when there is a frequency drop so that the power absorbed by the loads also decreases.

Additionally, a 100 mHz or alternatively a 200 mHz dead zone is introduced into the control structure to avoid any unnecessary tampering by the added element with the operation of the voltage controller.

Figure 8 shows the outcome of the simulation using this control approach. The frequency dependent voltage control improves the frequency markedly. As expected, the larger the share of the wind power, the better becomes the frequency behavior of the system. For the network used in this simulation, the gap between the most favorable (51.9% wind) and least favorable (no wind power) scenarios turned out to be 820 mHz. The behavior of the system for 100 mHz and 200 mHz dead zones is essentially similar, with the 100 mHz dead zone resulting in a smaller steady state frequency deviation as a result of the fact that the frequency dependent element becomes active earlier in the aftermath of the disturbance.

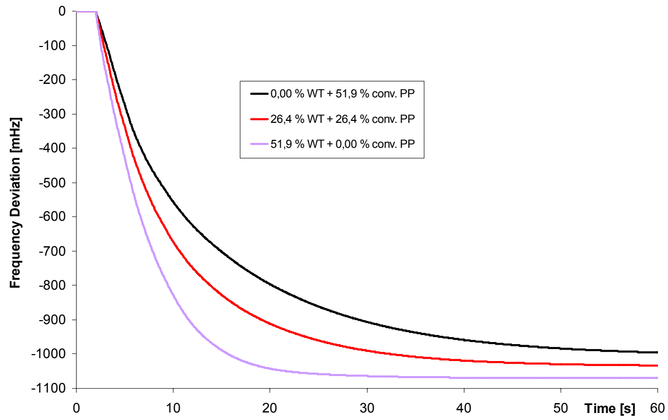

Fig. 6. Frequency deviation after a loss of 2.5 % generation, P and U controlled DFIM

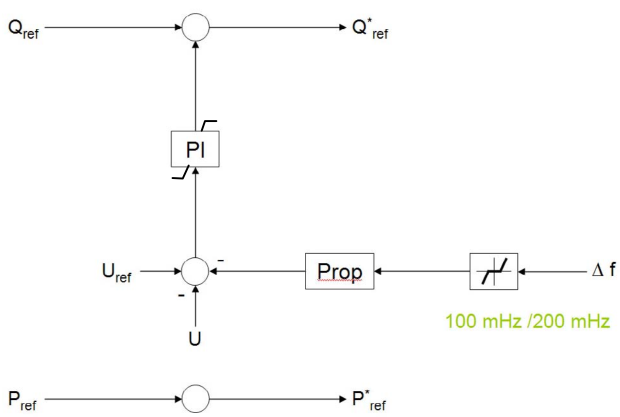

Fig. 7. P and static frequency dependent U controller

C. Static and dynamic frequency dependent voltage control

This option involves the expansion of the static frequency dependent voltage control described in the previous section by an additional, dynamic frequency element. The additional controller (also called "booster") is chosen to be a differential element. The structure of the setup is shown in Fig. 9. The reaction of the differential controller depends on the rate of change of the frequency. At frequencies below the nominal value, the booster is adjusted to become active only when the frequency gradient is negative. In other words, it acts only to stop the frequency decline and once this has been achieved (i.e. during the positive slope) the booster becomes inactive. Similar behavior can be realized when the frequency exceeds the nominal value and continues to increase. Activating the booster requires in this case positive frequency gradients.

Figure 10 shows the system frequency during the disturbance. The plot with the sustained drop in frequency describes the frequency characteristic for no wind power. The effect that the frequency dependent voltage control achieves is significant. For the largest wind power component, i.e. for a wind power share of 51.9%, the improvement in terms of frequency for the test network chosen here is approximately 850 mHz. The difference between the 100 mHz or 200 mHz dead zone is marginal, as discussed in the previous section.

The voltage controller augmented by a superimposed frequency control loop is impacting the system frequency indirectly. Because of the additional frequency dependent signal, the voltage reference value will be reduced. As a result, the voltage level within the grid is also slightly reduced, which leads to less power being drawn by the load. As a result, the power balance is reached faster. This can also be attained by using a simple proportional frequency dependet term for the voltage controller.

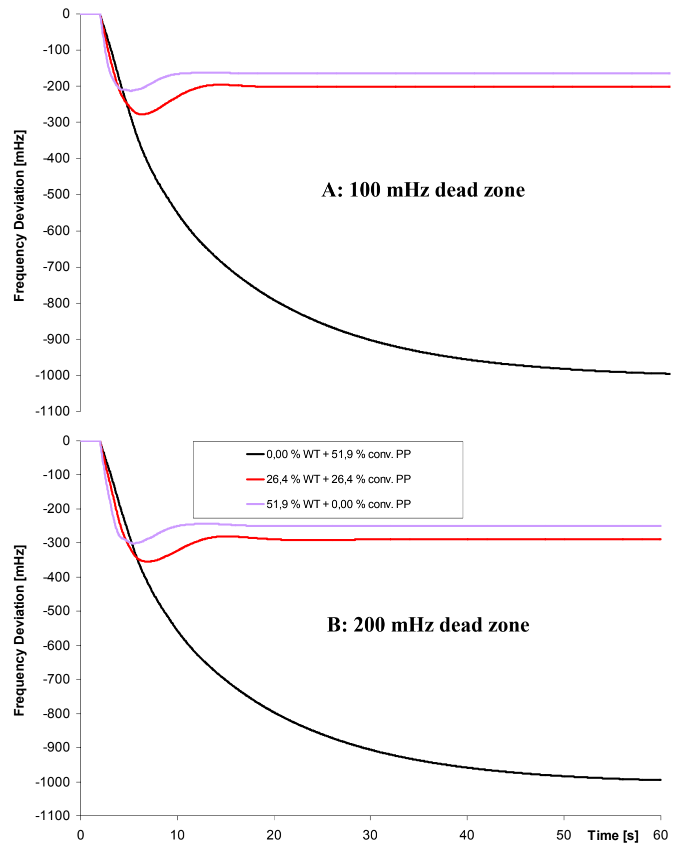

Fig. 8. Frequency deviation after a loss of 2.5 % generated amount, P and static frequency dependent U control

However, the "booster" amplifies this effect temporary when the frequency drop is high. Thus, the first frequency sag can be offset additionaly, the quid pro quo being accepting a lower voltage level for the grid. If the voltage drop can be kept small, it may be an acceptable solution for the short period of time at issue here.

It should also be mentioned that the method is not limited to wind generators only. On the contrary, conventional power plants and their excitation control system can be included, and this may even be recommendable to avoid local voltage dips within the grid.

D. Frequency dependent active power and constant reactive power control

This section outlines the control option whereby wind generators implement a frequency dependent P control. As a consequence of the frequency deviation, the controller is designed to reduce or increase the reference value of the real power controller (P_{ref}) for a brief period using derivative of -*Δ f* or +*Δ f*. *Δ f* is defined as the actual frequency minus the nominal frequency (50 Hz). Figure 11 shows an overview of the control structure.

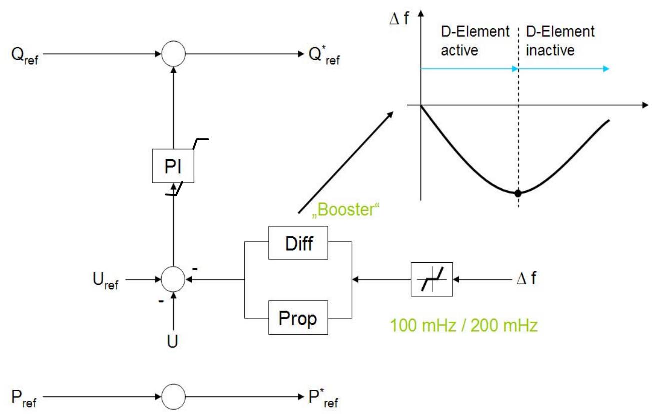

Fig. 9. Static and dynamic frequency dependent voltage controller

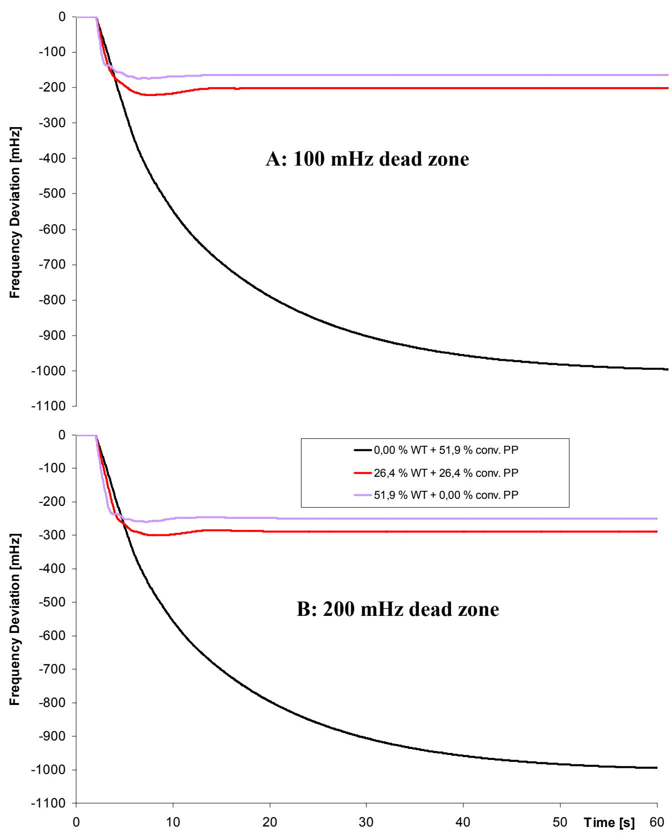

Fig. 10. Frequency deviation after a loss of 2.5 % generated amount, P and static & dynamic frequency dependent U control

Figure 12a shows the result of the control structure in terms of power output. For frequency drop, a negative *Δ f* multiplied by (-1), the signal initiates the wind units to generate more power. However, since the wind speed and thus the mechanical torque remain unchanged, more power supply leads to decreasing rotor speed. That means the additional power generation is supplied by drawing on the inertial energy stored in the rotating masses. According to the control scheme implemented, the speed control responds to the falling speed by reducing the reference power again. To get back to the targeted speed the power will be reduced even below the previous steady state value (see blue curve in Fig. 12). If this occurs before the frequency reaches its minimum, this could have adverse effect on the system frequency recovery process.

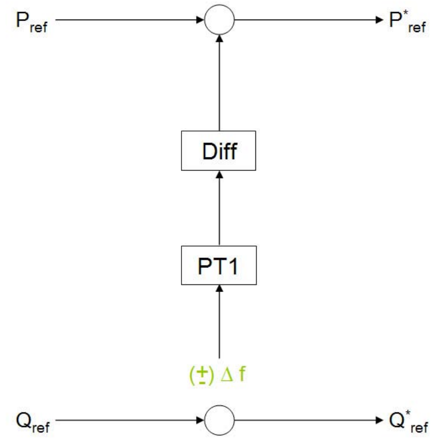

Fig. 11: Frequency dependent P and constant Q controller

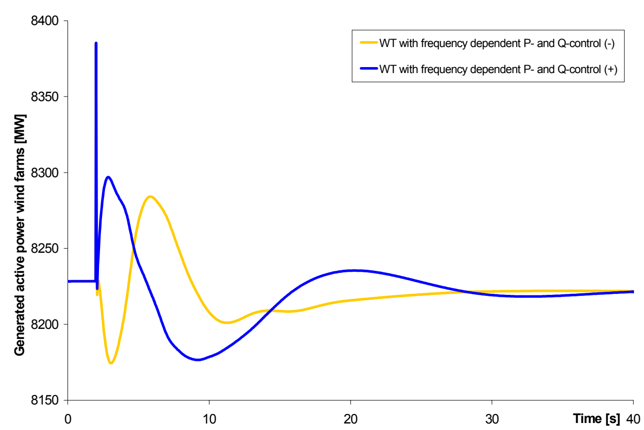

Fig. 12a. Comparison of output power for *Δ f* (blue) and - *Δ f* (yellow) with frequency dependent P control

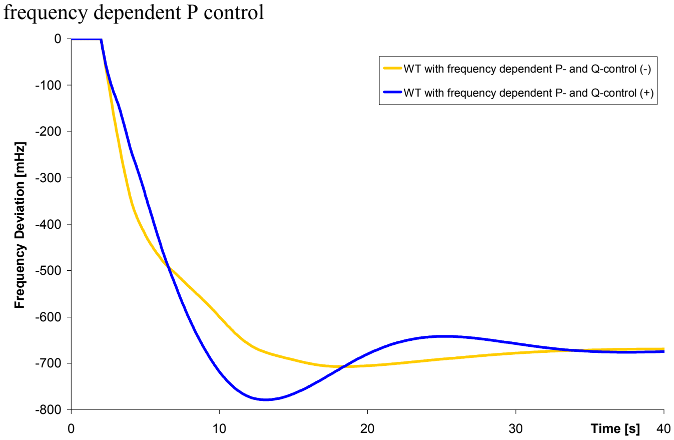

Fig. 12b. Comparison of frequency responses for *Δ f* (blue) and - *Δ f* (yellow) with frequency dependent P control

The strategy is totally different when the frequency deviation is provided with positive sign to the power controller. In this case, in the first stage when the frequency starts to drop the power generation is relaxed and thus the rotor speed increases. This results in further frequency drop. However, the speed controller acts subsequently and forces the power generations to increase. This will happen in the simulated case when the frequency is approaching its minimum (see yellow curve in Fig. 12a).

As a result, the frequency dip will be reduced. As can be seen from Figures 12b and 13, both strategies provide frequency support. However, it is obvious that a strong coordination between power and speed controllers is indispensable. From the physical point of view, in both cases the rotating masses are used temporarily as a sink or supply of energy which is then drawn from/supplied to the grid.

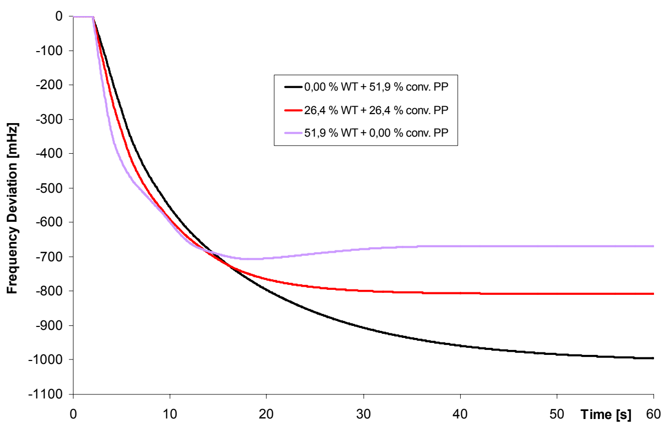

Fig.13. Frequency deviation after a loss of 2.5 % generated amount, frequency dependent P and Q control

IV. Summary of the Results and Comparison of the Control Concepts

Some of the results obtained using all the control options described in the previous sections have been put together in Fig. 14 for an easy comparison. In all cases, the loss of generation is assumed to be 2.5 % of the total generated amount. The comparison is between no wind power-generation versus 51.9 % of the overall generation being wind-based.

As stated above, the steady state frequency drop for this amount of loss of generation, with no wind generators connected to the system, would be 1000 mHz. All the results obtained using the various control options should, therefore, be evaluated against this backdrop.

The best result is achieved when wind generators employ a real power and static plus frequency dependent voltage control. A similar steady state result is obtained for a real power and static frequency dependent control. If a dead zone of 100 mHz is used, the steady state frequency deviation for the test network chosen in this study turns out to be 164 mHz. A steady state frequency deviation of 669 mHz is obtained when P and Q control is implemented, which in any case is the current control strategy for DFIM. A similar result is obtained for frequency dependent P control, but the initial frequency gradient tends to be steeper. However, it should be emphasized, that the last option requires a strong coordination between power and frequency controller. If this is not the case, system behavior may be adversely affected. The least favorable option in terms of frequency stability seems to be P and constant U control. The final frequency deviation in this case is 1070 mHz, which is well below the set point for the activation of frequency relays. This is due to the fact that the voltage controllers used in this study for wind generators are very strong and therefore, always stabilize the voltage very fast at the reference value. As a consequence, the voltage controllers should be designed not only with the view to maintaining constant voltage but also taking into account the effect of a softer voltage behavior on frequency stability. On the other hand, voltage control of wind generation plants will be necessary in the future due to the fact that all conventional generators to be replaced by wind are voltage controlled.

In case of constant U controlled wind generators, the overall reactive power supply (with or without wind generating plants) is nearly constant. For constant Q control, however, the overall reactive power output drops somewhat. This is caused by the reduced voltage profile in the network, especially at buses near the wind generation plants, and the resulting drop in the reactive power absorbed by the load. In terms of reactive power, the largest output reduction by the wind plants occurs in case of frequency dependent U control.

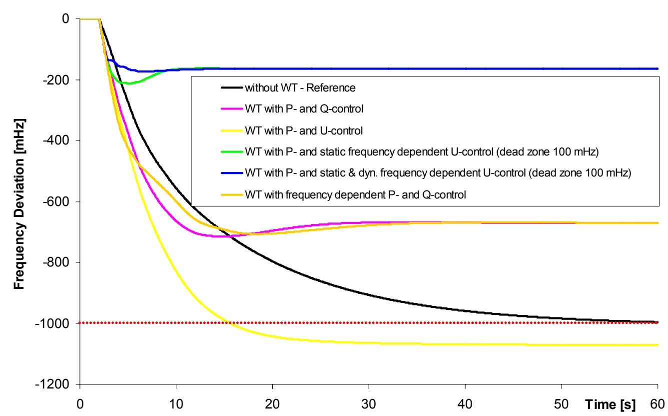

Fig. 14. Comparison of the frequency deviations after a 2.5 % loss of generation

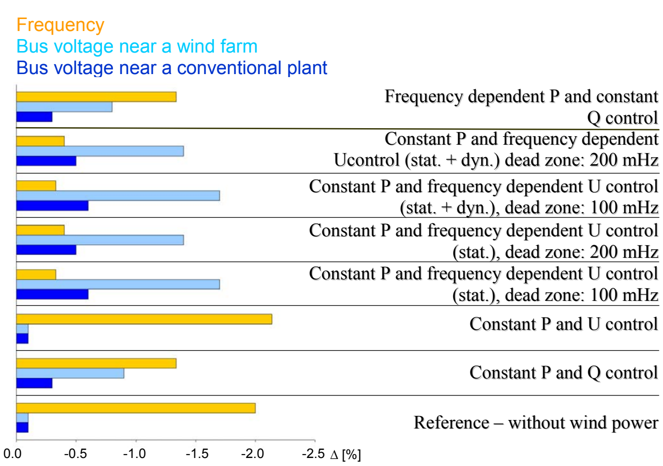

Fig. 15. Comparison of the control schemes

Concerning the voltage profile of the network during the disturbance each control option performs differently. Generally, voltage and reactive power control options cause lower voltage drops. The frequency dependent U controller causes a voltage drop, which depends on the level of the frequency sag.

The bar graph given as Fig. 15 summarizes the results just discussed, from which follows that an effective frequency-supporting role from wind generators involves a trade-off between frequency and voltage, especially at buses near wind generation plants. In other words, the voltage needs to be intentionally reduced so that the power absorbed by the load decreases so that the pressure on the frequency is reduced. However, in all cases the voltage sag does not exceed 2% which is still favorable given the level of frequency support these measures can provide. Further improvement and thus a reduction of the voltage sag is possible by applying frequency dependent voltage control not only to all wind turbines but also to conventional generators.

V. CONCLUSION

This paper explores the available control options for wind generating plants to participate on the maintenance of system frequency commensurate with their share in relation to the overall power. The study has revealed that there are indeed possibilities in terms of involving the wind generating plants by expanding the currently used control structures. A wind farm consisting of P and frequency dependent U controlled wind generators is capable of achieving a significant improvement in terms of frequency stability following a major power imbalance compared to the conventional generation plants. The downside of this approach is that it involves accepting a temporarily reduced voltage profile in the network, especially at buses near wind generation plants.

In summary, based on the outcome of this study the following observations can be made:

- An increasing wind power generation leads to a higher frequency gradient. With increasing wind power the initial frequency drop after a disturbance will be faster.
- Wind generators with frequency dependent voltage control are able, not only to maintain the grid voltage, but also to provide a considerable contribution to frequency stability by utilizing the voltage dependency of the loads.
- Ideally, voltage controlled conventional power plants should be substituted also by voltage controlled wind generators. However, voltage controlled wind generators may have an adverse impact on frequency stability, just like the conventional plants they are replacing. Therefore, the voltage controller of wind turbines necessary in the future for a different reason, should be designed taking also the frequency stability aspect into consideration.

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VII. BIOGRAPHIES

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