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POWER SYSTEMS STABILITY WITH LARGE-SCALE WIND POWER PENETRATION

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ABSTRACT

Power system starts to face problems when integrating thousands megawatts of wind power, which is produced in a stochastic behaviour due to natural wind fluctuations. The rapid power fluctuations from the large scale wind farms introduce several challenges to reliable operation and contribute to deviations in the planned power generation which may lead to power system control problems. Therefore, adequate models of an Automatic Generation Control (AGC) system which includes large-scale wind farms for long-term stability simulation is needed to investigate the capability of regulating power control at different load and production conditions. In this paper, the impacts of large-scale wind power penetration with regard to long-term stability are discussed. Results of the simulation studies are presented with discussions on how the power balance and system reliability with the increased wind power penetration can be maintained.

KEY WORDS

Automatic Generation Control, Power Balancing, Power System Stability, Frequency Stability, and Wind Power

1. Introduction

Large-scale wind turbine installations represent a new challenge to the power system operation. The fluctuating nature of wind power introduces several challenges to power system operation and contributes to deviations in the planned power generation which may lead to power system control and power balancing problems. Therefore, adequate models are needed to investigate the long-term stability. Simplified models of an Automatic Generation Control (AGC) system, wind farms, conventional power plants and Combined Heat and Power (CHP) units, together with a coordinated generation control for long-term stability analysis are developed. In this paper, the impacts of large-scale wind power integration in power systems with regard to reliable power system operation and frequency stability are discussed. An overview of a coordinated power generation control strategy is presented. Case studies are presented to investigate the capability and limitation of the regulating power to compensate the power fluctuation generated from wind farms. Results of the simulation studies are presented with discussion of how the power balance and system reliability with the increased wind power penetration can be maintained.

2. Impacts of Large Scale Wind Power

System integration of large scale wind power is raising important issues that must be evaluated. These include frequency stability, voltage stability, reactive power control and reserves. In this paper, the frequency stability with regard to system operational characteristics of the installed generation plants and inherent variability of control strategies related to treatment of imbalances are demonstrated.

2.1 Power system operation

In power systems where a significant part of the power generation comes from wind turbines, system operation issues become a challenge due to the variations in the available wind power [1]. In an offshore wind farm, the power fluctuations can be much more intense than from the aggregated wind power production on land, due to the geographically distributed nature of wind production [2]. With an increased of offshore wind farms, wind power fluctuations may introduce several challenges to reliable power system operation and may lead to power system control problems.

2.2 Frequency stability

The power system frequency is the basic indication of the system power balance between power generation and consumption [3]. There must be sufficient power available to cover transient power fluctuation to maintain the system frequency within required ranges with regard to frequency stability considerations. Due to the fluctuating and uncontrollable nature of wind power, wind power generation has to be balanced with other fast controllable generation sources. The uncertainty introduced by wind power will affect the allocation and the use of reserves in the system. Such regulating power demand will indeed increase with the increased wind power penetration in the future. This problem still requires a complete solution [4].

2.3 Control strategy

System frequency regulation becomes a challenge due to the normal variations in the available wind power. There may be system control problems, such as secondary control that not only affect the wind farm in question but the entire power system. This problem asks for flexible and improved solutions with respect to secondary generation control. These include the spinning reserve from CHP units, to smooth out the fluctuating power generated from wind generators and increase the overall reliability and efficiency of the power system. A study of the regulating power control to deal with the power balancing problem is described in [5]. Further studies must be carried out in order to find the possible control concept for dealing with this issue. Therefore, this paper introduces a coordinated generation control that maintains secure operation of the network, and allow for maximized and profitable integration of wind power.

3. AGC System with Wind Power Integration

Due to the high fluctuations and limited predictability of wind power, it is important to include this unstable generation source in the AGC system. Secondary control, so called AGC, restores system frequency to its nominal value by adjusting the load set-point of the generators. AGC represents an interesting scheme for controlling the power balance and for distributing the imbalance in an economical way in between selected units.

3.1 AGC system with large-scale wind power

The AGC control scheme is modified by an additional control input path representing the actual wind power generation and the estimated wind power production level. For AGC purposes, the variation in wind generation is measured at the point of common coupling (PCC). The measurement is send to the dispatch centre and the control system. The deviation in actual wind power generation from estimated generation, contributes to a Generation Control Error (GCE), which is then distributed according to participation factors (*pf*) among the selected power generation units in the AGC system. In Figure 1, an AGC system model which includes wind-farms is presented. The GCE is represented by the contribution from frequency deviations from thermal power plant and the deviations from the wind power generation. This is described in Figure 1 and mathematically written as:

$$GCE = -\Delta P_{Gen} - \frac{\Delta f}{R} \tag{1}$$

$$\Delta P_{Gen} = \Delta P_{Thermal} + \Delta P_{Wind} \tag{2}$$

where ΔP_{Gen}, $\Delta P_{Thermal}$, ΔP_{Wind} are the deviation of total power generation, thermal power and wind power from plan respectively, Δf is the frequency deviation in the system, $1/R$ is total frequency bias.

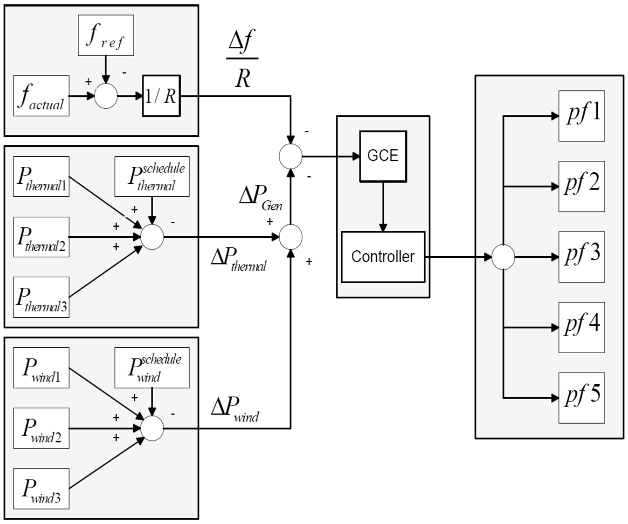

Figure 1. AGC system with wind power integration

3.3 AGC system model

The AGC system model for dynamic power system simulation in order to demonstrate the long-term stability is developed as shown in Figure 1 and explained in [6]. Based on measurement of system frequency and unit generations, the AGC computes unit set-points and sends set point change commands to the selected units. The selection is based on several objectives like economy, ramping capability, etc. determined by the *pf* value. This set-point will be used until the next execution of AGC, typical sample times (T_{AGC}: 2-4 sec.). The equations for finding the power set-point for all the power generation units can be written as:

$$\Delta P_{set} = K * GCE + \frac{1}{T}\int GCE \tag{3}$$

where ΔP_{set} is the correcting power set-point for all the selected units, K is the proportional factor (gain), T is the integration time constant.

3.4 The coordinated generation control

The model of the coordinated generation control to maintain the active power balance in long-term stability for power system simulation is developed. The coordinated generation control is integrated in the AGC system in order to manage the regulating power for power balancing. The operational priorities of the different generation units are analysed, based on their operation time constants and ramping capability by, the Load Flow Controller (LFC). With the coordinated generation control, the contributions of secondary control from different generation units are investigated with respect to their capabilities. Therefore, the regulating power will be requested from different generation units from fast ramp rate to slow ramp rate generation units. It is demonstrated in the case studies in section 5 how AGC system with the coordinated generation control can be utilized for power balancing purpose. The structure of the coordinated generation control model is shown in Figure 2.

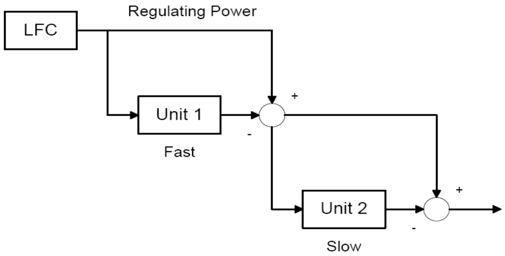

Figure 2. The coordinated generation control

4. Simplified Models of Generation Units

Aggregated models of a wind farm, a thermal power plant and a CHP unit for long-term stability simulations are implemented in DIgSILENT PowerFactory.

4.1 Wind farm model

For a power system impact study, when the impact of an entire wind farm to a power system is studied, a detailed model of every individual wind turbine would require too much calculation time [7]. An aggregated model of a variable speed, doubly-fed induction generator (DFIG) for long-term system simulation is developed based on the wind turbine model implemented in [8]. The wind farm is modelled by one equivalent model representing the entire wind-farm seen from the point of common coupling. One equivalent power electronic converter and control model and an equivalent generator model are used. One equivalent aerodynamic model is used as the differences in wind speed between different turbines in the wind farm are assumed to be small. One equivalent pitch angle controller is sufficient for representing the pitch-control in the aggregated model as the speed is assumed to be the same at any turbine. This is mathematically written as:

$$\left(\sum_i J_i\right)\dot{\omega}_t = \sum_i M_{ti} - \sum_i M_{ei} \qquad (3)$$

$$P_t = n c_p(\theta, \lambda_{eq})\frac{\rho}{2} A^2 v_{weq}^3 \qquad (4)$$

$$\text{with } \lambda_{eq} = \frac{R\omega_t}{v_{weq}} \text{ and } v_{weq} = \frac{1}{n}\sum_i v_{wi}$$

where J is generator inertia, M_t is turbine torque, M_e is electrical torque, ω_t is mechanical speed, P_t is mechanical torque, v_{weq} is equivalent wind speed, n is the number of wind turbines in the wind farm, c_p is a power coefficient, Θ is blade angle, λ_{eq} is equivalent tip speed ratio, ρ air density, A is wind turbine rotor area.

The wind farm power controller for balance control and delta control as explained in [10] is also included in the wind farm model. The power controller deliver power reference signal P_{ref} to the control model in wind farm. The aggregated wind farm model is developed as shown in Figure 3. The variable have the following meaning: ω_g is generator speed, P_{meas} is measured power at PCC, T_{ae} is aerodynamic torque.

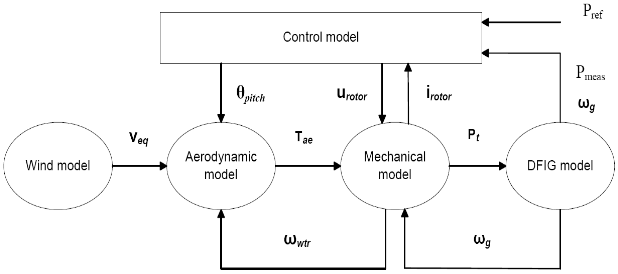

Figure 3. DFIG wind farm model

4.2 Thermal power plant model

Figure 4 shows an aggregated model of a thermal power plant with steam turbine and thermal dynamic boiler. A simplified model of a thermal power plant which consists of boiler turbine control, thermal dynamic boiler, speed governor and steam turbine has been developed. The unit response is mainly determined by the ramp rate limiter in the boiler turbine control, while other model components are used for a better fitting to the real response. The model has been developed to be used for secondary control purpose, so it has to deal with time constants in seconds. The turbine model defines mechanical power as function of main steam pressure (P_t) and control valve flow area (cv). The speed governor model details the turbine control logic in response to change in load reference (L_R), and speed (ω). The boiler turbine control block develops the load reference (L_R) input to the speed governor in response to the load demand (power reference, P^{ref}) set by the AGC system. In this study, 2 thermal power plants with different ramp rate capability are modelled. These thermal units have regulating power capability in different operating ranges as shown in Table 1. The thermal power plants are operated in the sliding pressure mode as described in [9].

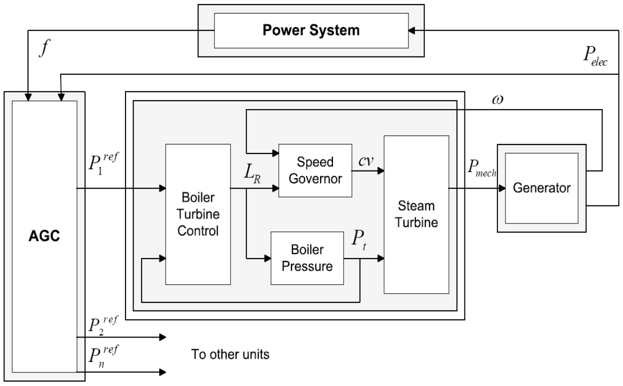

Figure 4. Thermal power plant model

Power Plant	Active Power (MW)	Ramp < 35% (%/min)	Ramp 35-50% (%/min)	Ramp 50-90% (%/min)	Ramp 90-100% (%/min)
Thermal G 1	400	2	2	8	2
Thermal G 2	400	1.5	2	4	2

Table 1. Regulating power capability in different operating ranges of thermal power plants

4.3 Combined Heat and Power (CHP) unit model

The CHP unit with simple-cycle gas turbines, which is capable of the fastest response of all units in the utility systems, is modelled. An aggregated CHP plant model with power control which consists of dead-band, ramp rate limiter and gas-turbine dynamic is developed as described in [9], shown in Figure 5. The unit response is mainly determined by the ramp rate limiter. A group of CHP units is integrated within the AGC system and can provide the fast spinning reserve with the coordinated generation control.

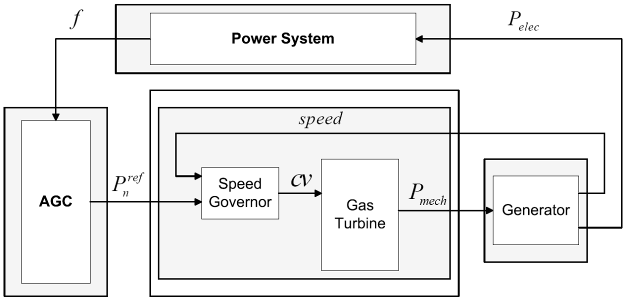

Figure 5. CHP unit with gas-turbine model

5. Case Study

In order to investigate the capability of regulating power control to compensate for power fluctuation from wind farms and long-term power system stability under different load and production conditions, a set of relevant simulation cases is developed. A wind farm with 160 MW rated power, 2 units of thermal power plants with 400 MW rated power and a group of CHP units with 40 MW rated power are represented in the simulation using aggregated models according to the proposed in section 4. The power system used for the model simulation is modelled as shown in Figure 6.

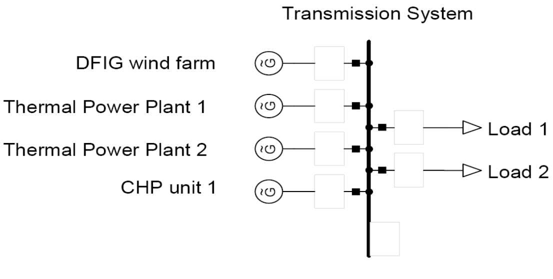

Figure 6. Power system used for model simulation

5.1 Power control of generation units

The power control capabilities of the different generation units are investigated as shown in Figure 7 and Figure 8. Figure 7 presents a simulation of the power control in the wind farm (Balance control and Delta control modes respectively, as explained in [10]) due to wind fluctuation with the use of a power gradient limit of 15 MW/min. Large offshore wind farms must also contribute to the active power balance and to the frequency control within a defined range. Obviously, this control can not limit the negative power gradient. Figure 8 presents the response of 2 thermal power plants with different ramp rate capabilities to a load step and the response of a group of CHP units which is capable of the fastest response to a load step.

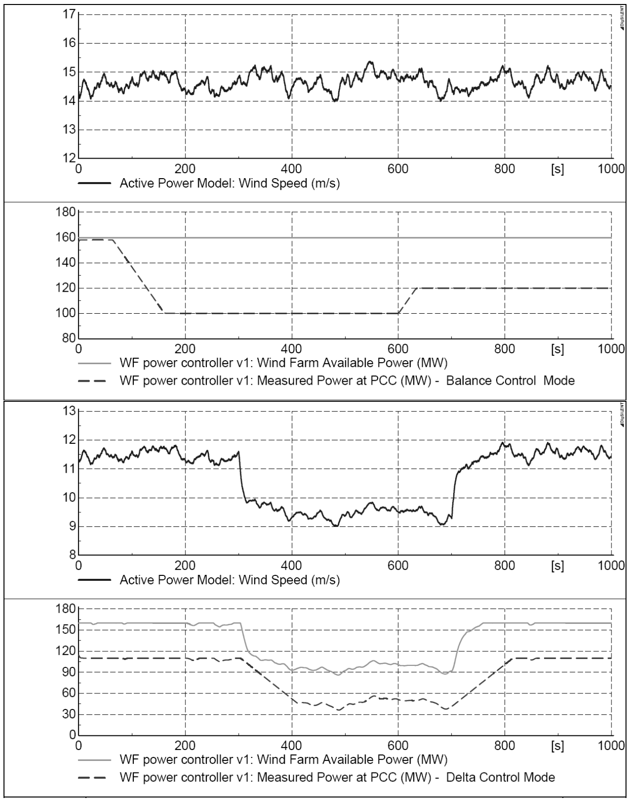

Figure 7. Power generation from wind farm

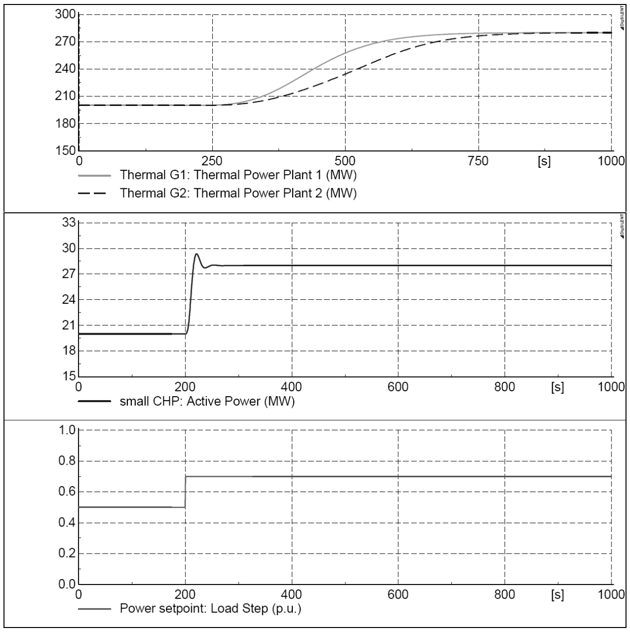

Figure 8. Response of thermal power plants and CHP units to a load step

5.2 AGC system with wind farm integration

The CHP units are involved to participate in the regulating market and contribute to the power balance in the power system. Figure 9 presents the capability of the secondary control of the thermal power plants and CHP units when a generation loss from wind farm is introduced. The ability of the secondary control of the thermal power plants and CHP units to restore frequency back to its nominal value is demonstrated.

This is illustrated in Figure 9, showing a result of a simulation verifying the performance of AGC system with wind power integration. At t = 100 s., a wind speed drop from 12 m/s to 8 m/s is introduced, resulting in a loss of power generation from the wind farm. A frequency drop is initiated due to the loss of generation, leading to a primary response of units. The secondary control adjusts the load set-point of the generating units and it restores frequency to its nominal value (50 Hz.). It can be observed that the secondary control of the thermal power plant restores system frequency back to its nominal value, at a limit equal to the ramping rate of the generation unit.

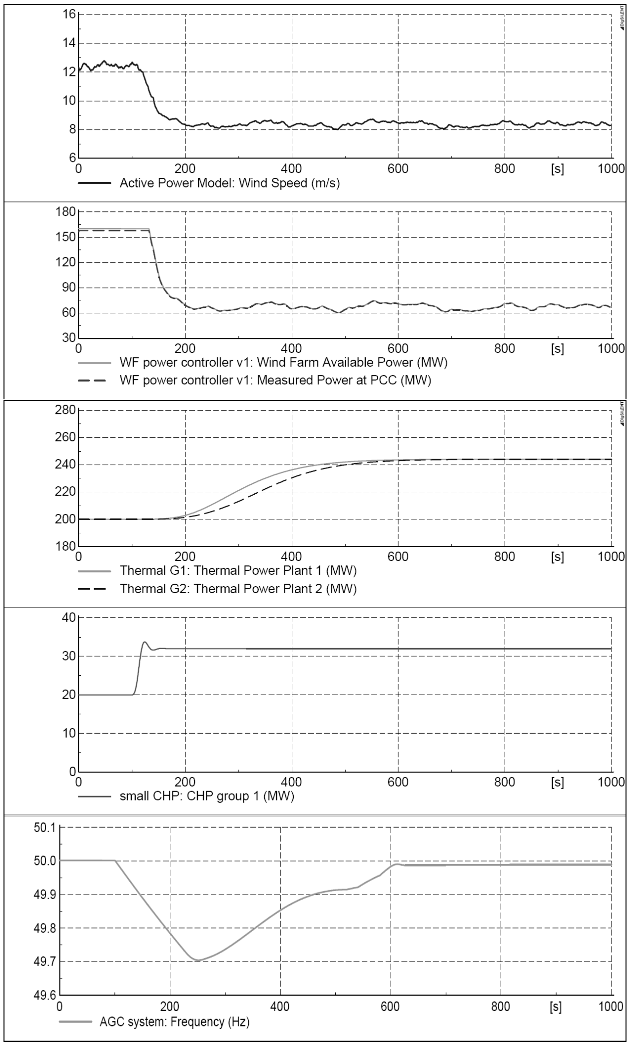

Figure 9. Response of the secondary control from thermal power plants and a group of CHP units

5.3 AGC system with coordinated generation control

Coordinated generation control shows how additional control flexibility can be utilized in systems, fulfilling system obligations with respect to maintaining power balance subject to the unpredictable variations in wind power. The CHP units are also involved to participate in the regulating market and contribute to the power balance with the coordinated control. Figure 10 presents the simulation results, the response of secondary control, with the coordinated generation control.

As illustrated in Figure 10, at t = 100 s., a wind speed drop from 12 m/s to 8m/s is introduced, resulting in a loss of power generation from wind farm as shown in Figure 9. With the coordinated active power generation control, the CHP unit is activated as the first priority to provide the spinning reserve for the secondary control. It can be observed that the CHP unit provides a fast secondary control response.

The regulating power required is also ordered from the thermal power plants. It can also be observed that the thermal power plant 1 is activated with the higher priority, compared with the thermal power plant 2, as it provides a faster secondary control response. The regulating power provided from the thermal power plant 1 give better performance for the secondary control to restore frequency back to the nominal value. The utilization of the regulating power resources is among the vital arrangements for better power balancing. This includes better utilization of local CHP units with the coordinated generation control.

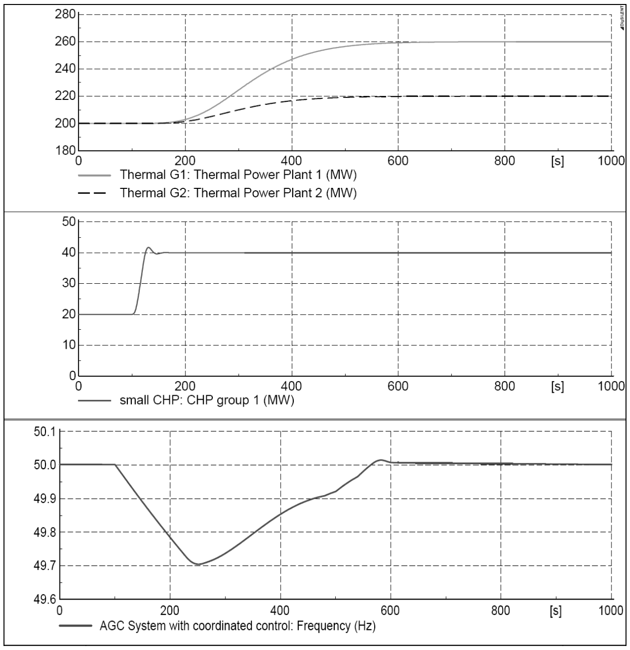

Figure 10. Response of the secondary control from thermal power plants and a group of CHP units with the coordinated generation control

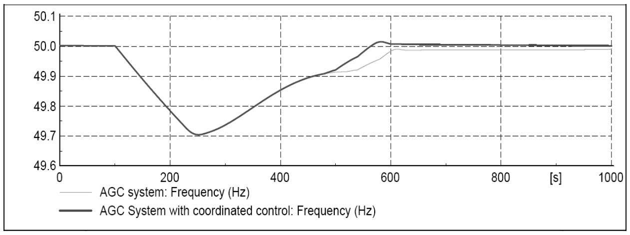

Figure 11. Frequency traces with a) no coordinated control, b) with coordinated control

The ability of regulating power control to restore system frequency back to its nominal value, when the generation loss from wind farm is introduced, is shown in Figure 11. The comparison of frequency traces can be observed that the system frequency is restored 40 seconds faster with the coordinated generation control. The intensity of such power fluctuations may increase when the additional wind farms will be commissioned in the future.

6. Conclusion

In this paper, the impacts of large scale wind power integration in power systems with regard to frequency stability and system reliability are discussed. The model of an AGC system with wind power integration for dynamic power system simulation is presented in order to demonstrate the long-term stability under the dynamic behaviour of the wind power sources. Results from simulation studies are used to illustrate the capability of the AGC system with a coordinated generation control. At wind farm power control under wind fluctuation, the loss of generation due to the sudden decrease in wind speed can cause problems in the power balancing. Therefore, a fast and controllable regulating power is needed. A simulation of an AGC system performing the secondary control of thermal power plants shows that the AGC is capable of keeping the active power balance at a limit equal to the ramp rate of the generation units. The coordinated generation control with spinning reserve from CHP units is capable of offering fast power control to restore the system frequency back to its nominal value.

Hence, sufficient amount of regulating power to compensate for such intense power fluctuations generated from large scale wind farms is one of the keys for maintaining the power balance and efficient operation of the power system. It can also be concluded that the wind power characteristics and coordinated power system operation, which allows for power system balancing might set up a limit for the wind power penetration. As large-scale wind farm replace existing conventional generation in the future, the frequency control may become more challenging.

Acknowledgements

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