Power System Balancing with Large Scale Wind Power Integration

Suwannarat, Akarin; Bak-Jensen, Birgitte; Chen, Zhe

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A. Suwannarat, B. Bak-Jensen and Z. Chen

Abstract--**Power system starts to face problems of integrating thousands megawatts of wind power, which produce 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 would lead to power system control and power balancing problems. In this paper, the impact of large scale wind power integration on power balance is discussed. A scheme of Automatic Generation Control (AGC) system which includes large scale wind-farms is presented. The ability of the secondary control of conventional power generating units and the spinning reserve from Combined Heat and Power (CHP) units for maintaining the power balance are investigated. Control concepts to achieve active power balance with the increased wind power integration in power system are discussed.**

***Index Terms*—Automatic Generation Control, Power System Simulation, Power System Stability, Wind Energy, Wind Power Generation**

I. Introduction

LARGE-scale wind turbines installation represents a new challenge to the power system. The fluctuating nature of wind power introduces several challenges to reliable operation of the power system and contributes to deviations in the planned power generation which would lead to power system control and power balancing problems. Keeping the balance in power systems simply mean that generation must meet contract volume of power consumption [1]. Proper control scheme is therefore developed to manage the imbalance. Wind power represents a variable power generation source which may contribute to the imbalance. Therefore, it should be included in the control scheme. In this paper, the impacts of large scale wind power integration on power systems with regard to long-term stability are discussed. The scheme of an Automatic Generation Control (AGC) system which includes large scale wind-farms is presented and the ability of the secondary control of conventional power generating units and spinning reserve from CHP units for maintaining the power balance is demonstrated.

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Akarin Suwannarat, Birgitte Bakl-Jensen and Zhe Chen are with the Institute of Energy Technology, Aalborg University, Aalborg East 9220 Denmark (e-mail: aks@iet.aau.dk, bbj@iet.aau.dk, zch@iet.aau.dk).

Power system simulations by using simplified models of an AGC system with wind power integration, thermal power generating unit and CHP unit in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources are presented. Possible control concepts to achieve active power balance with the increased wind power integration are discussed.

II. Impacts on Power System Stability

In power systems where a significant part of the power generation comes from wind turbines, system operation issues become a challenge due to the normal variations in the available wind power.

A. Wind Power Fluctuations

Wind power is characterized by fluctuations of the produced active power due to the wind fluctuating nature. Such fluctuations of the active power have been measured and found to be in the time scale from tens of minutes to a few hours [2]. In an off shore 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. With the increase of large scale (off-shore) wind farms in the future, the fluctuating nature of wind power may introduce several challenges to reliable operation of the power system and would lead to power system control and power balancing problems.

B. Large Scale Wind Power Integration

Wind power represents a variable generation source due to changing wind conditions. System integration of large scale wind power is raising a long list of important issues that must be evaluated. This includes transmission capacity, frequency stability, voltage stability, frequency control and reserves [3]. When integrating large scale wind power, the wind generation must be estimated when establishing the detailed generation plans for the conventional power plants. This is illustrated in that total wind and thermal power generation must meet the producers load in terms of contracts and market interchange. Detailed system and design studies must be carried out in order to find the best technical solution for dealing with these issues. The major issue in this paper is to comply with the fluctuating nature of wind power production.

The power fluctuations generated by the wind-farms at different weather conditions are of interest with respect to the needed spinning reserve.

C. Power System Balancing

Due to the fluctuating and uncontrollable nature of wind power as well as the uncorrelated generation from wind and load, wind power generation has to be balanced with other fast controllable generation sources. These include thermal power generating sources, as well as spinning reserve from CHP units, to smooth out fluctuating power from wind generators and increase the overall reliability and efficiency of the power system.

The power system frequency is the basic indication of the system power balance between power generation and consumption. If a substantial frequency drop is experienced, the droop characteristic of the generators must be corrected in order to find a new operation mode giving nominal frequency. When planning the operation of the entire network, there must be sufficient power available to cover both the long term variation in load as well as transient power necessary for power balance with regard to frequency stability considerations.

III. Load Frequency Control (LFC)

AGC is a control system having three major objectives to hold system frequency at or very close, to a specified value, to maintain the correct value of interchange power and to maintain each unit's generation at the nominal value (50 Hz). A control area is defined as a part of an interconnected system within which the power generation and consumption will be controlled according to predefined rules for keeping the area balance within limits.

A. Load Frequency Control and AGC control scheme

The main objectives of Load Frequency Control (LFC) are to balance the power generation and the load consumption in the control area to maintain the system frequency within required ranges and to keep the power exchange between areas at the scheduled values. LFC is organized in three levels.

Primary control is performed by the speed governors of the power generating units, which vary load when frequency changes to keep the instantaneous balance between power production and consumption. With primary control, a variation in system frequency greater than the dead band of the speed governor will result in a change in unit power generation. Generators are required to participate in this control by setting the droop according to specifications by the System Operator. Transients of primary control are in the time-scale of seconds.

Secondary control restores system frequency to its nominal value and also maintains the power interchange between areas in systems with several control areas. It adjusts the load set-point of the generators. Transients of secondary control are in the order of minutes. Secondary control is also called Automatic Generation Control (AGC).

Tertiary control is an economic dispatch. It is used to drive the system as economically as possible and restore security levels if necessary. Tertiary control is usually performed every 5 min [4].

AGC system represents an interesting scheme for controlling the power balance and for distributing the imbalance in an economical way in between selected units. The concept of AGC can include all automatic active power control actions except primary control. While speed governor based primary control can be found in most units, the AGC introduces a control feedback loop as illustrated in Fig. 1.

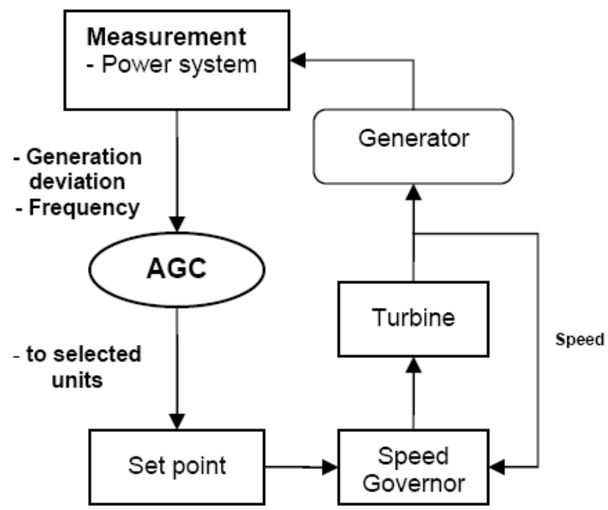

Fig. 1. AGC system control scheme and primary control

B. AGC system with large scale wind power

When implementing large scale wind farms, considerations should also include managing the variable generation from wind turbines due to wind speed variations. However, the total generation from a wind farm is usually smoothed compared to variations from the individual wind turbines.

For AGC purposes the variations in wind generation may be measured at the point of common coupling. The measurement is send to the dispatch centre and the control system. The deviation in wind generation, that is deviation in actual wind power generation from estimated generation, contributes to Area Control Error (ACE), and is then distributed according to participation factors (pf) among the selected power generating units under the AGC system.

The principle of AGC has been introduced in section 3A and the modifications needed for controlling wind power is now presented. The control scheme is modified by an extra control input path representing the actual wind power generation and the estimated wind power production level. Due to the wind speed variations and also the variations in wind power generation, it is important to include this unstable generation input in the AGC system. In Fig. 2, the scheme of an AGC system which includes large scale wind-farms is presented.

The ACE is now represented by the contribution from frequency deviations from thermal power generating unit and the deviations from the wind power generation. In case of several wind farms, the generation from each wind farm must be send to the control centre. The ACE presented now reflects the wind power generation. This is described in Fig. 2 and mathematically written in (1) and (2).

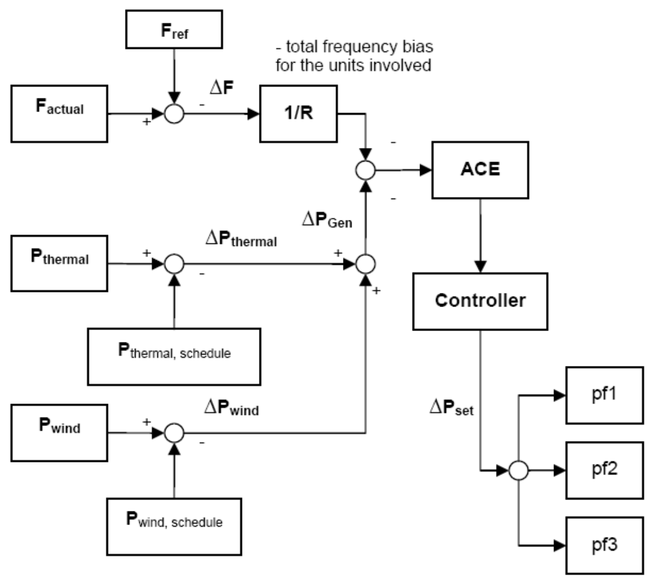

Fig. 2. AGC system with large scale wind power integration

The equations for AGC system with wind power integration can be written:

$$ACE = -\Delta P_{Gen} - \Delta f/R \quad (1)$$

$$\Delta P_{Gen} = \Delta P_{thermal} + \Delta P_{wind} \quad (2)$$

where ACE is the Area Control Error.

ΔP_{Gen} is the deviation power generation from plan.
$\Delta P_{thermal}$ is the deviation thermal power from plan.
ΔP_{wind} is the deviation wind power from plan.
Δf is the frequency deviation in the system.
1/R is total frequency bias.

C. AGC system model

The model of the AGC system with wind power integration for dynamic power system simulation in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources is developed based on the AGC system scheme in Fig. 2. To implement an AGC system one would require information about the unit's MW output for each thermal power generating unit, the total output from the wind farm, the total MW generation schedule for the total power generation from all units to be controlled in the balance area, and the system frequency. The output of the execution of the AGC is transmitted to each generating unit by sending raise or lower pulses of varying lengths. The local control system then changes the unit's generation reference set point up or down in proportion to the pulse length [4].

AGC system has system variables with typical sample times (T_{AGC}) between 2 or 4 s. Then, AGC computes unit set-points and sends them to the units. This set-point will be used until the next execution of AGC, T_{AGC} seconds later [5]. Based on measurement of system frequency and unit generations, the AGC sends set point change commands to the selected units, the selection may be based on several objectives like economy, ramping capability or others, determined by the participation factor (pf). The equations for finding the power set-point for power generating units can be written:

$$\Delta P_{set} = K*ACE + 1/T \int ACE \quad (3)$$

where ΔP_{set} is correcting power set-point for selected unit.

K is the proportional factor (gain).
T is the integration time constant.

For the comparison of the strategies, a power system having some units under AGC and others manually controlled is considered. Various attributes are to be assessed over a selected time window (duration of their comparison.) This comparison is made when the system operates as a single (isolated) control area. The concepts developed for the single control area case are then extended to that of an interconnection comprising several control areas (not included in this paper).

IV. Simulation Framework

In order to simulate a power system for system balancing problems, simplified models of the power system, the wind farms and the power generating units for long term stability simulations are developed. Outline of a case study is showed in Fig. 3, operation of a 120 MW wind-farm, 2 units of 250 MW thermal power generating unit and a 40 MW CHP unit when using an AGC system is presented.

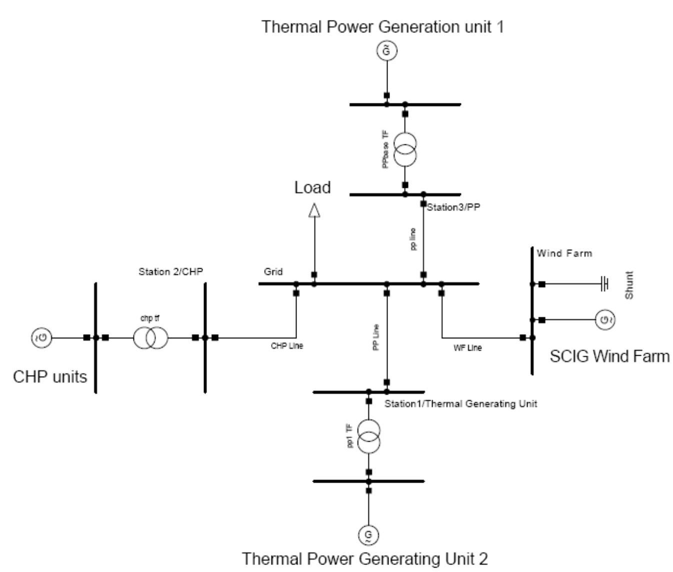

Fig. 3. Outline of case study with operation of a 120 MW wind-farm, 2 units of 250 MW thermal power generating units and a 40 MW CHP unit, implemented in DIgSILENT PowerFactory.

A. 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 [6]. In this simulation framework, an aggregated wind farm model for long term power system simulation is developed. The aggregated model of a wind-farm with fixed speed squirrel-cage induction generators (SCIG) is developed. The wind-farm should be modeled by one equivalent model representing the entire wind-farm seen from the point on common coupling. Because the speed deviations between fixed speed wind generators in a wind farm are only minor, a wind-farm built by fixed-speed wind generators can be approximated by one equivalent induction generator [7]. The wind speed differences between different turbines in the park can be assumed to be small. Because the speed is assumed to be the same at any turbine, one equivalent pitch angle controller is sufficient for representing pitch-control in the aggregated model. In this simulation framework, the typical mean speed wind model is applied for the simulation in the case studies.

B. Power generating units model

A simplified model of a thermal power generating unit which consists of power and frequency control, turbine control and speed governor including dead-band, ramp rate limiter has been developed. The unit response is mainly determined by the rate limiter, 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 constant greater than several seconds. The main effect of the dead-band is a delay in the unit response [8].

The most important effect in a unit's dynamic is a load change rate limiter in service in every generating unit. If the input slope is lower than the rate limiter's value, the output is equal to the input. If it is higher, the output is a ramp of slope equal to the rate limiter's value. A dead-band is applied to AGC power. If the absolute difference between AGC power and demanded power is lower than the dead-band's value, the dead-band's output for next control cycle is kept constant. If it is higher, the dead-band's output for next control cycle is equal to the AGC power. Fig. 4 and Fig. 5 show a simplified model of the thermal power generating unit and a model of the speed governor with droop and dead-band of thermal a power generating unit.

C. Combined Heat and Power (CHP) units model

An aggregated Combined Heat and Power (CHP) plant model as a group of local CHP units with power control is developed. A simplified model of CHP unit which consists of dead-band, ramp rate limiter has been modeled. The unit response is mainly determined by the rate limiter, while other model components are used for a better fitting to the response. A group of CHP unit is not integrated within the AGC system, therefore the spinning reserve can be ordered upon request.

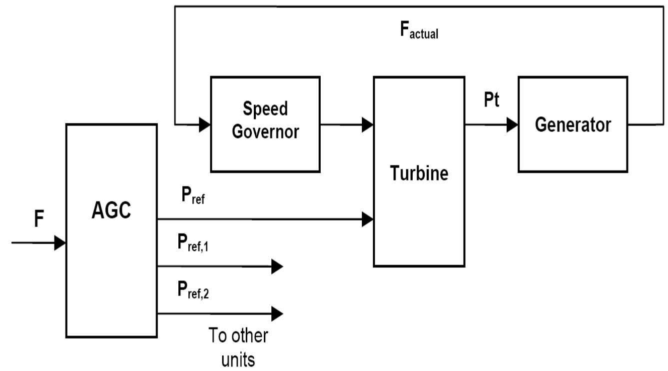

Fig. 4. A simplified model of thermal power generating unit

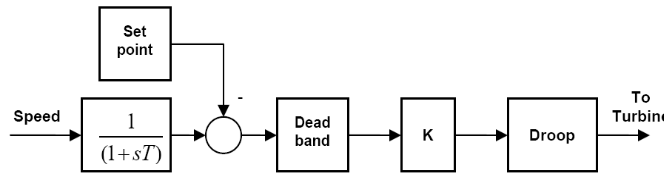

Fig. 5. Model of speed governor in thermal power generating unit

V. Case Studies

The project focuses on solving the power unbalance caused by rapid fluctuations observed in the (offshore) wind-farms and also to examine the ability of the secondary control of the thermal power plants to reduce the affect caused by power fluctuations generated from large wind-farms in the power system.

In these case studies, the thermal generating unit 1 is operated as a based unit; its production will not be changed in any case, only the thermal generating unit 2 is operated in the AGC system. The impacts of power fluctuations from large scale wind power integration on power system with regard to long term stability have been simulated in two study cases.

One is considering the primary and secondary controls of the power system with thermal power generating unit, and another is considering the power balancing with the spinning reserve from CHP units. The simulation time step for the case studies is one second. All models are implemented and simulated using the power system analysis package DIgSILENT PowerFactory.

A. Primary and Secondary Controls from Thermal Generating Units

Fig. 6 presents the simulated response of the thermal power generating unit with a load change. At t = 75 s., a load step of 10 MW is introduced, resulting in a generation step of the same size within 20-30 s. The active power balance with regard to the system stability and the ability of the secondary control of the power plants to restore frequency back to its nominal value caused by the power fluctuations from the large wind-farms on the power system is demonstrated.

This is illustrated in Fig. 7, showing a result of a simulation verifying the performance of AGC system. At t = 30 s., a wind speed drop from 12 m/s to 6m/s is introduced, resulting in a loss of power generation from wind farm. A frequency drop is initiated due to the loss of generation, leading to a primary response of units. Secondary control adjusts the load set-point of the generating unit and it restores frequency to its nominal value (50 Hz.). From the simulated result, it can be observed that the variations in wind power can be compensated by the thermal generating units. Response of secondary control from the thermal generating unit, restore frequency back to its nominal value. Increasing of wind turbines in power system would cause problem for the power balancing in the future.

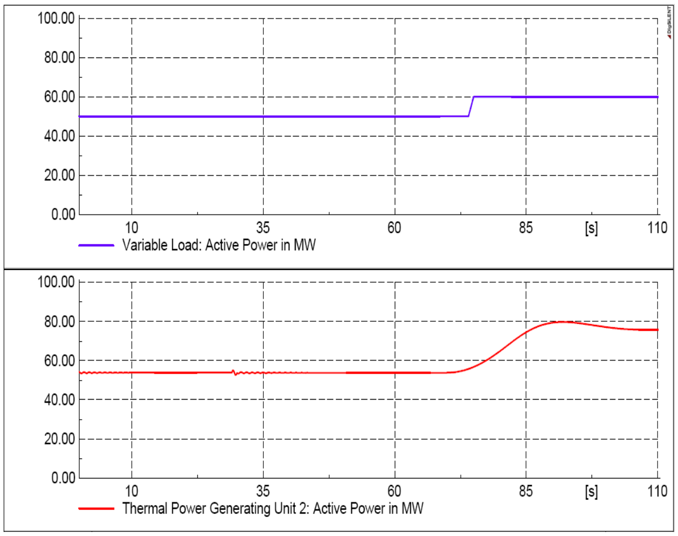

Fig. 6. Response of thermal power generating unit in MW (below) with a load step (above).

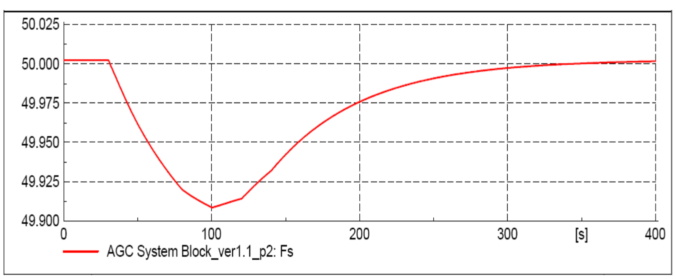

Fig. 7. System frequency (Hz), due to the response of secondary control from thermal generating unit 2

B. *Spinning Reserves from CHP units*

The growing amount of installed wind power capacity leads to increasing demand for regulating power [9]. A group of local CHP units operating on the market term may give a valuable contribution to solving the balancing problem. The CHP unit, particularly simple-cycle gas turbines are capable of the fastest response of all units in the utility systems, but since they are typically used as peaking units they are seldom equipped for operation under AGC.

In this case study, the CHP units are operating according to market signal. Therefore, the CHP units are involved to participate in the regulating market and contribute to the power balance in the power system. Fig. 8 presents a comparison of the simulation results between response of secondary control, with the spinning reserve from CHP units and response of secondary control, without the spinning reserve from CHP units. At t = 30 s., a wind speed drop from 12 m/s to 7m/s is introduced, resulting in a loss of power generation from wind farm. A frequency drop is initiated due to the loss of generation, leading to a primary response of units. Secondary control restores frequency to its nominal value (50 Hz.). From Fig. 9, it can be observed that the CHP unit provides a response much faster than a response of the thermal power generating unit. Spinning reserve provided by CHP units give better performance for the secondary control to restore frequency back to the nominal value.

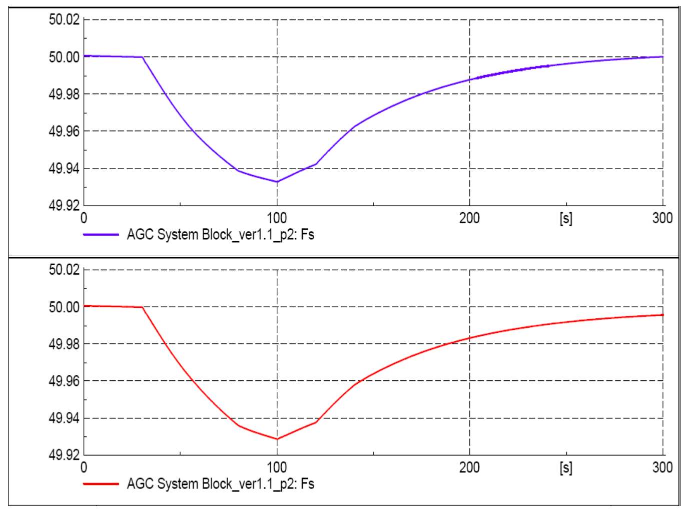

Fig. 8. Comparison of the simulation results (system frequency in Hz.) a) with the spinning reserve from CHP units (above) b) without the spinning reserve from CHP units (below).

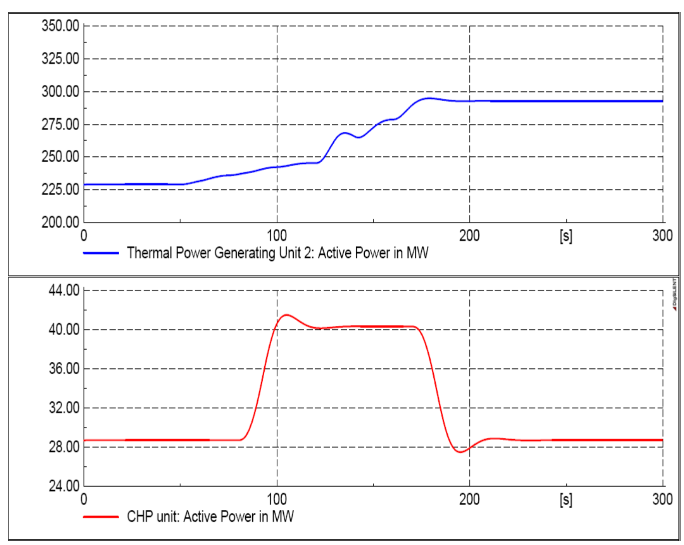

Fig. 9. a) Response from Thermal unit 2 (in MW) (above), b) Spinning reserve provided from CHP unit (in MW) (below)

VI. Conclusions

In this paper, the impacts of large scale wind power integration on power system with regard to long-term stability are discussed. A scheme of an AGC system with wind-farms integration including secondary control on the conventional generating units and the spinning reserve from CHP units is investigated. The model of an AGC system with wind power integration for dynamic power system simulation in order to demonstrate the behaviour of long-term stability under the dynamic behaviour of the wind power sources is presented.

Results from a simplified power system model simulation are used to illustrate the performance of primary and secondary controls to achieve active power balance with the fluctuating wind power generated from wind-farm. The comparison of the simulation results between the response of secondary control with the spinning reserve from CHP units and the response of secondary control without the spinning reserve from CHP units is presented. Spinning reserve provided by CHP units give better performance for the secondary control to restore system frequency back to the nominal value. With increasing amount of (offshore) wind-farm, it may be critical to compensate for the power fluctuation caused by large scale wind power. A sufficient amount of regulating power (spinning reserve) for such power fluctuation from wind farm would be one of the keys for solving the power balancing problem.

VII. References

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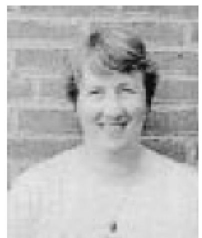
VIII. Biographies

Akarin Suwannarat was born in Bangkok, Thailand on June 4, 1978. He received the B.Eng degree in electrical engineering from Thammasat University, Thailand and the M.Sc. degree in energy conversion and management from University of Applied Sciences Offenburg, Germany, in 2000 and 2003 respectively. He did internships at Electricity Generating Authority of Thailand (EGAT), Thailand; FEW GmbH, Germany and Badenova AG&Co.KG, Germany. From 2003 to 2004, he was with RWE Solutions AG, Thailand, as a project engineer. He is currently a PhD candidate in the Institute of Energy Technology, Aalborg University, Denmark. His fields of interests are modeling and simulation of electrical components in power systems, power system stability.



Birgitte Bak-Jensen was born in Grenaa, Denmark, on August 27, 1961. She received the M.S. degree in electrical engineering and the Ph.D. degree in modeling of high-voltage components from Aalborg University, Aalborg East, Denmark, in 1986 and 1992, respectively. From 1986 to 1988, she was with Electrolux Elmotor A/S, Aalborg East, Denmark, as an Electrical Design Engineer. She is an Associate Professor in the Institute of Energy Technology, Aalborg University, where she has worked since August 1988. Her fields of interests are modeling and diagnosis of electrical components in power systems and power quality and stability.

Zhe Chen received the B.Eng. and M.Sc. degrees from Northeast China Institute of Electric Power Engineering, Jilin City, China, and the Ph.D. degree from The University of Durham, Durham, U.K. He was a Lecturer and then a Senior Lecturer with De Montfort University, U.K. Since 2002, Dr. Chen has been a Research Professor with the Institute of Energy Technology (IET), Aalborg University, Aalborg, Denmark. He is the coordinator of the Wind Turbine Research Program at IET. His main research areas are renewable energy and distributed generation, power electronics, power systems and protection. He has more than 100 publications in his field. Dr. Chen is an Associate Editor of the IEEE Transactions on Power Electronics, a Senior Member of Institute of Electrical and Electronics Engineers, a Member of the Institution of Engineering and Technology (London, U.K.), and is a Chartered Engineer in the U.K.