Wind power integration into the automatic generation control of power systems with large-scale wind power

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Abstract: Transmission system operators have an increased interest in the active participation of wind power plants (WPP) in the power balance control of power systems with large wind power penetration. The emphasis in this study is on the integration of WPPs into the automatic generation control (AGC) of the power system. The present paper proposes a coordinated control strategy for the AGC between combined heat and power plants (CHPs) and WPPs to enhance the security and the reliability of a power system operation in the case of a large wind power penetration. The proposed strategy, described and exemplified for the future Danish power system, takes the hour-ahead regulating power plan for generation and power exchange with neighbouring power systems into account. The performance of the proposed strategy for coordinated secondary control is assessed and discussed by means of simulations for different possible future scenarios, when wind power production in the power system is high and conventional production from CHPs is at a minimum level. The investigation results of the proposed control strategy have shown that the WPPs can actively help the AGC, and reduce the real-time power imbalance in the power system, by down regulating their production when CHPs are unable to provide the required response.

1 Introduction

The active power balance control is becoming more significant for transmission system operators (TSOs) over the years because of the dramatic increase of wind power penetration into the power systems. Nowadays, power systems are evolving from classical systems operated and controlled by the conventional power plants into power systems based on wind power to a larger extend. This means, that TSOs must be able to cope with new challenges in power system operation, raising concerns about dynamic security and reliability. In an interconnected power system, the TSO should maintain the system frequency of each area within specified limits and the tie line power flow at its plan. Traditionally, conventional power plants have the task of maintaining the active power balance and are capable of meeting the TSO guidelines. Their possible future replacement by wind power plants (WPPs) of similar size increases the risk of system failures, unless the TSOs revise and set new requirements for WPPs, that is, to participate in active power balance control.

Active power control from WPPs is a challenging technical issue, which has initiated an intensification of this research area in academia and industry. Several studies regarding active power control from WPPs have been performed in the past few years. For example, a comprehensive state-of-the-art review, regarding the frequency regulation and spinning reserves from variable speed wind turbines, is conducted in [1, 2]. Results from [3] show that increasing wind power integration alters the frequency behaviour and therefore TSOs must develop solutions to meet the challenges. A Dutch case study has been developed in [4] to assess the automatic generation control (AGC) performance in the presence of large-scale wind power and found that additional reserves are required for keeping the area control error (ACE) at the same level. Recent Chinese studies [5] have led to the conclusion that the fluctuation from WPPs can be controlled via conventional generators. In the USA, intensive work on the development of wind turbine control system to vary a turbine's active power output as demanded by the TSO has been conducted and described in detail in [6]. According to [7], the WPPs can participate in frequency regulation services with energy storage devices such as super capacitor banks, while [8] analyses the benefits of active power regulation from WPPs. However, the increasing wind power integration may replace or dominate the electricity generation from conventional power plants in future power systems and it may require active participation from the WPPs in the active power balance control on the power system level. Further studies in this context, for example, WPPs integration into the AGC system, are necessary to enhance operational security of future power system with large-scale wind power integration.

The objective of this study is to investigate how WPPs can actively participate in the secondary frequency control. This study proposes a coordinated control strategy for the AGC between the combined heat and power plants (CHPs) and WPPs in order to improve the active power balance in the power system with minimum secondary dispatch cost. The described control strategy regulates the active power production from CHPs and WPPs, depending on operating reserves, dispatch limit and the generating cost. The WPPs can only provide down regulation services if they are not operating in delta mode, where wind power is kept as reserve. The proposed strategy is developed and exemplified considering the Danish power system, as this is characterised by the highest wind power penetration level in Europe and aims to further increase the wind power capacity to cover almost 50% of the total energy requirement by 2020 [9].

This study is structured as follows. A brief description of the developed dynamic power system model implemented in Power Factory is provided first. The active power balance control, taking into account the hour-ahead (HA) regulating power plan for generation and power exchange with neighbouring power systems and real-time balance control, is then described. The implementation of the proposed control strategy for the integration of wind power into the AGC of the power system follows next. The high wind penetration scenario for the Danish power system in year 2020 is used to assess the performance of the presented coordinated AGC strategy between CHP and WPP through a set of simulations with the developed power system model. Finally, conclusive remarks are given in the final section.

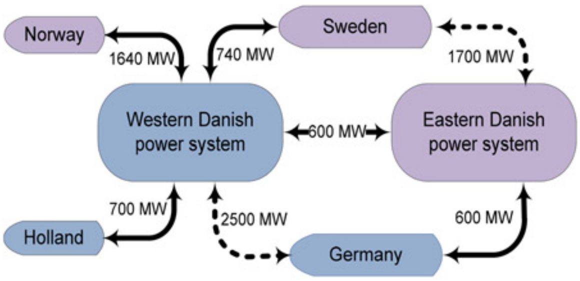

Fig. 1 *Interconnection capacities for the year 2020 [10]*

2 Dynamic power system modelling

As previously mentioned, the Danish power system is used to validate the performance of the proposed coordinated control strategy for AGC. The Danish power system is electrically separated into two synchronous areas, that is, eastern and western Danish power systems, and synchronised with the strong Nordic and Continental European (CE) synchronous power systems, respectively. Fig. 1 shows the interconnection capacities of the Danish power system with its neighbouring powers as planned for the year 2020 [10], where AC interconnections are presented as dotted line and the DC interconnections as solid line.

The electrical power generation in Denmark is a combination of conventional and renewable generation sources. The conventional power generation is typically from CHPs and de-centralised CHPs (DCHPs), whereas renewable generation is usually from WPPs. Studying the coordinated AGC strategy in the Danish power system requires a detailed representation of the power system that includes conventional power plants, WPPs and the interconnection with neighbouring power systems, as shown in Fig. 2. The aggregated models developed for this paper reduce the computation effort but still contain the dynamic features relevant for the present investigation, without missing relevant behaviours of the generating systems.

The developed power system model and the description of the HA planned and real-time inputs, provided by the power balancing model and the AGC, respectively, are based on the description in [11–15]. The power balancing model, called simulation power balancing model (SimBa), provides the HA regulating power plans for a balanced power system based on the input time series from day-ahead (DA) spot market and HA forecast of wind power.

2.1 Conventional power plants (CHPs and DCHPs)

Aggregated models for CHP and DCHP are developed based on the studies described in [12–14]. These models contain both the primary and secondary control capabilities and reflect the relevant dynamic features for long-term dynamic simulation studies. The response time associated with a CHP is in the order of minutes and is the dominant characteristic for power system studies. In the proposed strategy, the reference power for CHP and DCHP is calculated based on the HA plan from power balancing model (P_{plan_CHP} and P_{plan_DCHP}) and the power correction from the AGC (ΔP_{CHP}).

2.2 Wind power plants

At power system level, the aggregated performance of a large number of wind turbines is in focus rather than the detailed performance of individual wind turbines. An aggregated WPP model, based on the IEC61400-27-1 recommendations [15] and further simplified for the secondary active power control purpose of the present paper, has been implemented.

As illustrated in Fig. 3, the aggregated wind turbine model includes an active power controller and a generator system. The generator system simulates the wind turbine response. The wind turbine model provides the relevant dynamic response of WPP with respect to active power control capabilities, using as inputs the measured power at point of common coupling (PCC) and the reference power (P_{ref_WPP}) from the WPP active power controller. The P_{ref_WPP} to the wind turbine model is calculated inside the WPP active power controller based on two input signals. One input signal is conducted based on the primary response from the WPP (ΔP_c), whereas the other (P_{ref}) is determined based on the required secondary response (ΔP_{WPP}) from the AGC and the available wind power signal (P_{WPP_avail}) from the power balancing model. Besides the two mentioned inputs signals, the WPP active power controller is also using information on the measured power at PCC (P_{meas_PCC}) in the decision of the P_{ref_WPP}.

3 Active power balance control

The TSOs are obliged to securely operate the power system in transporting the generated electricity to the end consumers and maintain the power balance in the power system. This electricity is traded in the electricity markets by the balance responsible companies, who can produce, consume or retail. The balance responsible companies trade for each operating period during the next day in the DA market. The dispatch bids are selected with foremost intent of preserving system integrity and to minimise the production cost. The balance responsible companies also trade on the intraday (HA) market before the actual operation period, taking into account the updated wind power forecasts or unavailability of power plants. The following sections explain first the power balancing model with the generation of HA regulating power plan in a time scale of 5 min for the power plants and power exchange with neighbouring power systems and then the real-time power balance control in the power system.

3.1 HA power balance control

The TSOs use and combine information from different programmes to ensure the power balance in the power system. These

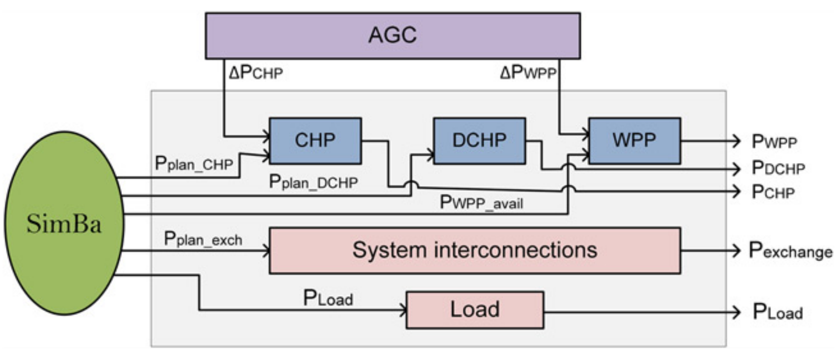

Fig. 2 *Inputs–outputs overview of the dynamic power system model*

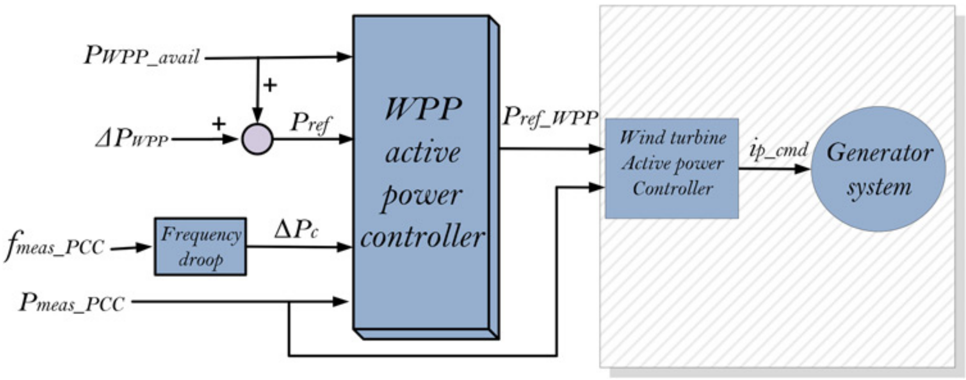

Fig. 3 *Aggregated WPP model [15]*

programmes provide information regarding wind power forecast and load demand, and also simulate the regulating power plan for balanced power system. SimBa, for instance, is the kind of programme used to simulate HA regulating power plan in Denmark. SimBa generates HA plans for the intra-hour balance with 5 min periods based on input time series from DA market model and HA forecast of wind power. The DA time series ($P_{\text{plan\_DA}}$) are provided by wind power integration in liberalised electricity market (WILMAR), whereas the correlated wind power fluctuations (CorWind) model provides the HA forecast of wind power ($P_{\text{WPP\_HA}}$), as shown in Fig. 4. The CorWind model also provides the DA forecast of wind power ($P_{\text{WPP\_DA}}$) and the available wind power ($P_{\text{WPP\_avail}}$).

SimBa models the power system taking into account the current grid regulations and the electricity market rules. SimBa uses inputs from WILMAR that include hourly values for energy production, load and the power exchange between interconnected areas and HA wind power forecasts from CorWind. Based on these inputs, SimBa balances the power system and provides HA 5 min period plan for generating plants and power exchange with neighbouring power systems, that is, $P_{\text{plan\_HA}}$.

3.2 Real-time power balance control

The active power reserves are always needed to keep the power system in balance. In a highly wind power integrated power system, the reserves from fast conventional generating units increase the system reliability and also ensure the power supply security. According to European Network of Transmission System Operators for Electricity (ENTSO-E), the type of reserves needed to keep the power system in balance can be classified as frequency containment reserves (FCRs), frequency restoration reserves (FRRs) and replacement reserves (RRs) [16]. FCR are activated automatically within 30 s to constantly control frequency deviations and maintain the power balance in the whole synchronously interconnected system. FRR maintains the active power balance in the power system, and the power exchange with neighbouring power system at its schedule, and are typically activated (manually or automatically) within 15 min. RR restores the FRR back to the required level and responds from several minutes up to hours. The total volume of FCR in CE and Nordic region is ± 3000 and ± 600 MW, respectively [16]. In this paper, power imbalance is controlled through FCR and automatic FRR. Conventional power plants and WPPs provide the FCR, whereas FRR is activated from CHPs and WPPs through AGC.

In Denmark, the active power balance is controlled through activation of regulating bids from the Nordic Operational Information System (NOIS) list in the TSO's control room and also through AGC, with a reserved capacity of ± 90 MW acting on the border of western Denmark with Germany. However, for the present investigation, it is assumed that the power imbalance is controlled only through AGC. As the focus in this study is on integrating WPPs into the generation control, an AGC for eastern and western Danish power systems is implemented together with WPPs to investigate the AGC action in the Danish power system as in 2020 with an active integrated role of WPPs in the AGC.

4 Coordinated AGC between CHP and WPP

A coordinated control methodology for AGC, where both CHP and WPP are participating actively, is presented in this paper. The following sections explain first the implementation of an AGC and

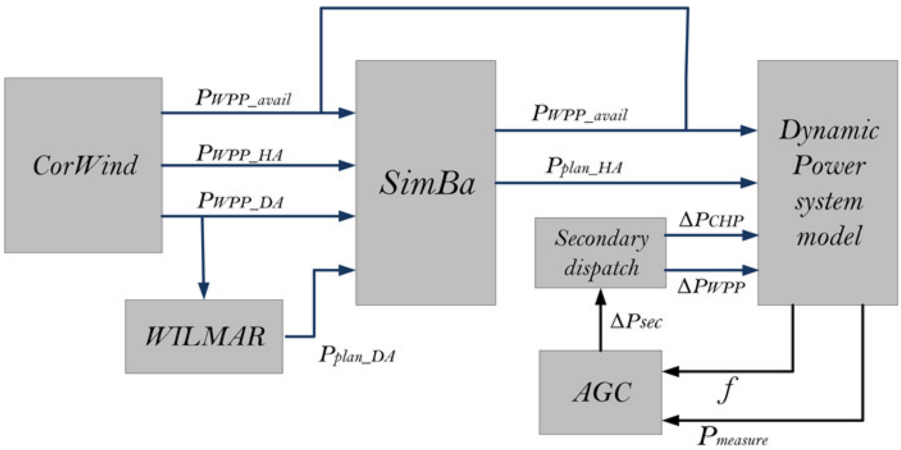

Fig. 4 *Overview of the signals between CorWind, WILMAR, SimBa, the dynamic power system model and the AGC*

then the coordinated control dispatch strategy between CHP and WPP.

4.1 *Automatic generation control*

The AGC is used to routinely balance the power system and makes the power system operation more reliable [17]. In the CE, the AGC is used to maintain the tie line interchanges at their plan level [18], as in the western Danish power system.

The AGC developed and implemented in this investigation, for the eastern and western Danish power system, is sketched in Fig. 5. In each part of the Danish power system, AGC measures the frequency deviation (Δf) from its nominal level and the possible power mismatch (ΔP) between generations (CHP, DCHP and WPP) and power exchange with neighbouring power systems and system load. The sum of ΔP with the product of Δf and system frequency bias factor (B) is called the 'area control error' (P_{ACE}). B is determined from the droop characteristics of all generating units taking part in the primary response [20]. Equations (1) and (2) show the P_{ACE} and ΔP, respectively

$$P_{\text{ACE}} = \Delta P + (\Delta f \times B) \tag{1}$$

$$\Delta P = P_{\text{Load}} + P_{\text{exchange}} - P_G \tag{2}$$

As indicated in Fig. 5, the P_{ACE} is processed by a central controller, usually a proportional–integral (PI), which calculates the required change in production (ΔP_{sec}) for the power plants to bring the P_{ACE} to zero, that is

$$\Delta P_{\text{sec}} = K \times P_{\text{ACE}} + \frac{1}{T}\int P_{\text{ACE}} \tag{3}$$

where 'K' and 'T' are the gain and integration time constants, respectively, and are adjusted based on the recommendation from [21] for the CE power system. The ΔP_{sec} is then distributed using the 'dispatch strategy' block among the actively participating generators, namely CHP and WPP assumed in this paper. This dispatch thus decides the change in reference power for the generating units CHP and WPP, that is, ΔP_{CHP} and ΔP_{WPP}, by using as input signals ΔP_{sec}, CHP generation (P_{CHP}), WPP generation (P_{WPP}) and the available wind power ($P_{\text{WPP\_avail}}$). Moreover, the dispatch strategy also takes into account the power generation limits (minimum and maximum) from the participating generating units.

4.2 *Dispatch strategy between CHP and WPP*

Traditionally conventional power plants provide the secondary frequency control in real-time operation. However, the increasing wind power integration may require active participation from WPPs in secondary frequency control in future power systems along with conventional power plants, as some conventional power plants might be replaced by WPPs. Coordinated AGC with dispatch between conventional power plants and WPPs is therefore of high priority for operational security and stability. This can be achieved by taking into account the generation and available reserves capacity from all participating generating plants for the secondary power control.

In the present paper, the secondary dispatch between CHP and WPP is performed based on cost minimisation. The following set of equations decides the positive and negative secondary dispatches for the WPP and CHP, (4)–(9) (positive) and (10)–(14) (negative)

$$\begin{aligned}&\text{minimise } C = C_{P_{\text{WPP}}}\Delta P_{\text{WPP}} + C_{P_{\text{CHP}}}\Delta P_{\text{CHP}}\\ &\because \text{positive dispatch cost}\end{aligned} \tag{4}$$

Subject to

$$\Delta P \geq 0 \tag{5}$$

$$\Delta P_{\text{CHP}} \leq \Delta P_{\text{CHP\_UpLim}} \tag{6}$$

$$P_{\text{CHP}} \leq P_{\text{CHP\_max}} \tag{7}$$

$$\Delta P_{\text{WPP}} \leq P_{\text{WPP\_avail}} - P_{\text{WPP}} \tag{8}$$

$$P_{\text{WPP}} \leq P_{\text{WPP\_avail}} \tag{9}$$

$$\begin{aligned}&\text{maximise } C = C_{P_{\text{WPP}}}\Delta P_{\text{WPP}} + C_{P_{\text{CHP}}}\Delta P_{\text{CHP}}\\ &\because \text{negative dispatch cost}\end{aligned} \tag{10}$$

Subject to

$$\Delta P < 0 \tag{11}$$

$$\Delta P_{\text{CHP}} \geq \Delta P_{\text{CHP\_LowLim}} \tag{12}$$

$$P_{\text{CHP}} \geq P_{\text{CHP\_min}} \tag{13}$$

$$P_{\text{WPP}} \leq P_{\text{WPP\_min}} \tag{14}$$

where $C_{P_{\text{WPP}}}$ is the power generation cost from WPP, $C_{P_{\text{CHP}}}$ is the power generation cost from CHP, $P_{\text{WPP\_min}}$ is the minimum generation level of WPP, $P_{\text{CHP\_min}}$ is the minimum generation of CHP and $P_{\text{CHP\_max}}$ is the maximum generation of CHP.

As mentioned in Section 3, the WPP will generate the available wind power ($P_{\text{WPP}} = P_{\text{WPP\_avail}}$). Therefore, during positive secondary dispatch (4), only CHP will participate. However, during negative secondary dispatch, as $C_{P_{\text{WPP}}} \ll C_{P_{\text{CHP}}}$, the wind power is down regulated only when CHP is unable to follow AGC command. Otherwise, the WPP will generate its maximum available power. The assumption is useful for the situation when WPP is generating highly and the conventional power plants are running on their lower level. In this paper, the dispatch for CHP (ΔP_{CHP}) is limited to ± 90 MW, as is the case for the AGC acting on the border of western Denmark with Germany, and WPP can reach their minimum generation level and available wind power.

The secondary dispatch in this paper, based on the above equations, will be as follows: the WPP is down regulated only when the output of AGC is negative, that is, $\Delta P_{\text{sec}} < 0$, whereas the

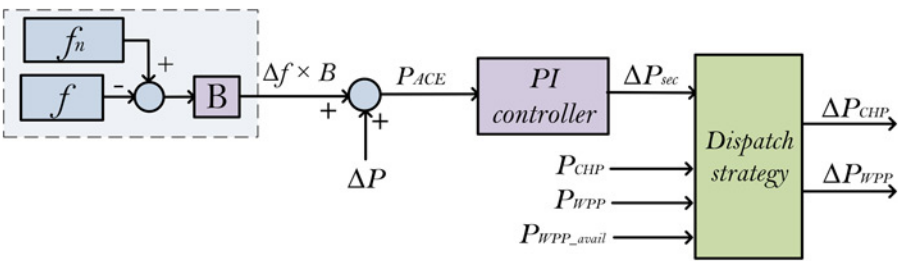

Fig. 5 *AGC and dispatch strategy model – [19]*

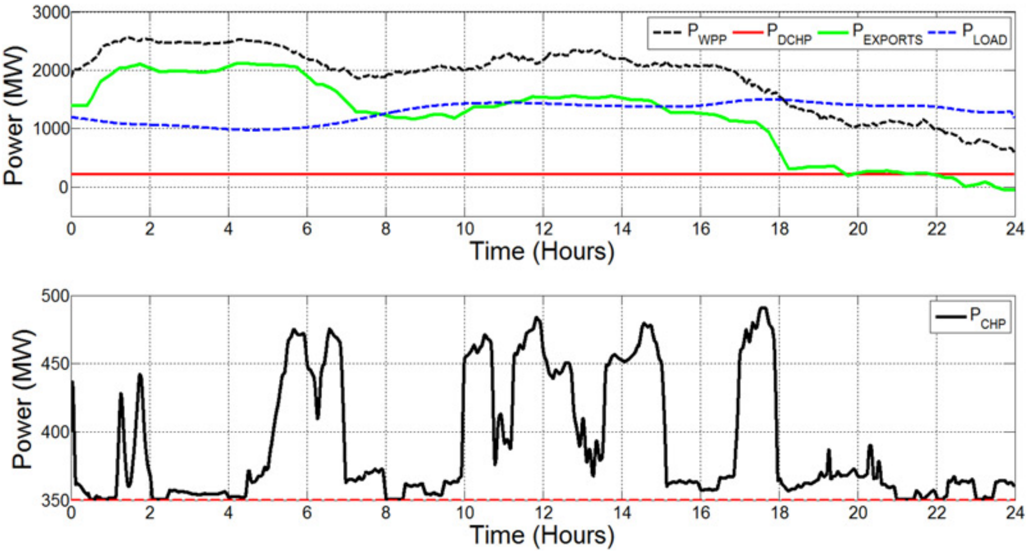

Fig. 6 *Generation, load and power exports – eastern Danish power system*

CHP provides secondary response for positive or negative value of ΔP_{sec}. For down regulation, the WPP will receive reference power signal only when CHP generation touches the lower generation limit (P_{CHP_min}) or ΔP_{sec} reaches to ΔP_{CHP_LowLim}, that is, −90 MW. However, in case of up regulation, that is, $\Delta P_{sec} > 0$, only the CHP provides the secondary support, as the WPP is already generating the available wind power.

5 Simulations and results

A set of simulations has been carried out to illustrate the dynamic performance of the proposed and implemented active power balanced control strategy, where wind power is directly integrated in the AGC control. The simulations are performed using the time series for generation, load and power exchange corresponding to one particular day of the year 2020 with high wind power. These time series are generated by the HA power balancing model (SimBa) for the Danish power system based on the real data from the year 2009. In this paper, the power exchange is kept at its planned level, whereas the reference powers of CHP and WPP are altered from the HA plan within the operating hour, as directed by the AGC. The power generated within the operating hour by WPP and CHP in the eastern and western Danish power systems is shown in Figs. 6 and 7, respectively. These figures also show the load demand and the planned power exports with neighbouring power systems. The power exports with neighbouring power systems are calculated by subtracting the total import power from the total export power within their respective power systems.

From Figs. 6 and 7 it can been seen that the WPP is generating higher then the CHP. The online capacity of CHP in eastern and western Danish power systems on the particular day is 1754 and 1944 MW, respectively. CHP is frequently operating near the minimum operating point, that is, 20% of the online capacity, marked as dotted line in these figures. The higher production from WPP also permits positive power exports with neighbouring power systems.

Power mismatch between generation and load appears when the actual wind power generated within the operating hour differs from the HA forecast or when other unpredicted events take place in the power system, like generator failures or line loss. The generating unit responds to the power imbalance by releasing FRR through the AGC. Fig. 8 shows the power imbalance in the eastern and

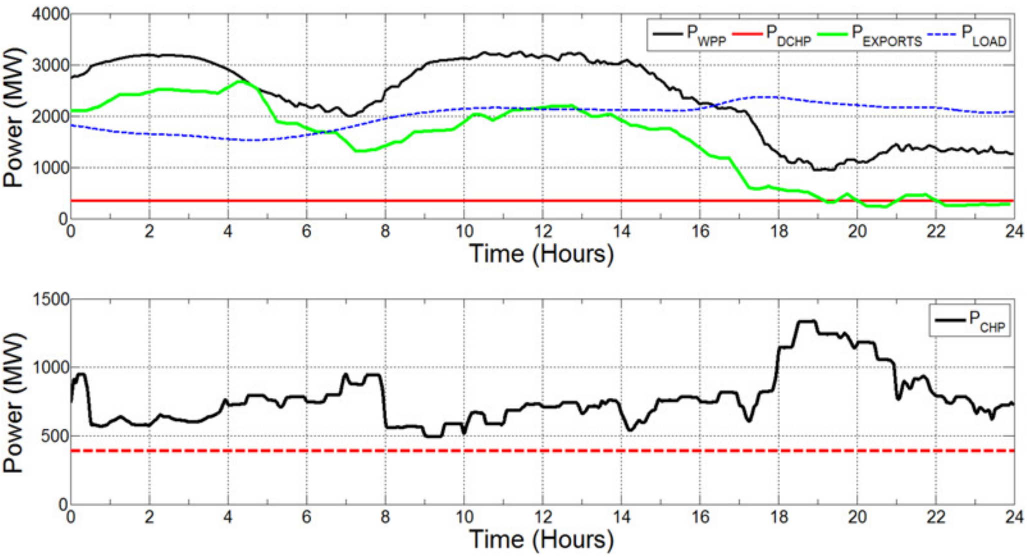

Fig. 7 *Generation, load and power exports – western Danish power system*

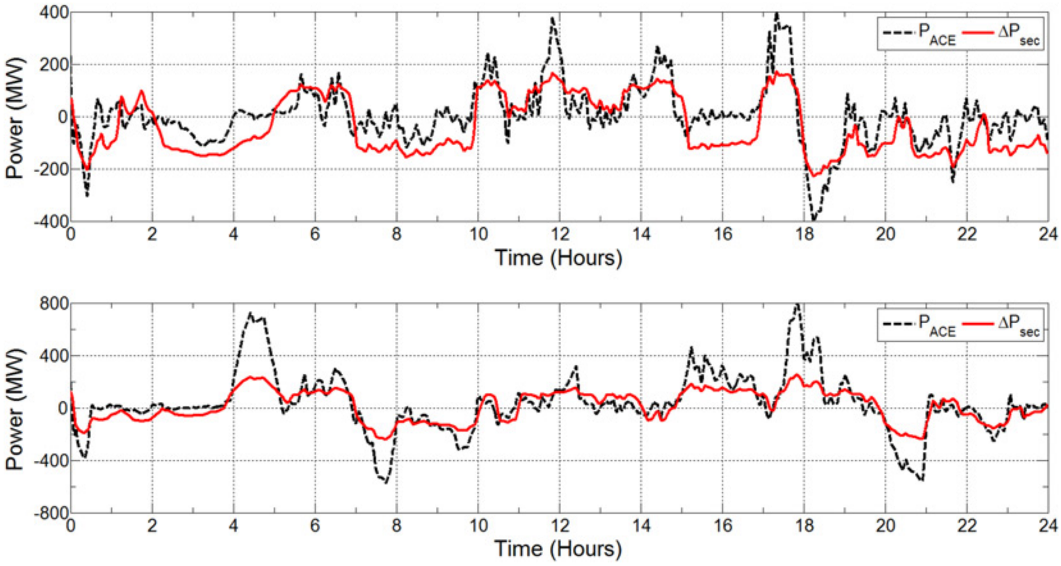

Fig. 8 *P_{ACE} and ΔP_{sec} – top: eastern Danish power system; bottom: western Danish power system*

western Danish power systems, reflected by the ACE signal, that is, P_{ACE}. As depicted in Fig. 5, the P_{ACE} is the input signal used in the PI controller of the AGC to decide the necessary secondary response (ΔP_{sec}) from the generating units to compensate for the power imbalance. As shown in Fig. 8, the ΔP_{sec} lags behind P_{ACE} because of the delays in the AGC system and the delays associated with the power plants response. These delays are because of the ramp in the reference power (i.e. 30 MW/min considered in this paper) and also because of the slow boiler response of CHP units (i.e. the boiler needs 5–6 min to modify its output pressure when demanded).

The new reference power signals for CHP and WPP are then determined by the dispatch strategy. The change in reference power signals for CHP and WPP in the eastern and western Danish power systems, calculated through the proposed dispatch strategy, is shown in Fig. 9. Note that WPP only participates in the down regulating process, whereas CHP contributes to both up and down regulating processes. The down regulating secondary dispatch to the WPP (ΔP_{WPP}) is activated only when CHP is unable to provide the required response. This simulation shows the strength of the proposed coordinated AGC between WPP and CHP, namely that when the CHP dispatch (ΔP_{CHP}) touches the lower limit (−90 MW) or they are operating at their lower generation limit (20% of the online capacity), this being quite frequent, the WPP can actively help the AGC, and reduce the real-time power imbalance in the power system, by down regulating their power production. It is worth mentioning that on the particular day considered in the present investigation, out of the available wind energy in eastern and western Danish power systems of 46.6 and 56.93 GWh, respectively, 1.06 GWh and 320 MWh are spilled out in the down regulation of the WPP to compensate for the power imbalance. The amount of energy lost for maintaining power balance is thus 2.2 and 0.56% of the available wind energy in the hugely wind power integrated eastern and western Danish power systems, respectively, when CHP is not able to provide the required response. This shows that active participation of WPP in AGC is an attractive solution for future power systems with large scale of wind power.

Fig. 10 compares the initial power imbalance in the eastern and western Danish power systems with the power imbalance when secondary dispatch is controlled with AGC controlled CHP and AGC

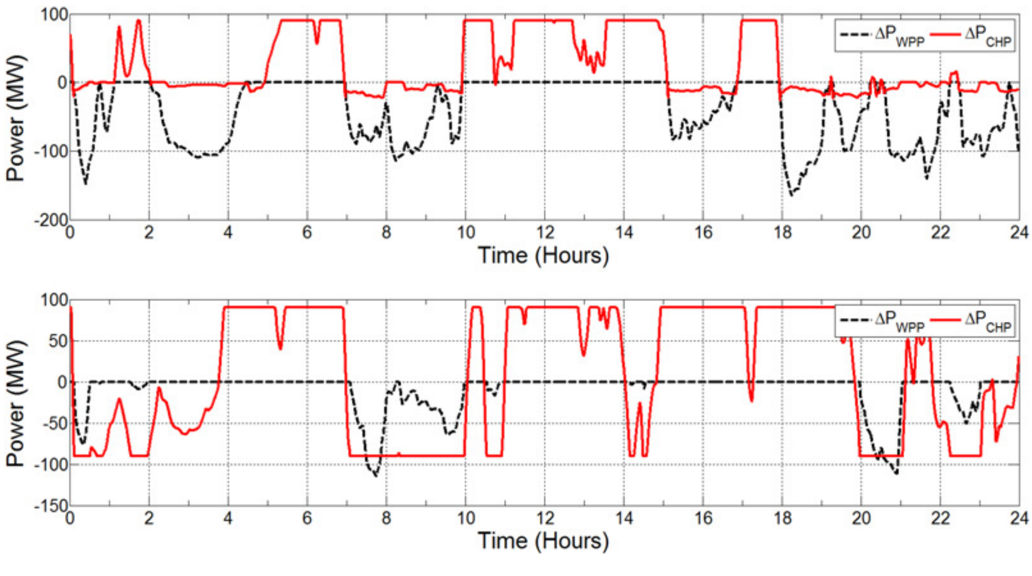

Fig. 9 *ΔP_{CHP} and ΔP_{WPP} – top: eastern Danish power system; bottom: western Danish power system*

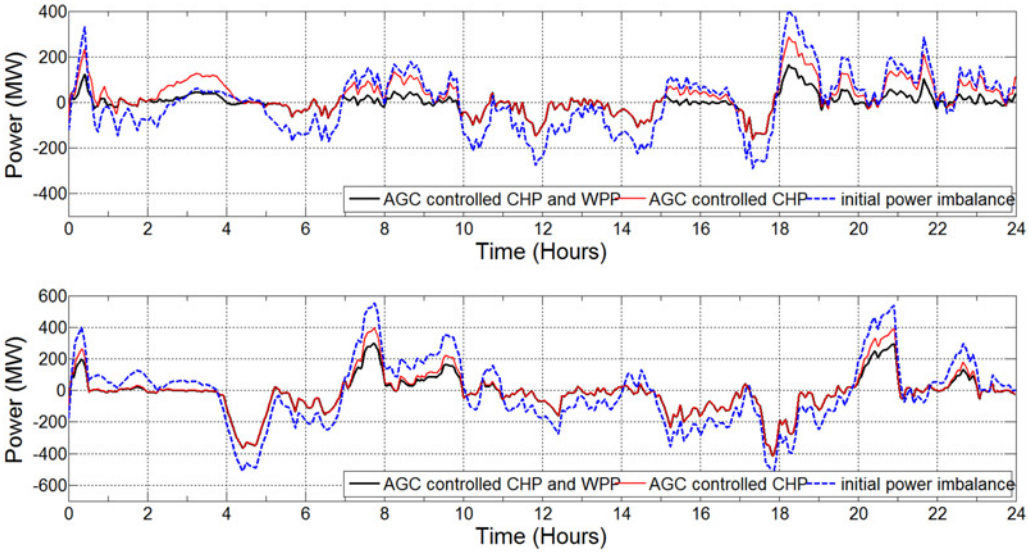

Fig. 10 *Power imbalance – top: eastern Danish power system; bottom: western Danish power system*

controlled CHP and WPP. It can be seen that without WPP integration, the power imbalance is larger in the case of generation excess than in the case with WPP, as CHP is frequently operating at the minimum level or ΔP_{CHP} reaching to its lower limit. The simulations show that the integration and active participation of WPP in the AGC system reduces the real-time power imbalances and makes power system operation more reliable.

6 Conclusion

This study proposes and presents a novel and practical approach for integration of wind power into the AGC of power systems to compensate the power imbalances between demand and generation in real time, provoked by wind power forecast errors. It is based on a coordinated control strategy between CHPs and WPPs. The Danish power system, with high wind penetration corresponding to year 2020 scenarios, is used as a case study in the verification of the proposed method. The new control methodology for the AGC system with WPPs integrated is using input time series from a power balancing model on power generation, power demand and power exchange with the neighbouring systems. Study with high wind penetration scenarios, corresponding to one particular day with high wind speed in 2020, is performed and presented in order to illustrate how power imbalances between demand and generation can be compensated by regulating the active power production from conventional and WPPs.

The present investigation shows that the active integration of wind power into the dispatch of the AGC is an attractive active power balancing control solution for power systems with large-scale wind power penetration. The strength of the solution is of high relevance, particularly in situations when wind power is contributing with large portion of the total electricity production and when the conventional power plants are operating at the minimum level and cannot be further down regulated in case of generation excess. The down regulation of the wind power reduces the power imbalance in real-time operation and because of its fast ramp rates can also provide quick ACE compliance. Furthermore, a good forecasting of wind speed and load demand and an increased automatic generation controller capacity, are always important for a secure and reliable power system operation of a large-scale wind power integrated power system. Further research can also investigate the programmed control of regulating bids in real time to enhance the secure and reliable power system operation for highly integrated wind power scenarios.

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