

Performance of Automatic Generation Control Mechanisms with Large-Scale Wind Power

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Abstract — The unpredictability and variability of wind power increasingly challenges real-time balancing of supply and demand in electric power systems. In liberalised markets, balancing is a responsibility jointly held by the TSO (real-time power balancing) and PRPs (energy programs).

In this paper, a procedure is developed for the simulation of power system balancing and the assessment of AGC performance in the presence of large-scale wind power, using the Dutch control zone as a case study. The simulation results show that the performance of existing AGC-mechanisms is adequate for keeping ACE within acceptable bounds. At higher wind power penetrations, however, the capabilities of the generation mix are increasingly challenged and additional reserves are required for keeping ACE at the same level.

Index Terms — Wind Power, System Integration, Secondary Control, Automatic Generation Control, Dynamic Simulation

1. INTRODUCTION

In the past decade wind power has become a generation technology of significance in a number of European countries. With further development of wind power on the horizon, the impacts of wind power on power system operation will increase as well. In particular the unpredictability and variability of wind power challenge real-time balancing of supply and demand in electric power systems. This is because significant amounts of wind power not only introduce additional power variations and uncertainty but may also decrease generation capacity available for secondary control. For balancing the fluctuations of wind power, additional power reserves may be required on top of power reserves already held for managing existing power variations in the system, which are caused by load variations and unscheduled generation outages.

In liberalized markets throughout Europe, participants have been made free to make arrangements for trading power in a number of forward markets. In order to guarantee a balanced power system, generation, load and energy trades are scheduled on beforehand and laid down in energy programs, which are sent to the system operator (TSO). In the Netherlands, the responsibility for maintaining the power balance in the system lies not only with the TSO but also with market participants responsible for delivering according to their energy programs. Based on the energy exchange programs received from these program responsible parties (PRPs) day-ahead, the TSO takes care of all real-time power imbalances using reserve power. PRPs are penalized for energy exchanges with the system different from specified in their energy program. Interestingly, in the Netherlands, wind power is subject to program responsibility as well, compared to the more common priority dispatch. Failure of a Dutch PRP to balance the partial predictability and variability of

wind power with other generation/load in its portfolio therefore results in the payment of an imbalance price to the TSO [1]. Wind power will therefore impact the secondary control actions performed by PRPs.

Little research has been performed on the impacts of wind power on secondary control performance in general, and the integration of wind power into liberalized electricity markets in particular. Dynamic interactions between wind power and system frequency have been investigated in [2]. It is shown that the displacement of conventional generation with wind results in increased rates of change of system frequency for that particular system. However, for larger systems, system inertia may be considerably larger and impacts of wind power on this can be delineated as being less severe or absent [3]. Impacts of wind power on secondary control and the need for spinning reserves [3], [4] may however be more significant, also at low wind power penetration levels. Quantifying these using classical models for power-frequency control (Automatic Generation Control, AGC) does not consider energy program responsibility since these approaches implicitly assume a direct physical link between a secondary control signal by the TSO and a generator set-point change. Furthermore, any strategic behaviour by market participants is assumed to be absent. It is the objective of this paper to demonstrate a possible extension of existing models with such aspects and to illustrate the impacts wind power may have when fully integrated into program responsibility.

This research is focused on modelling load-frequency control dynamics in the presence of large-scale wind power subject to program responsibility. Simulation results are presented for different variants with wind power balancing by separate conventional generation portfolios subject to program responsibility, such as the case in the current market design in the Netherlands. A two-area power system model, representing a control area as part of a large interconnection, is set-up based on realistic data for generation units, loads, wind power production and forecasts. The novel contribution of this work consists in modelling the imbalance control by PRPs via minimization of their energy program deviations. The impact is assessed of different market designs on the total amount of reserve and regulation applied for balancing wind power and on Area Control Error performance.

This paper is organised as follows. First, the Dutch market design and its impact on wind power are briefly re-introduced in Section 2. Section 3 describes the development of a dynamic power system model for frequency stability and secondary control adequacy assessment, from both the perspective of the TSO and PRPs. In Sections 4 and 5, the set-up and the results obtained from the simulations are covered. Conclusions and an outlook on further work are presented in Section 6.

2. MARKET INTEGRATION OF WIND POWER

The responsibility for balancing large interconnected systems such as UCTE is typically divided between different transmission system operators (TSOs), each responsible for balancing its respective area (control zone). The whole process of power system balancing comprises many stages, starting with energy trade and ending with real-time balancing of unscheduled power exchanges of market participants with the system. In order to organise trade and guarantee a balanced system on beforehand, the concept of program responsibility is applied. This is illustrated and discussed in more detail below for the Netherlands.

2.1. Program Responsibility

With program responsibility, PRPs or program responsible parties (PRPs) have been made responsible for keeping their own energy balance. Each customer (generator or load) connected to the system is associated to a PRP. A PRP must maintain its energy balance (MWh) for each market settlement period or program time-unit (PTU). Program responsibility requires program responsible parties to provide energy programs (e-programs) to the TSO, describing the energy exchange with the system for each PTU, and to act accordingly. The e-programs in fact contain the sums of all scheduled generation, load and trade of one PRP with other PRPs: generation is delivered to the power system only if there is a load to match it. The sum of all e-programs of all PRPs should add up to zero.

PRPs have different markets to their disposal for trade, comprising bilateral contracts (blocks for long terms for physical position settlement), spot markets (up to one day preceding operation) and adjustment markets (up to one or a few hours before the hour of operation). At gate closure, all trading for the physical delivery of electrical energy ceases: PRPs submit their final schedules to the TSO. The schedules contain their intended energy exchanges with the system for each trading period. It is then the TSO who manages power reserves for maintaining the system balance. On top of the automated primary actions for system security, the TSO continuously manages secondary (available within 15 minutes) and tertiary reserves (available after 15 minutes) in order to maintain the balance in the system in real-time. Secondary and tertiary reserves are in general made available by PRPs submitting bids for operating reserves to the TSO. Since the capacity for system balancing is made available by PRPs who themselves must keep their energy balance as well, it should be noted that secondary control actions by the TSO and PRPs will coincide or, occasionally, interfere during operation. Furthermore, it is important to realise that program responsibility is based on economic incentives: the balancing costs encountered by the TSO are passed on to PRPs deviating from their submitted energy programs. Thus, PRPs will behave strategically in order to minimize their imbalance costs.

2.2. Program Responsibility for Wind Power

In the Netherlands, wind power is subject to program responsibility, just like conventional generation, which is unlike most market designs for wind power. PRPs are thereby financially encouraged to limit possible imbalances resulting from wind power variability and partial unpredictability: a power imbalance as a result of wind power implies an energy program deviation. In order to

prevent imbalance costs, Dutch PRPs therefore monitor and manage their unit portfolio taking into account wind power predictions and real-time measurements.

Balancing wind power output deviations can be done by adjusting generation or load within the PRPs' portfolio or by taking precautionary measures on the market [1]. In order to be able to do so, wind power unpredictability and variability must be taken into account during unit commitment and dispatch calculations of an individual PRP with wind power in its portfolio. Wind power thereby is part of the overall operating decisions continuously made by PRPs.

As the amount of wind power increases, individual PRPs will be inclined to reserve more of the generation capacity within their portfolio for minimization of energy program deviations, while the TSO may not need significant extra reserves for balancing wind power. At the same time, any imbalances remaining after secondary control actions by PRPs must still be matched by the TSO, using the capacity made available by the PRPs. Wind power therefore challenges existing AGC-mechanisms applied both by PRPs and by the TSO for imbalance minimization.

3. POWER SYSTEM MODEL DEVELOPMENT

In order to assess the impacts of wind power on the performance of secondary control or automatic generation control (AGC) mechanisms, a power system simulation model for the UCTE-area is developed. This dynamic model can be used for the simulation of long-term frequency stability, i.e. the ability of a power system to maintain steady frequency following a severe system upset, resulting in a significant imbalance between generation and load [5]. As an immediate consequence of such power imbalances, the system frequency changes and an area control error (ACE) is introduced. The TSO will then send out signals to selected PRPs for secondary response in order to re-install the system frequency at the set value. Below, the development of the model is described.

3.1. System Inertia and Primary Control

From a system point of view, frequency stability is determined by two system parameters comprising the response of the system as a whole: power system inertia and the system power frequency characteristic.

The model developed here effectively describes the power system as a mass rotating at a speed of 50 Hz. The actual rotational speed is dependent on the amounts of mechanical power added to or taken from this mass. A uniform frequency is assumed using an aggregated inertia constant of an equivalent one-machine infinite bus system, such as applied in [6]. The power frequency characteristic (the overall dynamic response of generation and load to a power balance) consists of a load self-regulation factor of 1 and an aggregated primary response of generators in the UCTE as a whole. Detailed primary responses of 70 units in the Dutch system have been modelled explicitly using historical unit models available to the authors. The resulting aggregated primary response of the model has been compared to frequency data supplied by Dutch TSO TenneT, using an approach as presented in [7].

For the estimation of system inertia and primary response of the UCTE-interconnection, 4s. frequency deviation measurements were obtained for 88 significant instantaneous

power imbalances in the UCTE-interconnection from 10/2004 to 12/2006. The power frequency characteristic was found to lie between $19 \cdot 10^3$ MW/Hz and $47 \cdot 10^3$ MW/Hz, with a mean of $26 \cdot 10^3$ MW/Hz and a standard deviation of $9 \cdot 10^3$ MW/Hz. With an allowable measurement inaccuracy of 10 mHz in place for generators on primary control, a primary response of the model is obtained as shown in Fig. 1, illustrated with a small number of recordings representative of the full data set.

3.2. Secondary Control

The area control error (ACE) represents the total power deviation of a system (MW) and comprises unscheduled power exchanges of the area with neighbouring areas and the frequency deviation of the system. For secondary control purposes, ACE is typically processed using a PI-controller (processed ACE, PACE) before it is sent to units on secondary control. The PACE-logic has the objective of minimizing ACE while neglecting fast dynamics in system frequency, which would result in unnecessary, fast changes in demands for secondary control. In this model, it is assumed that ACE occur in the Dutch area only and that Dutch secondary control alone returns ACE to zero. The rest of the UCTE-system is balanced but will contribute to primary reaction in case of significant frequency deviations. Dutch ACE and PACE have been modelled using the mechanisms developed and currently applied by Dutch TSO TenneT. A power frequency characteristic of 900 MW obtained from operational experiences of the TSO is applied, which is then compared to a two-stage threshold for fast response to significant events. Also, PACE is set such that its integral term does not increase (decrease) further in case ACE is positive (negative) but decreasing (increasing).

For real-time power system balancing, the TSO applies secondary reserves made available by PRPs through a bidding ladder (selection of cheapest bids). Bids are orderly arranged based on price in a power reserve bidding ladder, a separate ladder for upward and downward reserves. During real-time operation, the TSO continuously determines the amount of reserve power that is needed, based on the actual PACE. Using the bidding ladder, the amount of required reserves is mirrored onto the available bids which are then called off by the TSO. This is done by sending a *delta*-signal (MW-set point) to the PRP associated with each bid called, using a separate delta for both upward and downward reserves. The rate-of-change of delta does not exceed a ramp-rate value pre-specified by the associated PRP. Every four seconds, the PACE is re-calculated to determine whether the sum of all bids called (MW) is sufficient for balancing the control zone and which bid should be used up to which extent. In case PACE drops below an active bid's threshold and the bid is no longer necessary, the bid is reduced with a ramp rate no more than the maximum specified in the bid. Because of this ramp rate limitation, positive and negative bids may be active simultaneously. It is the responsibility of the market party associated with the bid called off to adjust its generation operating points and/or load schedules accordingly.

3.3. Energy Program Responsibility

When a power imbalance is picked up by the TSO (i.e. ACE) and secondary control is activated, the generation/load deviations from scheduled values causing it will also be

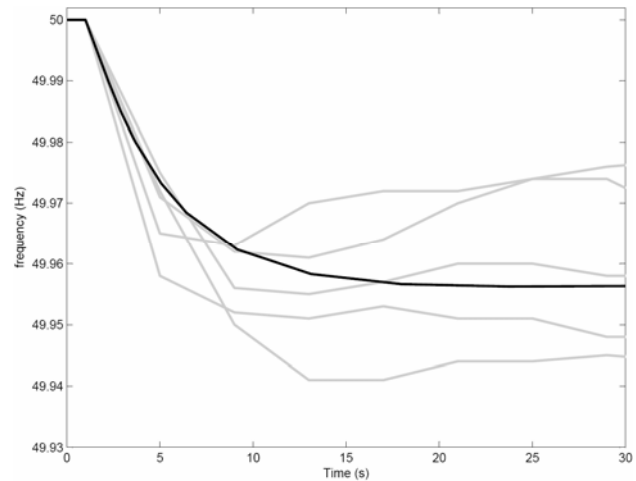


Fig. 1. Validation of system inertia and power frequency characteristic

picked up by the PRP responsible for it. Simultaneously with secondary control at the system level, the PRP will take measures in order to minimize its energy program deviation (not necessarily its power imbalance) in order to avoid imbalance costs. The PRP will not only monitor its power imbalance (MW), but also physical position within the PTU (MWh). The actual power imbalance of each PRP is constantly assessed by monitoring generation and load deviations from scheduled values while settling the secondary control signal received from the TSO. For imbalance minimization, a fraction of the actual power imbalance is integrated and subtracted from the set-point of generation units selected by the PRP for imbalance management. Because participation in secondary control is taken into account in calculating its imbalance, both the PRPs' imbalance and the system imbalance are eventually returned to zero.

Since imbalance costs are settled not on a MW but on an MWh/PTU basis, the energy imbalance for each PTU is the most relevant parameter for a PRP. The MWh-value specified in the PRPs' energy program is the operational objective: during each PTU, the overall energy deficit or surplus compared to the energy program must be minimized. For the counter-balancing of power deviations, different operating strategies for imbalance minimization may be applied in order to reach the energy value objective, as shown in Fig. 2 (area under all three modi is equal). Interviews by the authors with Dutch PRPs have revealed that the preferable operation modus is the most gradual one (B), even though this involves a continuous adjustment of operation set-points of units under secondary control, which could partially be prevented by opting for strategies A and C, or other. In the model, the energy program deviation is constantly calculated and fed back into the secondary control signal. At the start of each PTU, the energy-program deviation is reset to zero.

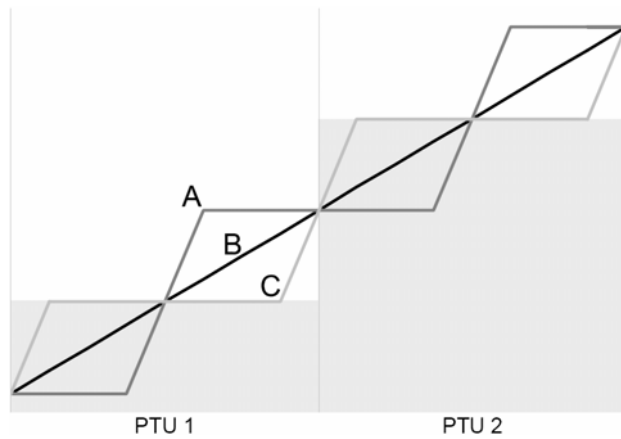


Fig. 2. Different operating strategies between energy-programme set-points

3.4. Generation Units

A number of existing dynamic generation unit models for Dutch plant have been compared to literature models [8]. It is found that, for long-term frequency control simulations, a differentiation must be made between initial responses and more persistent ones. The former are determined mainly by the governing system (valve positions) while in the longer term, the physical processes in the boiler become more important. For unit start-up or shut-down, these physical processes may require hours up to days, which must be taken into account when calculating the unit commitment and economic dispatch (UC-ED) of these units.

In this work, dynamic response (seconds) and primary reaction of 70 Dutch units part of PRPs' portfolios have been modelled explicitly. The models incorporate typical aspects as primary reaction and speed, power-frequency, turbine and fuel control. Longer-term physical aspects (minutes) have been delineated; instead, fixed ramp-rates not governed by physical limitations but by controls have been assumed, as is current practice for all units part of the PRPs' dispatch. UC-ED (weeks to hours) of the main Dutch generation units is calculated using a commercial optimization tool previously applied in [9].

As an example of the dynamic models of the generation units, Fig. 3 shows the simulated responses of some unit models developed for this research: a coal unit, a combined cycle gas turbine (CCGT) and a cokes gas unit in the Dutch system. All units are at a 0.6 p.u. operating set-point. At $t = 0$ s., a frequency drop of 0.004 p.u. is introduced, leading to a primary response of all units (a dead zone of 0.002 p.u. is assumed), resulting in a full primary response within 10-20 seconds. As can clearly be seen, the units all show a fast initial and a slower, more persistent response. At $t = 30$ s., the operating set-point is stepped up from 0.6 to 0.65 p.u. In this case, the dynamic response of the unit is governed by the unit ramp-rate controls. More detailed modelling of the unit dynamics therefore does not translate into added value for the simulations and have therefore not been incorporated. Notably, several Dutch PRPs have indicated to the authors that detailed physical models of their units are in fact not available to them.

3.5. Wind Power

With the modelling of wind power, it has been borne in mind that it is the objective this work to investigate the impacts of

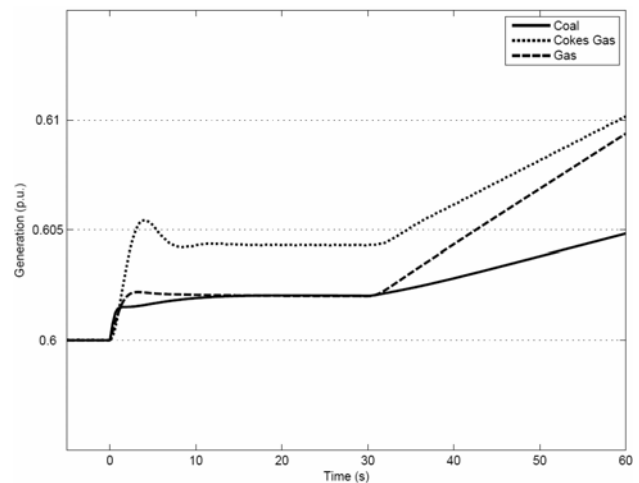


Fig. 3. Simulated responses of three generation unit responses to frequency and a operating set-point steps

wind power on automatic generation control performance. Since the overall power fluctuations of wind power clusters are of importance here, detailed models for wind turbines fall outside of the scope of this paper. Wind speeds at representative locations of Dutch wind parks onshore and offshore have been developed using wind speed data obtained from the Royal Dutch Meteorological Institute (KNMI). The data concerns 10-minute wind speed averages with a resolution of 0.1 m/s for 18 locations in the Netherlands (9 onshore, 3 coastal and 6 offshore) measured between June 1, 2004 and May 31, 2005. Wind speed time series for the study period are created for 15-minute time intervals in such a way that the spatial correlation between the sites is taken into account. The development of wind speed data is described in more detail in [9]. For simplification, it has been assumed that the effects of turbulence on the aggregated output of each wind farm within each 15 min. interval are small because of smoothing of fluctuations [10].

4. SIMULATION SET-UP

4.1. Simulation Method

The operation schedules of conventional generation units are governed by a number of longer-term aspects which fall outside the scope of the dynamic simulation model developed here. These aspects include scheduling of maintenance, market trading and settlement procedures of markets, which lead to the calculation of UC-ED schedules for each unit in the system. In order to arrive at a realistic starting point for the dynamic simulations, the following simulation set-up is applied:

- *Calculation of UC-ED:* A chronological UC-ED model with the same make-up as the dynamic model (generation units, wind power etc.) is run for a week or any longer period of time using a 15-min. time step. Steady-state operating set-points for each generation unit are obtained and saved.
- *Select cases:* The output of the UC-ED model is analysed and interesting cases for dynamic simulation (simultaneous wind power drop and load increase, generation outages etc.) are selected. A small number of

consecutive states including the selected state are isolated.

- *Import of unit set-points:* The operating set-points for all units are imported into the dynamic model. Interpolation is applied to obtain continuous operating signals serving as an input for the dynamic model of each unit.
- *Initialization and dynamic simulation:* The dynamic model is initialised around the operating points of the first state and then run. Power deviations occurring in real-time may be simulated by adding these deviations (i.e. wind gusts or random noise) to the set-points imported from the UC-ED-results. Valid parameters such as system frequency, ACE and PACE and power imbalances and energy program deviations of PRPs are reported.

For each PRP, one or more units are selected for AGC by the PRP, based on daily operating routines of Dutch PRPs. Furthermore, PRPs make bids available to the TSO for secondary reserves, which are then taken into account with the scheduling of UC-ED. Notably, PRPs prefer to use base-load coal units – if available within the portfolio of the PRP – for managing e-program deviations.

4.2. Simulated Variants

The following simulations are run:

- System operation without wind power
- Large variation of 2 GW wind power
- Forecast error and large variation of 2 GW wind power
- Large variation of 4 GW wind power
- Forecast error and large variation of 4 GW wind power

Simulation a) is used to provide a base-case for comparison with the simulations with wind power. Since for this simulation, no data are added compared to the set-points imported from the UC-ED-model and no wind power is present, the power imbalance at any moment in time should be small, resulting in a small ACE and PACE. Also, the results imported from UC-ED will be different since wind power will impact the scheduling of conventional units.

In simulations b) and c), wind power increases between $t = 450$ s. and $t = 1350$ s from 553 MW to 1207 MW (+654 MW) and then decreases between $t = 1350$ s. and $t = 3150$ s. to 707 MW. In simulation b) it is assumed that wind power is perfectly predicted and no real-time deviations occur. Therefore, the UC-ED will incorporate wind power and ACE and e-program deviations resulting from wind power imbalances can be expected to be small, although a more dynamic operation of conventional units is expected. In simulation c), a 'real-time deviation' signal of wind power is added to the wind power set-points imported from the UC-ED-results in order to simulate unscheduled wind power output. Thus, PRPs and the TSO will apply secondary reserves to balance forecast errors and ACE as a result of it. PRPs experiencing wind power deviations in real-time apply secondary control in order to avoid energy program deviations.

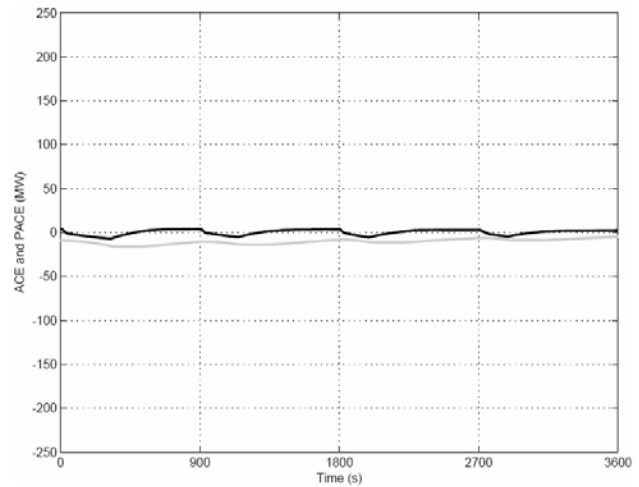


Fig. 4. Area Control Error (ACE, black line) and Processed Area Control Error (PACE, grey line) of the Dutch control zone with 0 GW wind power.

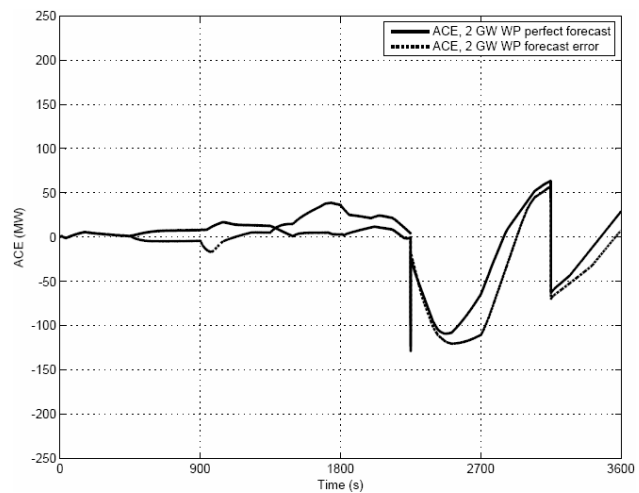


Fig. 5. ACE for the Dutch control zone with 2 GW wind power with perfect forecast b)(line) and with forecast error c)(dotted line).

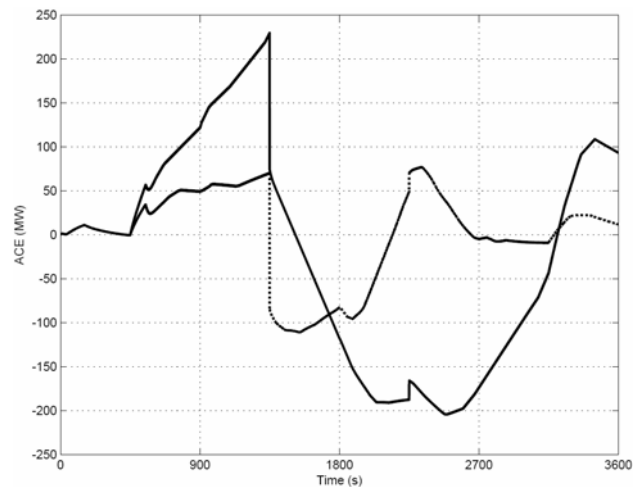


Fig. 6. ACE for the Dutch control zone with 4 GW wind power with perfect forecast d)(line) and with forecast errors e) (dotted line).

In simulations d) and e), wind power increases between $t = 450$ s. and $t = 1350$ s from 983 MW to 1736 MW (+753 MW) and then decreases between $t = 1350$ s. and $t = 3150$ s. back to 743 MW. In simulation d) it is assumed that wind power is perfectly predicted, in simulation e) wind power deviates in real-time from scheduled values.

5. SIMULATION RESULTS

5.1. System Perspective: ACE

In Fig. 4, the simulation results for a selected one-hour simulation period of the model is shown. Since for this simulation model, the generation and load set-point results from the UC-ED calculations are directly imported into the dynamic program and no sudden changes in unit output are present, ACE is very close to zero. As a result, PACE is also small.

Fig. 5 shows the simulation results of the same one-hour period, but now with 2 GW wind power. The UC-ED of other units in the system is scheduled to respond to this. As a result of the significant wind power variations, the UC-ED is changed compared to the situation without wind power: two units are now taken out of operation ($t = 2250$ s. and $t = 3150$ s.) and one unit starts operation ($t = 1350$ s). Since these conventional generation units have a minimum power output level, committing or de-committing these units results in a sudden steps in ACE. ACE is also influenced by wind power forecast errors: apparently, PRPs are unable to take these into account fast enough as to prevent power imbalances, which directly result in an increase of ACE, as can be seen in the figure.

In simulation variants d) and e), the variations of wind power are even higher than in simulation variants b) and c) and therefore a different UC-ED schedule has been chosen. At $t = 1350$ s, one large unit is taken out of operation while at $t = 2250$ s. a smaller unit is committed. Because of the large wind power variations, ACE significantly increases between $t = 450$ s. and $t = 1350$ s. Apparently, the reserves committed for balancing the wind power variations (Fig. 6) are not sufficient to keep ACE within a range comparable to Fig. 5.

It can be noted that for simulation e), the forecast errors actually improve ACE performance. For some PRPs, forecast wind power variations were actually larger than actual wind power variations. Because of this, more capacity was available for secondary control actions requested by the TSO. It can also be noted that UC-ED calculates the de-commitment of a large unit at $t = 1350$ s. Apart from the high possible risk for a PRP actually doing so, ACE performance would suggest the commitment of more power reserves.

5.2. Market Perspective: E-Program Deviation

In Fig. 7, above, scheduled generation and total generation level delivered during real-time operation are shown for one program responsible party, PRP1, for simulation b) (2 GW wind power, perfect wind power prediction). The scheduled total generation of this PRP is rather constant. Because PRP1 does have wind power in its portfolio, its other generation units have apparently been scheduled in such a way that wind power variations are balanced. Initially, PRP1 stays very close to its scheduled generation output, but at $t = 450$ s. it increases its generation. This can be explained by considering the demand for secondary control by the TSO, to which PRP1 then responds by increasing generation units

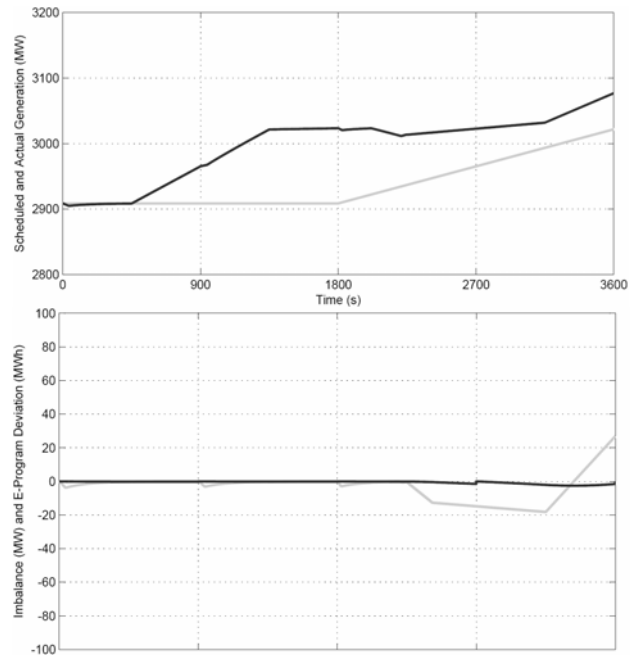


Fig. 7. Above: Scheduled (MW, grey line) and actual generation (MW, black line). Below: power imbalance (MW, grey line) and energy program deviation (MWh, black line). All for PRP 1 for simulation b).

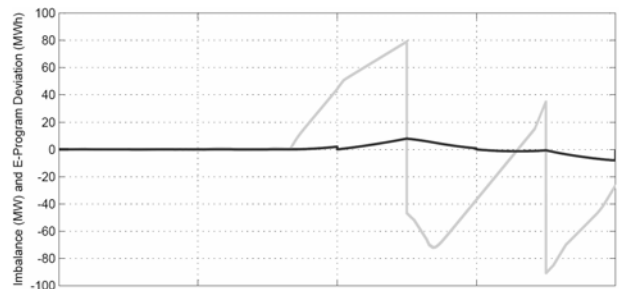


Fig. 8. Power imbalance (MW, grey line) and energy program deviation (MWh, black line) .for PRP 1 for simulation b)

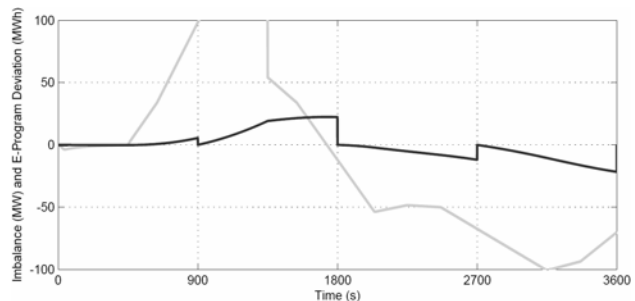


Fig. 9. Power imbalance (MW, grey line) and energy program deviation (MWh, black line) .for PRP 2 for simulation d).

selected for this and by any secondary control actions of PRP1 itself in order to minimize energy program deviations.

In the lower graph of Fig. 7, the real-time power imbalance and energy program deviation of PRP1 are shown for the same simulation. Clearly, PRP1 is initially very successful in minimizing its real-time power imbalance and energy program deviations. After $t = 2250$ s., however, the real-time

imbalance increases considerably, although strategic imbalancing between $t = 2700\text{s.}$ and $t = 3600\text{s.}$ still keeps the energy program deviation small. It should be noted that the energy program deviation at the end of each PTU (900s., 1800s., 2700s., 3600s.) is the value which the final imbalance costs are based upon. At the beginning of each PTU, the e-program deviation is reset.

Fig. 8 shows PRP2 who intends to minimize its energy deviation by strategically timing its power imbalance. Since this PRP has chosen to take two large units out of operation during this period in order to balance the foreseen wind power decrease between $t = 1350\text{s.}$ and $t = 3150\text{s.}$ In order to minimize its energy program deviation, PRP2 first overshoots, then takes its first unit out of operation, after which it reduces its imbalance again. The overall result of these actions is that the energy program deviation at the end of PTU 3 is very close to zero. However, PRP2's control actions have an impact on ACE as can be seen in Fig. 5.

In case PRP2 has more wind power in its portfolio, a different UC-ED is chosen. Apparently, it is now more optimal to de-commit one unit at $t = 1350\text{s.}$, compared to the two units in simulation b) / Fig. 8. However, PRP2 is not able to balance its own portfolio including wind power while responding to secondary control signals from the TSO at the same time. Since its ramping capabilities for balancing wind power balances are already heavily used, PRP2 runs into a large power imbalance since it is unable to respond to the TSO signal. The secondary control actions upwards and downwards are not enough to prevent significant energy program deviations. PRP2 needs larger amounts of secondary reserves and/or reserves with higher ramp rates in order to prevent this.

6. CONCLUSIONS

A model has been developed for the simulation of power system balancing and the assessment of AGC performance in the presence of wind power. The Dutch control zone is used as a case study for the integration of wind power under program responsibility. The simulation results show that the performance of existing AGC-mechanisms of both TSO and program responsible parties are adequate for returning ACE to small values within one PTU (15 min.) and energy program deviations within bounds. It is shown that the variability of wind power may lead to higher ACE, especially if insufficient amounts of reserves are taken into account during the unit commitment and economic dispatch calculations.

A notable simulation result is that the variability of wind power not only has a direct impact on ACE and power imbalances of program responsible parties, but also an indirect one. Significant wind power variations are shown to have an impact on commit and de-commit decisions of conventional units in the system, which in turn trigger strategic imbalancing by PRPs. The ACE as a result of this then requires the TSO to apply additional secondary reserves. Thus, even though the steady-steady UC-ED schedule is in balance for each state, variations in real-time as well as demands for secondary control by the TSO may require additional ramping capabilities of the units. These must be taken into account in the UC-ED in order to minimize power imbalances during operation.

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