Demand Response and Wind Power Ramp Limitation for Reducing Frequency Excursions in Power Systems with High Wind Penetration

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***Abstract*—Traditionally, the grid frequency is controlled by conventional power plants in most of developed countries. The main goal of this control is to keep the frequency within specified limits depending on each Grid Code. The conventional generators are usually equipped with so-called primary and secondary control, and the inertia in the power system grid limits the rate of frequency change in case of imbalance between supply and demand power. This power imbalance has to be catered by the generation, since demand-side is generally considered as not controllable. In recent years, the rapid development of wind turbine technology and the increasing wind power penetration have resulted in a continuous reformulation of wind power requirements. Some Transmission System Operators have unified requirements and connection rules for all production units, which makes it very difficult for wind turbine producers and wind farm developers to fulfill these modified Grid Codes. Moreover, the primary source for wind turbines is not controllable and the frequency control problem emerges as a relevant issue, specially in countries with high wind energy penetration. Indeed, wind power fluctuations may produce significative frequency excursions. Under such conditions, some authors suggest the participation from the demand-side as an additional contribution to maintain the power system stability. With this aim, this paper is focused on studying power imbalances in high wind energy penetration power systems considering frequency-sensitive demand responses. Power fluctuations due to the wind stochastic nature as well as different conventional power plants regulation strategies, combined with demand-side contribution and wind power positive ramp limitation technique are compared and included in the paper.**

***Index Terms*—Wind Power fluctuations, Demand Response, primary frequency control, positive ramp limitation**

I. Introduction

In some countries, the increasing levels of wind generation in the power system have resulted in new challenges, as the necessity of studying their impacts on frequency control. In this way, system inertia is directly related to the amount of synchronous generators in the power systems. This inherent relation is not obvious in wind turbine generators, where considering the stochastic nature of the primary energy source, will result in a short-term as an important concerns about the system frequency control [1].

Taking into account that, nowadays, most of loads are very sensitive to the frequency behavior, maintaining the frequency within a thin interval around the nominal value in a power system is a very important operational requirement. Furthermore, keeping a tight frequency control is a relevant concern to maintain a close balance between the supply-power and power demanded by the customer in a power system [2]. In this scenario, the primary frequency control involves all the actions performed locally at the generator to stabilize the system frequency after a power disturbance. After these actions, the grid frequency is stable but different from the nominal value. The goal of the secondary frequency control is to maintain the power balance within a bigger area —not just locally— as well as taking the system frequency back to its nominal value.

The main point to control the frequency balance in a power system is the generator primary energy input in controllable generators, such as steam and water turbines. Another way of influencing the frequency control is through the switching–off of some loads, but this kind of actions have usually been considered only in emergency situations so far, to save the power system. Nevertheless, some authors consider that 61% of such residential appliances are compatible with the proposed load control strategies. Due to the high penetration of cooling and heating loads, about 20 percent of the load in the U.S. comes from consumer appliances that cycle on and off and which could make a contribution to frequency control during a normal state operation, [3]. Additionally, Demand Response resources such as load curtailment have been only used under severe stability conditions, mainly load shedding actions for under–frequency operations due to important unbalances between generation and demand —or damping of electro-mechanical oscillations—. For example, interruptions of demand for 30 minutes, triggered automatically by low frequency relays —normally 49.7 Hz—, has been accepted with a minimum of 3 MW aggregated, expecting between 10 and 30 interruptions per year. In this context, different load shedding schemes have been proposed taking into account a certain frequency threshold as well as a Rate of Change of Frequency (ROCOF), [4]–[6].

In this work, the contribution of the demand-side to the frequency primary control is studied together with the classical primary energy input control in steam and hydro turbines, taking into account the power fluctuations of a wind farm within a high wind penetration power system. That contribution is studied as well when the power produced by the wind farm is limited as described in [7]. In Section II, the different components of the model used in this study are described. Section III provides a brief discussion of how participation from the demand side might affect the overall control of the frequency in the system. A description of the simulations as well as the results obtained are given in Section IV. Finally, conclusions are discussed in Section V.

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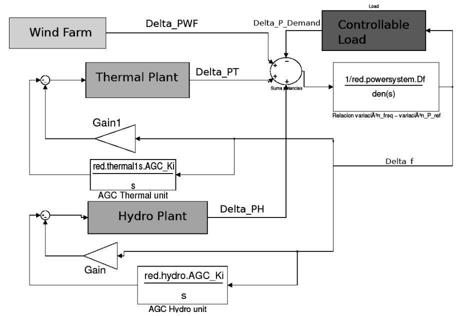

Fig. 1. Power System model: General Scheme

II. Power System Model

A scheme of the power system model used for this work is presented in Fig. 1. In this system, two conventional power plants and an offshore wind farm are considered from the supply-side —1 GW is assumed as average power demand—.

A. Conventional Generators

The conventional generators have been modeled to participate both in primary and secondary frequency control. From the point of view of these generators, the objective of the primary control is to change the primary energy input in order to maintain their rotating speed as close as possible to the rated speed. This speed may change as a consequence of any modification in the power demanded by the customer-side, or by a raise or fall in the power produced by other generators. Thus, a sudden disconnection of power demand will produce a speed generator increase, and consequently, an increasing of the grid frequency. The primary control actions have to take place from some seconds to minutes.

The model used in this paper includes the transfer functions for the two main elements of the generators: the primary energy–mechanical torque converter and the mechanical torque–electrical power converter. The block diagrams for these systems are shown in Fig. 2 and 3 respectively. The proposed thermal plant consists of a single steam turbine with no–reheating system. Slope limitations have been included for both generators as well.

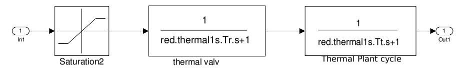

Fig. 2. Model of the thermal–plant

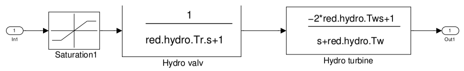

Fig. 3. Model of the hydro–plant

The aim of the secondary frequency control is to return the frequency to its nominal value around some minutes. This is achieved by the loops on the left part in Fig. 1, affecting both conventional plants. Its target is to detect any change in the system frequency, and modify the power reference of the generator. These power references may depend on the specific technical characteristics of the unit as well as the other units involved in the secondary control, such as maximum and minimum powers and power ramp limitations. The values taken for the parameters in the transfer functions can been found in [2].

B. Wind Farm Generation

The simulated wind farm is an offshore wind farm of 506 MW compound by 10 rows with 22 wind turbines each one of them. The distance between columns is about $500m$, whereas rows are separated around $900m$. The simulator is the implementation of the aggregated power fluctuations model of a WF described in [8], [9]. These model was previously validated by comparing its results with real power fluctuations meassured in Nysted Offshore Wind Farm.

Several 2–hour time intervals of supply power are simulated for the proposed wind farm. From these data series, one of them has been used hereinafter. The selected data series is relevant enough, as it represents a period with high wind penetration into the system and proper wind fluctuations. It is depicted in blue in Fig. 4. In this fugure, the wind power is expressed in pu of wind farm nominal power, which represents half of the system nominal power.

1) Positive Ramp Limitation: the Danish code fixes some conditions about regulation of active power within a wind farm, [10] [11]. The grid code defines different types of regulation that can be carried out by using these controllers. From those available types of regulation, the positive ramp regulation can be useful for reducing the effects of the power fluctuations, and thus the frequency excursions.

The positive ramp regulation strategy consits in a limitation of the maximum increasing gradient of the current production, i.e, it prevents the wind farm production from rising too fast. It doesn't have any effect when the wind energy decreases. When this strategy is applied, the resulting power is less or equal to the available power. In Fig. 4 the available wind power and the curtailed power produced by the wind farm

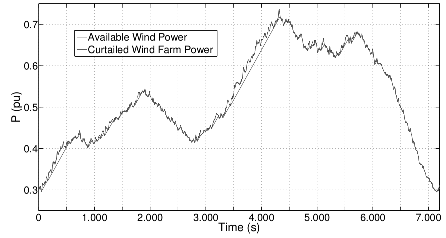

Fig. 4. Positive ramp limitation applied to the available wind power, expressed in per unit of wind farm nominal power

are shown. The energy loss during the 2–hour series due to the application of this technique can be easily calculated as the area between the two curves. For the simulations carried out in the present work, the curtailment shown in Fig. 4 implies the loss of aproximately 1% of the available energy.

C. Power System Simulation

The simulated power system consists of 1 GW average power demand. The aim of the control system is to detect any modification in the grid frequency, and switching on–off customer-side loads in order to balance the power system. Thus, when the grid frequency decreases, some loads are randomly switched–off, and when it increases, some of them are switched–on respectively. Every controllable load has its Δf–*time* curve as it is discussed in the following section. For this work, the maximum load that can be disconnected from the grid in order to compensate negative frequency excursions is been set up to 10 % of the nominal power.

The natural modifications in the customer-side power demand due to changes in the system frequency is modeled through a dumping factor D_f by the following expression:

$$\Delta P_m - \Delta P_D = D_f \Delta f + \frac{d(\omega_k)}{dt}, \qquad (1)$$

where $\Delta P_m - \Delta P_D$ is the power imbalance between the supply and demand power, Δf is the consequent variation of the grid frequency, and ω_k is the kinetic energy stored in the rotating mechanical systems [12]; and assuming a load-sensitivity factor of 2% MW/Hz [13].

In reference to the primary frequency regulation reserve characteristic, and within the UCTE, the full deployment of this primary reserve must occur before a deviation of ± 200 mHz has happened, activating the primary control before the frequency deviation achieves ± 20 mHz, with an accuracy of ± 10 mHz —usually adopted in continental Europe—. These requirements are also taken into account, and it provides additional constraints for the generator output power profile, which has to be continuous up to 1 Hz frequency excursions — see Fig. 5. In the same way, other restrictions related with ramp limits and minimum up and down times are also considered, as well as limits of time period in which a generator unit can increase its output in response to a frequency drop, [14] [15].

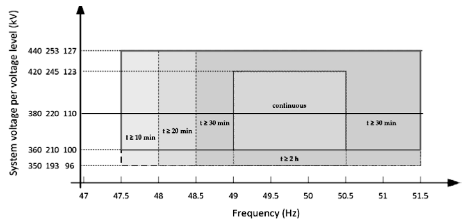

Fig. 5. UCTE requirements for output from generation units

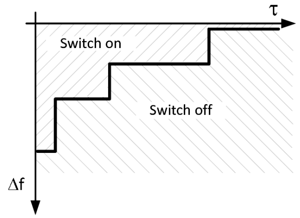

Fig. 6. Elemental load controller performance

III. Frequency Responsive Load Controller

A basic frequency-responsive load controller turns a load on or off when the frequency goes above or below some threshold values [16]. The generalized load controller described in this paper considers not only the frequency deviation Δf, but also the evolution over time of Δf. For each load controller a Δf–*time* characteristic determines when the load starts taking part in the control of frequency —see Fig. 6. The load controller measures the frequency over time window Δt_ω and the parameter τ represents the time during which the controller has measured a particular value of the frequency. As long as the frequency deviation does not exceed a certain threshold for a certain time, the load controller remains passive and the load follows its intrinsic evolution (by remaining on). On the other hand, if the frequency deviation moves below this *frequency excursion–time* characteristic, the controller enters its active mode and will start switching the load off and on to contribute to the control of the frequency. Because of the shape of this characteristic, larger frequency deviations will trigger a faster reaction of the controllers while smaller deviations are allowed to persist for a longer time before the load starts contributing to frequency regulation.

The loads corresponding to the Demand Response are classified in different groups, attending to their performance characteristics —quick (slow) response, maximum switching off allowed time, recovery time…— and patterns of use. Therefore, the Δf–*time* characteristic corresponding to a group of similar loads —for example, air conditioner loads— would theoretically present the same profile. However, since the dynamic time window of each load controller can be initialized at different time instants, and there are small differences in the frequency measurements of controllers, a horizontal and vertical uncertain band appears respectively around the switching limit lines when a Δf–*time* characteristic for a load group is represented.

According to Fig. 6, if Δf variable keeps inside the switching on region, the loads continue their ordinary demand profile. However, when this variable is inside the switching off region, an interruption process begins attending to the minimum comfort level required by the customer. This process involves several parameters that contribute to the design of individual load controllers and are mainly related to frequency setpoints and maximum and minimum time intervals.

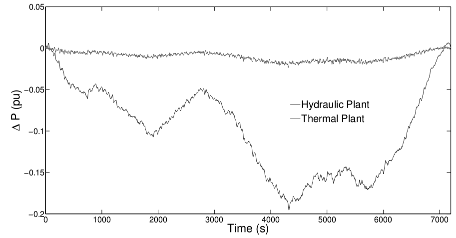

Fig. 7. Conventional Power variation, Scenario 1: uncontrolled demand-side

IV. Simulation and Results

A 2-hour simulation is carried out for the data series of wind power production —see Fig. 4. Three different scenarios have been considered: uncontrolled customer-side power demand, Demand Response facing frequency excursions through controllable load groups —thermostatically residential loads— and combinated effect of Demand Response and positive ramp limitation applied to the wind farm power output.

Fig. 7 and 8 show the conventional power variation respect the nominal value along the 2–hour simulation, when demand response is not and when it is considered, respectively, and Fig. 9 show the evolution over time of the same variables, when both Demad-Response and ramp limitation are considered. Additionally, Fig. 10 and 11 shsimulationow the frequency excursions in the two first scenarios, respectively, while Fig. 16 shows the frequency behaviour during the simulation in the second and third scenarios, respectively.

As an example of Demand Response, Fig. 12 shows the modification of the demand-side power for the data series when controllable load groups are considered. As can be seen, these power demand modifications are not constant along the frequency excursions, since they take into account the thermal and electrical constraints of each individual load considered according to the minimum comfort levels required by the customer.

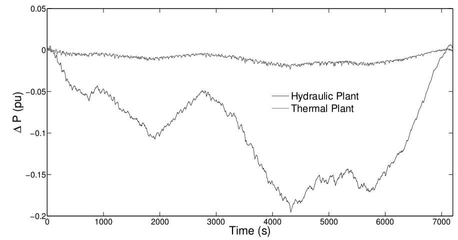

Fig. 8. Conventional Power variation, Scenario 2: considering Demand Response

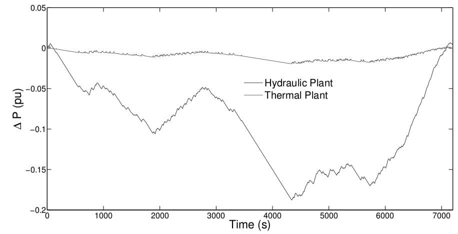

Fig. 9. Conventional Power variation, Scenario 3: controlled demand-side and positive ramp limitation

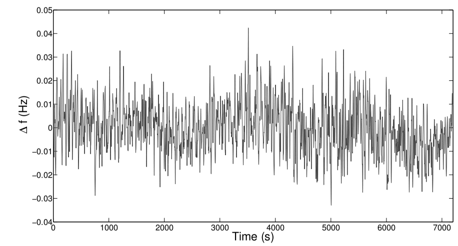

Fig. 10. Grid frequency excursion, Scenario 1: uncontrolled demand-side

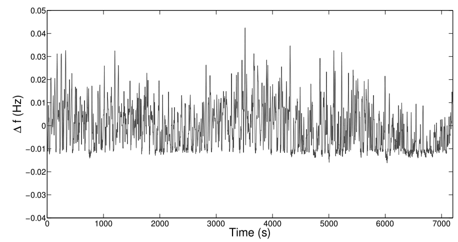

Fig. 11. Grid frequency excursion, Scenario 2: considering Demand Response

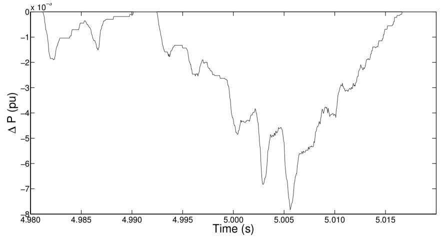

Fig. 12. Example of Demand-side power modification (From $t = 4980$ s to $t = 5020$ s)

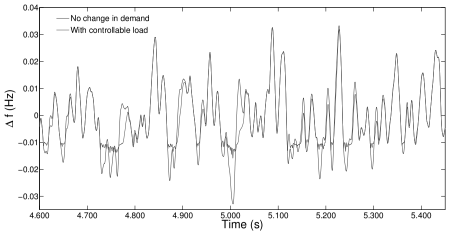

Fig. 13. Example of comparison of frequency excursions

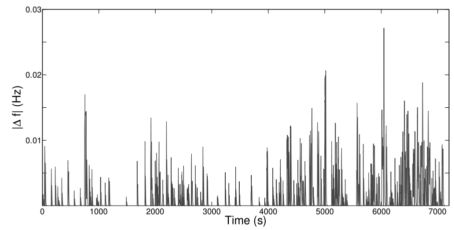

Fig. 14. Comparison of frequency excursions: Uncontrollable Demand-side vs Demand Response

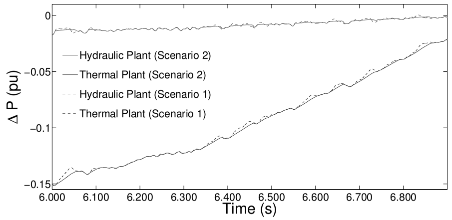

Fig. 15. Conventional Power variation, Scenarios 1 and 2 (from $t = 6000$ s to $t = 6900$ s)

Fig. 13 shows a comparison between both frequency excursions when Demand Response is (or not) considered. As can be seen from these figure, frequency excursions can be significantly reduced when power unbalance is suffered on a power system as a consequence of wind power oscillations. For the data series used, an average frequency excursion decreasing of 18.15% is obtained when Demand Response actions are considered in comparison with the uncontrollable load scenario —see Fig. 14—. For the case study, 10% power demand is assumed as controllable load. From these results, the active role of customer-side should be taken into consideration as a potential energy reserve, mainly in future power systems where renewable energy sources will not be neglected and it will be necessary to offer additional ancillary service from the customer-side as well. Fig. 15 shows the variation of the power produced by the conventional generators between $t = 6000$ s ans $t = 6900$ s, in scenarios 1 and 2. As it can be seen in the figure, the actions of these plants in the frame of the primary frequency control, i.e., the fastest oscillations, are a little bit smoothed because of the actuation of the Demand Response.

In scenario 3, the aim of the analysis is to assess the behaviour of the system frequency and the controllable load when the positive ramp regulation technique described in Section II-B1 is applied (see Fig. 4). For the case study, the ramp limitation is such that approximately 1% of the available power is lost due to the curtailment. This power loss corresponds with the area between the two curves.

In Fig. 16 the frequency excursions when positive ramp regulation is applied to the wind farm is compared with the previous scenario, without curtailment. It becomes clear from the observation of this figure, that positive frequency changes get much lower, and the combined effect of the wind farm regulation technique and the Demand Side contribution reduces the interval of variation of Δf when compared with that in Fig. 10.

Fig. 17 shows the comparison between the demand-side behaviour and the frequency excursions during the significant time interval $[3300, 4400]$ s, in which, as it can be seen in Fig. 4, a big rise in wind power occurs. From the upper graph in Fig. 17, it can be highlighted that the controllable load is not required to contribute to the primary frequency control whilst the wind power is curtailed, since there are no drops in the wind farm power production. On the other hand —see the lower part of the figure— the positive frequency excursions are much lower than in the case in which no regulation technique is applied. Nevertheless, the frequency excursion is estabilized at approximately 0.005 Hz over the rated frequency, since the conventional power plants see a constant $\Delta P_m - \Delta P_D$.

V. Conclusions

The contribution of the demand–side to the primary frequency control in high wind penetration power systems has been discussed in this paper. A wind power regulation technique, positive ramp limitation, has been implemented as well to assess its impact in the system frequency. Classical primary energy input control in steam and hydro turbines has been also considered to model the power system. An offshore wind farm compound by 10 rows with 22 wind turbines each one has been considered as renewable power supply. An aggregated model previously proposed and assessed by the authors is suggested to simulate power fluctuations. In this way, two different wind power data series have been used to simulate different power system conditions, when Demand Response facing frequency excursions is (or not) considered. Both selected data series are relevant enough to simulate periods with high wind penetration in power system. For analyzing the influence of the positive ramp limitation technique, a curtailment to the first series of data has been carried out, such that 1% of the available power is lost.

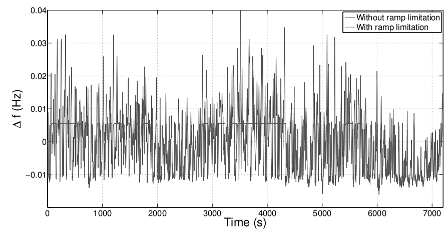

Fig. 16. Comparison of frequency excursions: Without ramp limitation Vs With ramp limitation

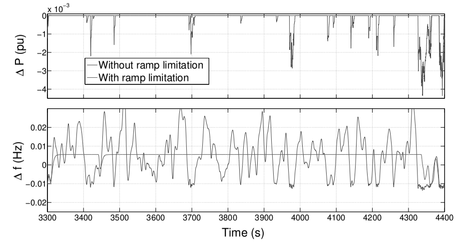

Fig. 17. Comparison of variation in power demanded by the load and frequency excursions: Without ramp limitation Vs With ramp limitation, during the time interval $[3300, 4400]$ s

Demand-side is considered as a contribution to primary frequency control using a decentralized approach not requiring explicit communications. Simple devices can thus control individual loads in response to deviations between the frequency and its nominal value over time. The aggregated behavior of a large number of such controllers is simulated to investigate their effect at the system level when power fluctuations due to high wind energy penetration are considered. These simulation results show lower frequency excursions when this additional energy reserve from the demand-side is included. When positive ramp limitation is applied to the wind farm power production, the behaviour of the demand-side is improved when significant rises in wind speed occur. Future work in this area should develop methodologies to characterize another renewable energy sources —for instance Photovoltaic technologies— as well as robust statistical upper and lower bounds on the aggregated demand frequency response.

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