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Power System Dynamic Performance: Primary Governing Frequency Response

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***Abstract* -- An efficient ancillary services mechanism implies a good coordination between the regulatory side, transmission system operators and power producers. In continental Europe, ancillary services represent a formal relationship between the actors. The regulatory side establishes recommendations. Transmission system operators adapt them according to the power system specificities and demand the generators elementary participations.**

For technical and economical reasons, European power producers must have good knowledge of power plant dynamic performance in terms of ancillary services. The performance associated to primary governing frequency response may differ in function of various factors; the most important are the type and the age of the power plant.

***Index Terms* – ancillary services, frequency control, power producer, primary response.**

I. INTRODUCTION

PRIMARY governing and frequency control has always been crucial for any power system operation [6]. Since the deregulation of the electricity industry, primary governing and frequency control became an 'ancillary service' that must respect various quality criteria established according to security and reliability based standards and recommendations. For power producers, frequency control implies the existence of a power reserve (energy which is not produced and commercialized) [1][3][10] on every participating generator that un-optimizes the producer's operating costs. In addition, it is known that rapid power variations provoke overheating and mechanical vibrations that could degrade the equipments lifetime. Consequently, in order to compensate the above-mentioned drawbacks, transmission system operators often remunerate the power producers (through bilateral contracts or spot market mechanisms) [2].

The paper is focused on primary governing control from a power producer perspective. It is organized as follows: the 2nd section deals with a global overview on the European and French environment, the 3rd section presents French power producers contractual obligations, the 4th section discuss some theoretical aspects on generators performance in terms of primary governing and the 5th section details the way the performance control is performed in France.

II. OVERVIEW

A. *European Regulatory Environment*

The "Union for the Co-ordination of Transmission of Electricity" (UCTE) is the association of TSOs in continental Europe. UCTE co-ordinates the operational activities of TSOs in 22 European countries. Their common objective is the security of the interconnected power system. Through the networks of the UCTE, 450 million people are supplied with electric energy. The annual electricity consumption totals about 2100 TWh.

Since the 50's, UCTE has developed a number of technical and organizational rules and recommendations that constitute a common reference for a smoother operation of the power system [7].

In terms of primary governing and frequency control, UCTE prescribes a governing reserve of 3000 MW that must be mobilized entirely in case of a sudden major disequilibria between the generation and the consumption. Each of the 22 European partners must contribute to the synchronous area governing reserve. As France produces about 25% of the European electricity, France must provide around 750 MW of the European governing reserve. A sudden loss of 3000 MW generating capacity should not provoke a load shedding activation and the frequency signature must be framed by the caliber shown in Fig. 1:

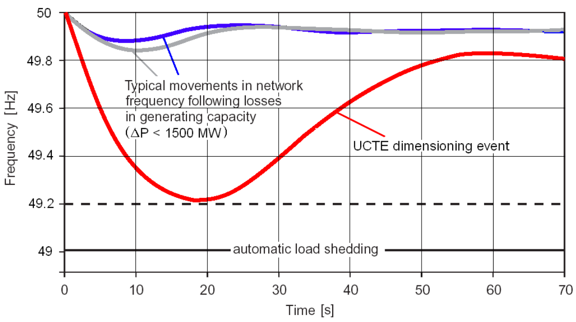

Fig. 1. The caliber of the European dimensioning event [7]

The caliber of the considered disturbance (frequency drop) is described by the dynamic frequency deviation (800 mHz) and the steady state deviation (200 mHz)[2]. Half of the

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[2] If the load self-regulation is taken into account (1%/Hz) the steady state deviation is about 180 mHz.

European reserve must be activated in less than 15 seconds and the entire reserve must be deployed in less than 30 seconds and must be able to last at least 15 minutes. The global minimum performance in terms of governing reserve deployment is given in Fig. 2:

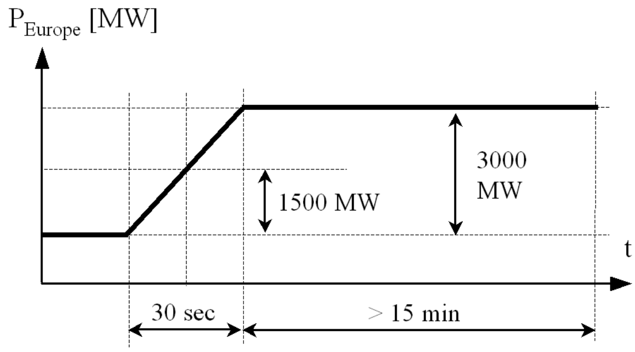

Fig. 2. Deployment performance of the European governing reserve

B. French Environment

In France, RTE[3] is responsible of the ancillary services existence in appropriate quantities. They are not organized through a spot market, but through specific bilateral contracts. Ancillary services contracts are signed in addition to the grid connection agreement. They define the practical conditions in which ancillary services are provided by each producer (remuneration and penalties, prescribed volume, daily scheduling process) and the performance monitoring mechanism that will be used to guarantee the quality of the service (frequency and voltage control) [9].

In France, all power plants connected to the transmission grid must be able to participate in frequency control, independently of the primary energy nature. Nuclear power plants (NPP) generate a significant part of the electricity in France (~86%). The weight of the nuclear-based energy imposed a particular design of the French NPPs. After the oil crises in the 70's, the French government desired the energy independence of the country. Consequently, it was decided to replace all discarded fossil power plants by NPPs. EDF and Framatome[4] researchers started to look for technical solutions for varying rapidly the nuclear based produced power in order to contribute dynamically to the equilibrium between the generation and the consumption:

- increase/decrease the produced power amount in function of the demand,
- activate the real power reserve in case of frequency deviations,
- participate in balancing mechanisms.

The above-mentioned issues were managed due to new control techniques developed for French nuclear reactors (PWR technology). Some additional control rods have been added to the usual design. Reactivity control consists of a three parameters coordinating management: the reactor coolant temperature, the control rod assemblies and the boron concentration [4]. The adopted solution allows today the load following and the NPP primary governing frequency response. However, it is today known that operating NPPs at their maximum load improves significantly their overall efficiency. It is often stipulated [13] that frequent load following cycles and frequency control participation could accelerate the NPPs wear and tear. Even if the NPP flexibility costs (maintenance and possible lifetime reduction), it creates great market opportunities and gives elasticity to the power system management.

Consequently, French NPPs are nowadays maneuverable. Nevertheless, EDF (the power producer who operates the 58 nuclear generators) limits NPPs solicitations by imposing four operating points only:

- no primary and secondary reserves,
- primary reserve equal to $2\%\cdot P_{max}$, secondary reserve equal to $5\%\cdot P_{max}$,
- primary reserve equal to $2\%\cdot P_{max}$, no secondary reserve,
- primary reserve equal to $7\%\cdot P_{max}$, no secondary reserve.

Nowadays, EDF realizes a global optimization of the generation portfolio (nuclear, fossil, hydro, etc.) in terms of generation, primary reserve and secondary reserve. The objective function is to minimize the generation total cost with respect to technical and geographical constraints [5].

III. French Power Producers Obligations

Generator design and operation prescriptions are defined by the French grid code [8]. This document stipulates general principles of the transmission grid operation, security and exchange information. It is written in conformity with the lows, the regulator rules and the UCTE recommendations [7].

According to the transmission grid code[5]:

- all UCTE recommendations must be respected;
- all generators must have the constructive capacity to provide primary governing response and frequency control. The minimum constructive reserve amount is 2.5% of the generator maximal power;
- all rotating generators must have an available reserve when the producer optimal reserve dispatch puts them on the 'availability list';
- all generators must be able to adjust (within the technical boundaries) their produced power according to a speed droop;
- generators have to transmit to the TSO in real time active power measurements;
- the governing regulator natural dead-band (if there is any[6]) must be inferior to 10 mHz. French generators do not have any dead band.
- geographically, the governing reserve must be distributed in a relatively uniform manner all through the French territory.

[3] The French TSO: 'Réseaux Transport Electricité'

[4] Framatome was a company that developed and built nuclear reactors. It became Areva Nuclear Power.

[5] All new generators must respect the rules unconditionally. The existing ones have to behave according to the ancillary services participation contract.

[6] Ideally, for a better performance in frequency control, all generators should not have any dead-band.

IV. Power Producers Performance in Terms of Primary Governing and Frequency Control

In order to meet the UCTE recommendations and the TSO requirements, power producers must have good knowledge of power plant static and dynamic performance.

A. Static performance

The governing reserve of the rotating generators is directly linked to the speed droop. It represents the gain of the primary frequency regulator and it links power variations to frequency variations [6]. Droops vary in a light manner (±10%) in function of the operating point and the control mode. Theoretical values usually established on French generators are given in Table II. These values were set up in the plants' designing phase according to the requirements and the technical constraints:

TABLE I
French Power Plants Theoretical Speed Droop

Nuclear	4% or 5.7%
Hydro	from 4 to 12%
Fossil	4%

Due to the relatively small values of the speed droops, some generators are more reactive in terms of governing reserve quantity than the UCTE recommendations. For instance, considering their static characteristics only, French nuclear power reserve is mobilized for a frequency variation of about 60 – 80 mHz (instead of 200 mHz). In addition, technical constraints do not allow a significant augmentation of the NPPs speed droop. This is the physical reason the French NPPs provide a significant amount of MW/Hz to the UCTE system.

B. Dynamic performance. Simplistic global approach

The aim of this section is to illustrate the global performance of a system like UCTE system in function of the generator's standard dynamic behavior. The global behavior of a system to a frequency drop is the sum of every individual behavior.

Measuring every generator performance allows a good computation of the global response.

But, as sometimes it is fastidious to perform measurements and accurate computations, it is possible to establish a global portfolio response starting from a very small quantity of real information. In order to manage it, models are necessary for each plant typology. They could be minimalist theoretical models based on the engineering experience that are convenient to provide standard indicial responses of each plant typology[7]. This section deals with such simplistic, non-rigorously established models for the European generators.

NPP dynamic performance

Nuclear generators dynamic performance is linked to the primary governing reserve mobilization that depends on each plant technology.

[7] These models are not appropriate to be used for stability studies.

Generally, nuclear power plants do not provide primary governing response and automatic generation control in reaction to frequency deviations. Most of them are also limited in providing voltage support [15]. The limited capability to provide reserves (real and reactive power) to support the transmission grid and to stay connected during voltage excursions are serious constraints for the transmission system operators. The North American blackout in 2003 and the Florida's outage in 2008 are typical examples [16].

The French NPPs are the only exception to the rule: they are maneuverable, they can provide ancillary services. French NPPs' (which are able to respond to frequency deviations) dynamic response to a frequency sudden deviation splits up in three parts:

- the high-pressure turbine reaction. It covers 40% of the frequency deviation in one to two seconds;
- the low-pressure turbine reaction. It covers another 40% of the frequency deviation in less than 5 seconds;
- the steam pressure drops. It covers around 10% of the frequency deviation in about 20 seconds;
- the automatic reaction of the steam generator regulations. It covers the rest of the frequency deviation in about 5 seconds.

Starting from the physical behavior, the obtained NPP standard indicial response (governing reserve mobilization) to a frequency drop is given in Fig. 3.

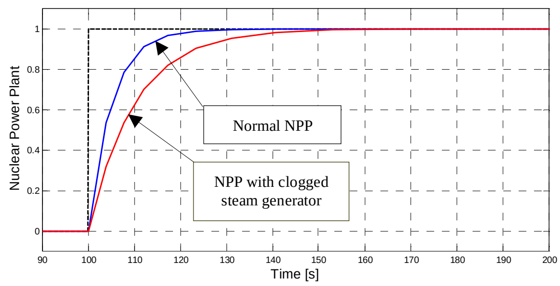

Fig. 3. French NPPs standard indicial response to a 200 mHz frequency deviation

The dynamic response meets the recommendations and requirements (§2A). If the NPP has a clogged steam generator (old plants), then the global response becomes lightly slower.

Fossil plants dynamic performance

Unlike NPPs, fossil power plants performance are the same, independently of the geographic borders. They are all maneuverable. Fossil power plants have different responses in function of the primary energy nature. There are two types of steam turbines: drum-type and once-through. Drum-type boilers boil water to generate steam and separate the vapor from the steam in the boiler drum. The once-through design raises water's supercritical pressure and consequently, there is no identifiable gas or liquid phase of the water. For fossil power plants there are four possible control modes: boiler follow, turbine follow, coordinated control and sliding pressure control [14].

A coal fired power plant having drum type boiler acts quicker than a power plant having an once-through boiler because it has more stored energy. Oil based power plants act almost as coal fired power plants having drum type boiler.

Fossil generators dynamic response to sudden frequency deviations splits up into three parts:

- the kΔf signal opens the valves and the steam energy reserve contained upstream of the valves is mobilized;
- the boiler is not able to follow the energy increase and consequently the power decreases;
- the power/pressure regulations provoke a fuel increase and consequently a power augmentation.

A minimalist standard global performance of fossil plants (coal fired), is given in Fig. 4:

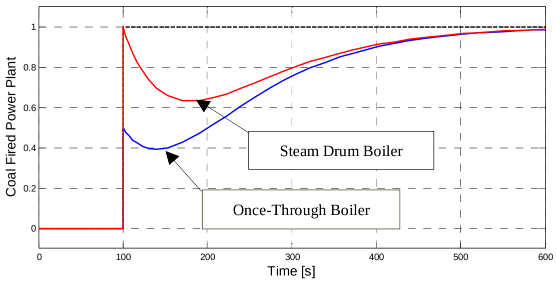

Fig. 4. Coal fired standard indicial response to a 200 mHz frequency deviation

Hydro plants dynamic performance

Hydro plants response to a frequency sudden deviation depends on the turbine type (Francis, Pelton, Kaplan) and the natural environment (river flow, waterfall height). The primary response of a hydro generator is impacted by turbine characteristics, inertia of the water column, control loops external to the turbine-governor system and other various settings [14].

In response to disturbances that are not considered as major incidents frequency deviations, some hydro power plants are designed to have slow governing reserve mobilization characteristics. They are equipped with governors that are optimized to react to large frequency excursions (>600 mHz) and insulated grids operation. In this kind of situations they are able to respond extremely effective, to do the black-start and to operate safely in an insulated power system. The nonlinear behavior of the turbine governor was observed during the 4th November 2006 UCTE event when the frequency dropped to 49 Hz in Western Europe.

Some other hydro generators are not able to react quicker because of the plant's technology.

As it can be deduced, the hydro plant type diversity does not allow to conclude on one general typical response: slow and fast responses should be considered simultaneously.

UCTE global performance

The net electricity generation in UCTE is given for the year 2006 in Fig. 5 [17].

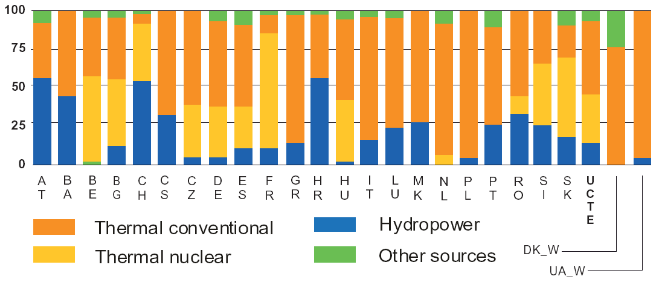

Fig. 5. The net electricity generation in UCTE in 2006 [17]

It can be seen that every UCTE partner had a different generation mix. The UCTE system generated 2600 TWh in 2006, energy which was disseminated in: 12% hydro based energy, 30% nuclear based energy, 50% thermal conventional based energy and 8% renewable energy. The problem is that the real power reserve dispatch is often radically different from the energy dissemination because each power producer does its own portfolio optimization and the reserve is not always associated to all generators in operation. As the reserve cannot be valorized as a produced energy, producers often associate the reserve to the most expensive generators. Furthermore, each power system has its own particularities and the reserve optimal dispatch could be altered by various constraints. It can be concluded that it is practically impossible to determinate a realistic distribution of the governing reserve for the whole UCTE that would be based on a simple combination of elemental dynamic contributions of various plants.

In addition, the UCTE requirements are interpreted differently in each individual system and consequently generators do not react to disturbances exactly in the same manner.

It can be concluded that all these inaccuracies et discrepancies obstruct a good estimation of the global dynamic performance using a simplistic approach. Therefore, the robustness of the method is put in question because the obtained result depends significantly on the reserve dispatch. Any chosen particular case is not obviously realistic when extrapolated because the reserve distribution could vary significantly from a given period to another, even a few times during a day.

In addition, when superposing responses, the smoothing effect could have a significant consequence on the results and it should be taken into account, for instance by a probabilistic approach.

C. Dynamic performance. Rigorous approach

It can be seen in the previous section that establishing the UCTE response to frequency deviations is not possible in a simplistic approach. Another possibility is to have a good knowledge of the exact performance of each generator and the real power reserve dispatch. Once each generator response to a 200 mHz disturbance is well-known, system operators are able to determinate individual systems performance. Finally, systems performance superposition gives easily the whole UCTE performance. This rigorous approach demands a new policy in terms of information exchanges between actors: producers and system operators.

In addition, performing measurements on every power plant is long and fastidious. These measurements process allow to establish generators dynamic performance and to ratify/improve dynamic models of generators and control loops. It is more accurate to detail the individual generators response analysis and to superpose real measurements (or real behaviors) instead of standard indicial responses.

In France, all generators performance are already the purpose of a bilateral contract between producers and the system operator. They are measured and controlled periodically.

V. Power Producers Performance Control

A. *Performance control carried out by the TSO in France*

The French power system is first system in UCTE where the TSO carries out a continuous performance control of all generators connected to the transmission grid. The performance monitoring mechanism has been added to the ancillary services participation contract in 2005 [9]. It is based on an ‘a posteriori’ continuous checking of the performance of each generator. The performance control is carried out essentially by analyzing the measurements at the delivery point. In case of deviations from the required performance, the operator of the unit has to bring it back into compliance according to a schedule agreed with the TSO. During the deviation and according to its importance, the remuneration is reduced. Penalties are applied if the performance is not brought into compliance at the agreed date [11].

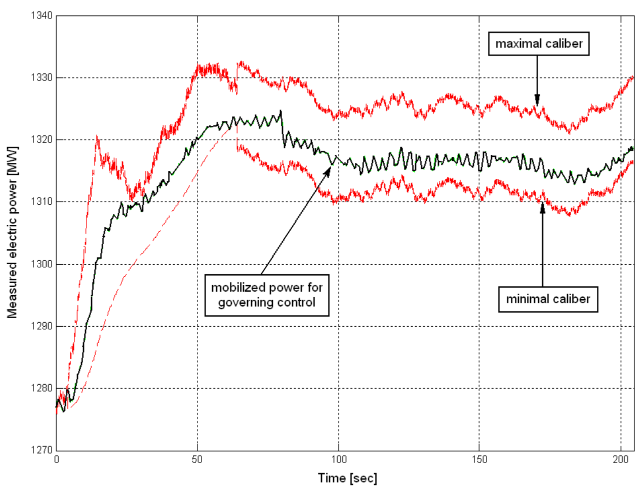

Fig. 6. Performance control performed by the TSO

In France, current contractual performance in terms of governing control is characterized by: the duration of delivery, the speed droop and the mobilized reserve for a 200 mHz deviation (in 15 seconds and in 30 seconds). These indicators are controlled using a software that detects the major differences between real and contractual performance. The above-mentioned software uses as inputs the dispatched power, the dispatched reserve and the K-factor of each generator, the grid frequency, the produced power online measurements and the contractual performance [12].

A performance check result for a 1300 MW nuclear generator is given in Fig. 6[8].

The French TSO computes an expected generation power caliber in function of the operating point and the contractual performance. The generator has a normal behavior if the output power is framed by the above-mentioned caliber (as we can observe in Fig. 6). Otherwise, for a performance inferior to the caliber, the generator has to disburse the contract stipulated penalties.

B. *Performance control carried out by the producers*

In the designing phase of a power plant, producers specify the desired performance to the equipments constructor. Before the grid first connection, they verify (numerical simulations and physical proofs) if the generator behavior meets the TSO requirements.

Periodically, during the plant operation, physical tests are also performed. The idea is to detect any performance deviation that could affect the plant functioning and attract any penalties. The governing control is checked offline by analyzing the generator response to frequency deviations. A performance measurement[9] for a 1300 MW nuclear generator is given in Fig. 7[10]:

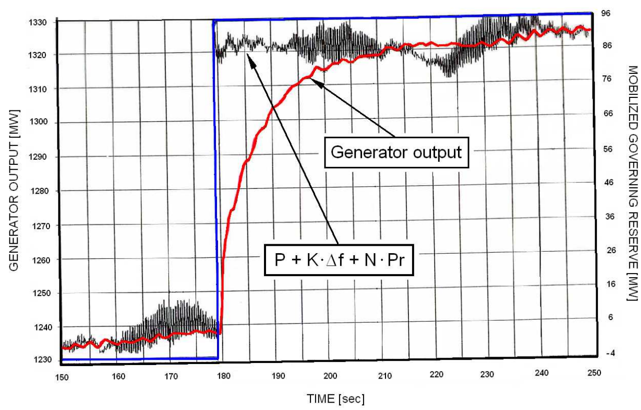

Fig. 7. Performance control performed by power producers

The governing reserve deployment (70 MW in 15 seconds and 85 MW in 30 seconds) due to a frequency deviation[11] can be observed.

In addition, performance control is carried out continuously using onsite-monitoring systems. These systems acquire data on each generator and process it both online and offline.

VI. Conclusion

Since the deregulation of the electricity industry, primary governing became an ‘ancillary service’ and consequently must respect various quality criteria established according to security and reliability based standards and recommendations.

[8] The curves come from EDF internal studies.

[9] 10 points per cycle

[10] The curves come from EDF internal studies

[11] After the governing response, the secondary control commands the secondary reserve deployment. The aim of the secondary frequency control is to bring back the frequency to the rated value, to re-establish the scheduled flows through the interconnection lines and to restore the governing reserve for the generators outside the area where the frequency was disturbed.

The document analyses some results and discussions on generators response to frequency sudden deviations. We can conclude that having good knowledge about plants performance is beneficial for both, power producer (better management of the generation portfolio) and TSO (increase of the grid security).

VII. Acknowledgements

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IX. Biographies

Stefan Sterpu received his engineering degree from Polytechnic University of Bucharest in 2001 and his MS and PhD degrees from the National Polytechnic Institute of Grenoble in 2002 and 2005 respectively. In 2005 he joined EDF. In EDF, he is presently R&D engineer. Throughout his career he has been involved in and led studies related to aspects of power systems modeling, dynamics and control.