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Performance Evaluation of Ancillary Services in the Turkish Power System

***Abstract**. This paper proposes a central monitoring system of frequency and voltage control of the Turkish Power System, consisting of a reference model that compares the real operation of the generating units with the desired behaviour established by the technical requirements of the Turkish grid code. A number of quantitative measures, based on the deviation between the real and the desired response are proposed to evaluate the adequacy of each unit behaviour. Application examples are provided using real data of different Turkish power plants.*

***Streszczenie.** W artykule zaprezentowano system monitorowania częstotliwości i napięcia w systemie dystrybucji energii w Turcji. Zaproponowano model odniesienia umożliwiający porównanie wartości rzeczywistych z wymaganymi. Wprowadzono miary umożliwiające ocenę parametrów każdej jednostki w sieci. (**Ocena pomocniczych narzędzi monitorowania systemu przesyłu energii w Turcji**)*

Keywords: Ancillary Services, Voltage Control, Frequency Control, Monitoring System.
Słowa kluczowe: serwisy pomocnicze, monitorowanie, przesył wenergii, sieć dystrybucyjna.

1. Introduction

Ancillary services can be defined as the set of functions related to the secure and reliable operation of a power system [1-3]. They can be classified into frequency control (active power control) and voltage control (reactive power control). The system operator is the entity responsible for the secure operation of a power system and in this way, the management of frequency and voltage control is considered a specific function of the system operator. These services are mainly provided by generators..

Active power control is designed to re-establish the necessary equilibrium between generation and demand in order to maintain the frequency of the power system within admissible bands. Active power control include primary, secondary (AGC) and tertiary (non-spinning reserve) regulation operating within different time scopes. Voltage control is designed to maintain an adequate voltage profile within the transmission network. A correct voltage profile assesses an acceptable value of transmission losses and an operating point far away from voltage collapse. Generators incur in an extra cost for providing frequency and voltage control and should be recovered through regulated or market –based tariffs. Several studies have explored the cost of providing AGC and tertiary regulation incurred by the generating units in order to develop bidding strategies under a deregulated framework [4-7]. The main key characteristics of the voltage control ancillary service have been explored in [8] and the structure and computation of the cost incurred to provide the service widely analyzed [9-12].

Under this framework, it becomes of crucial importance for the system operator to monitor the correct provision of these services by the generating units. In order to develop a monitoring method, the specific technical and economical definition of the services should be taken into account depending on the power system considered. Within the Turkish power system, frequency and voltage control have been defined as mandatory remunerable ancillary services, defined in the Turkish Grid Code and Ancillary Services Regulation [13-16].

This paper proposes a central monitoring system of frequency and voltage control of the Turkish Power System in order to validate the correct fulfillment by generating units. It should be noted that this paper focuses on generating units, thus frequency and voltage control provided by other means (for instance by shunt devices or demand response strategies) are not considered within this paper. Even though both services present different technical, time-scope and complexities by definition, the system proposed share the same intuitive approach: both frequency and voltage control monitoring is based on a reference model that compares the real operation of the generating units with the desired behavior established by the technical specifications of the Turkish grid code. A number of quantitative measures, based on the deviation between the real and the desired response are proposed to evaluate the adequacy of each unit behavior. Application examples of the central monitoring system are provided using real data of different Turkish power plants. It should be noted that the simple and intuitive central monitoring of frequency and voltage control proposed in this paper can be applied to any power system by just specifying the desired response based on the system technical requirements of the grid code.

The paper is organized as follows. Section 2 explains the frequency control monitoring with an overview of frequency control in Turkey, the description of frequency control monitoring system and an illustrative example. Section 3 deals with the voltage control monitoring, containing an overview of voltage control in Turkey, the description of voltage control monitoring system and an illustrative example. Finally, conclusions are drawn in Section 4.

2. Frequency control monitoring

2.1 Frequency control in Turkey

Frequency control by means of active power provision include primary, secondary and tertiary regulation.

Primary control can be defined as the automatic increase or decrease of the output power of a generating unit due to frequency deviations and is based on its speed–droop characteristic. The order of magnitude of the time constant of the dynamic response of primary regulation lie within the range of a few seconds (1 to 10s). Primary regulation is affected mainly by the speed-droop characteristics of the generating units.

Following a system disturbance, primary control can prevent large variations of frequency, but on the contrary it does not bring the system frequency back to its scheduled value. Thus, a frequency deviation will exist in the steady state of the system after primary control operation. The aim of secondary control (AGC) is to bring the system frequency to its scheduled value. Power systems are usually divided into different interconnected areas with possible scheduled interchanges between them. An additional objective of AGC is to maintain area interchanges at the scheduled values. The order of magnitude of time constants associated to the provision of secondary regulation lie within the range of a few minutes (1 to 3min). Secondary regulation is affected mainly by the up and down speed variation of the generating units and the maximum and minimum technical operational limits of the units.

Generating units controlled by AGC change their generation within the secondary control operation. Thus, they use part of their available regulation band, which is therefore reduced. The aim of tertiary regulation to replace this secondary reserve in use, thus increasing the available reserve to the initial scheduled value. Tertiary reserve is usually provided by non-spinning generators that can be started and connected to the grid before 15-20 minutes since the order is sent.

As long as the secondary reserve within the system is not exhausted, the correct behavior of system frequency around a specified nominal value is the result of the joint operation of the primary and secondary regulation control schemes. In other words, if system frequency deviates from admissible values it becomes difficult to detect the reason: a deficient primary regulation, a deficient secondary regulation or both. The approach followed in this paper is to monitor the combined response of the primary and secondary regulation of frequency control.

Although the AC links with neighboring countries have already been developed, the Turkish power system is not yet synchronously connected to the UCTE European system (tests of the synchronous connection of the Turkish and UCTE European systems are currently being performed). High quality frequency control is crucial not only in isolated operation of Turkish system but also for the successful interconnection to UCTE European system.

Within the Turkish power system, plants with 50 MW or more installed capacity must participate in primary frequency control (excluding solar, wind, wave and tidal power plants and canal and river hydropower plants), with a limit of 5% of their corresponding rated power. This reserve can be supplied by another legal entity approved by the system operator contracted by the power plant in case the generator is not able or is not willing to provide the service. Power plants, excluding renewable generators, with more than 100 MW installed capacity are obliged to participate in secondary frequency control. For these purpose they should have monitoring infrastructure and sign secondary frequency control agreement with TEIAS (Turkish system operator).

Associated remuneration of primary and secondary control is fixed by the Turkish ancillary services regulation [13-16]

2.2 Description of frequency control monitoring

The monitoring of frequency control is based on a reference model. Thus, the actual response of a unit is compared to that of its reference model, which takes into account unit characteristics and desired response. Both primary and secondary components of frequency control are monitored at the same time since the global response of the unit is due to a combination of the response of the primary and secondary control. The reference model is outlined in Fig 1.

Taking as input the system frequency deviation *FreqDev* [Hz] and the unit power setpoint *PSet* [MW], the output of the reference model establishes the desired power output *PDes* [MW] of the unit, based on the dynamic primary response of the unit (modeled by a first order linear system of gain *k_PR* and time constant *T_PR*), the secondary regulation response yielded by the ramp limits of the units, the primary and secondary regulation maximum and minimum limits, and the overall operating unit maximum and minimum limits. A certain error is allowed between the actual and the desired response. Thus, a certain permitted band around the desired power is fixed. If the actual power *PGen* lies within the permitted band the response of the unit is considered adequate. Whenever the actual power *PGen* goes outside this permitted band, the response is considered inadequate. It should be noted that in order to remove high frequency components, both signals *FreqDev(k)* and *PGen(k)* are filtered using a moving average filter, obtaining the filtered frequency deviation *FreqDevFilt(k)* and the filtered active power *PGenFilt(k)*.

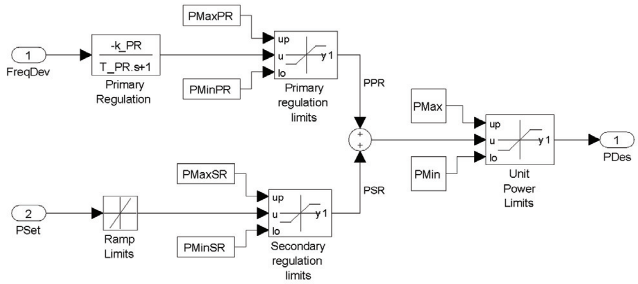

Fig 1: Reference model for primary and secondary regulation monitoring

The frequency control system presented is monitored at a unit level. A unit can be a single generator if the generator is directly controlled or a plant comprising several generators (for instance a CCGT comprising a gas and a steam turbine) if primary and secondary control is performed at a plant level. The behavior of each unit is evaluated by means of the total number of samples with inadequate performance, both in absolute value (*NInadeq*) and relative value (*PCInadeq*):

(1) $$NInadeq = \sum_{k=1}^{NSamples} PInadeq(k)$$

(2) $$PCInadeq(\%) = \frac{NInadeq}{NSamples} \cdot 100$$

where *NSamples* is the total number of samples during the monitored period, and *PInadeq(k)* corresponds to the flag indicating whether the response of the unit is inadequate in control cycle k (*PInadeq(k)*=1) -actual filtered power is not within the permitted band-, or adequate (*PInadeq(k)*=0) -actual filtered power is within the permitted band-. In addition, the total energy deviation during the monitoring period (*TotalEDev*, in MWh), and mean relative active power deviation (*MeanPCPDeviation*, in %) with respect to the permitted band *PBand*, indicate the quality of the unit response to frequency control:

(3) $$TotalEDev(MWh) = \frac{T_S}{3600} \cdot \sum_{k=1}^{NSamples} PDeviation(k)$$

(4) $$MeanPCPDeviation(\%) = \frac{\sum_{k=1}^{NSamples} PDeviation(k)}{PBand \cdot \sum_{k=1}^{NSamples} PInadeq(k)} \cdot 100$$

where *PDeviation(k)* is the active power deviation from the permitted band PBand of the unit in control cycle *k*

2.3 Application example

This section illustrates the central monitoring system of frequency control using real data of a hydro Turkish power plant G1.

G1 hydro power plant has a 4% droop, 1800 MW of rated power, 360 MW/min of maximum up and down ramp rate. During the monitoring period the regulation band for secondary regulation was within 1320 MW and 1680 MW (maximum and minimum limits for secondary regulation). Primary maximum and minimum limits have been set to 5% of unit rated power (±90 MW) as established by the Turkish Ancillary Services Regulation. Maximum and minimum unit power limits have been set to unit rated power (1800 MW) and 0 MW, respectively. A time constant of 8s has been used for primary regulation, and 30 samples have been used for both frequency deviation and active power filtering. Real data was collected from 12:00:00 to 13:59:59 on the 5th May 2010, with a sampling time of 1s for the frequency deviation signal and sampling time of 4s for the secondary regulation setpoint.

Fig 2 shows the setpoint for secondary regulation (*PSet*) together with the filtered power generation (*PGenFilt*) and filtered frequency deviation (*FreqDevFilt*). Unit setpoint due to secondary regulation is at or near its minimum during the first hour. However, during the second hour the whole secondary regulation band is used and a fast increase between minimum and maximum limits is demanded around t=1.3h. Frequency deviation varies from 100 mHz to –150 mHz. Power generation follows quite well secondary regulation setpoint even when fast changes are demanded.

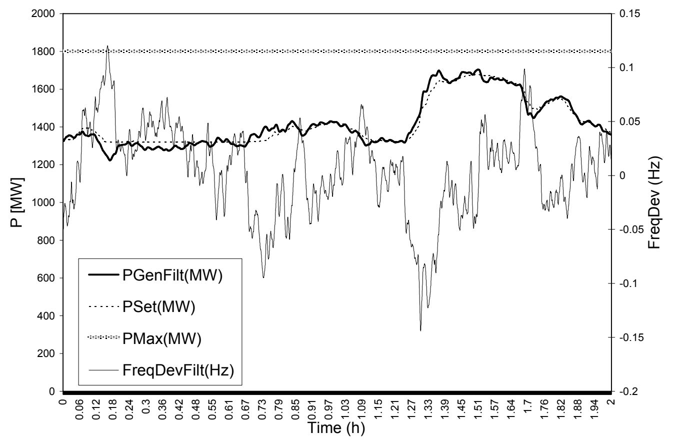

Fig 2: G1 hydro power plant: setpoint for secondary regulation (*PSet*), filtered active power (*PGenFilt*) and filtered frequency deviation (*FreqDevFilt*).

Fig 3 shows the maximum and minimum allowed values for power generation (PDesMax and PDesMin) together with the filtered power generation (PGenFilt). A permitted band of ±38MW has been assumed (approximately 7% of the total regulation band, 180MW for primary regulation and 360MW for secondary regulation). As can be seen in the figure, the power generation is most of the time within the permitted band showing that the response of the unit is adequate. A special remark can be done for the first hour when the power generation is all of the time within the permitted band.

Fig 4 shows the accumulated number of samples with inadequate response (NInadeq), together with the mean relative active power deviation with respect to the permitted band during the monitoring period (MeanPCPDeviation) assuming ±38MW of permitted band. TABLE 1 summarizes the performance evaluation of the frequency control by the unit. The final value of samples with inadequate response for the 2 hours period of monitoring is about 164 samples (2.28%), thus, the response of the unit is adequate during most of the time. The final mean relative active power deviation is 32.7%, showing that the mean power deviation from the permitted band in the periods where the response is not adequate is also small.

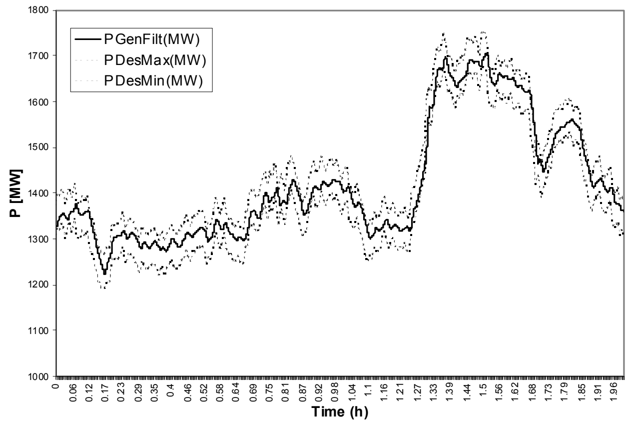

Fig 3: G1 hydro power plant: filtered active power (*PGenFilt*) and maximum (*PDesMax*), desired (*PDes*) and minimum (*PDesMin*) allowed active power assuming *PBand*=38MW

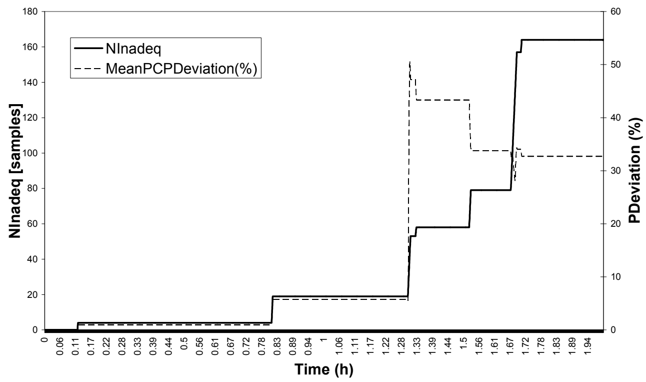

Fig 4: G1 hydro power plant: number of samples with inadequate response (*NInadeq*), together with the mean relative active power deviation (*MeanPCPDeviation*)

Table 1. Summary of frequency control performance evaluation of hydro unit G1

NInadeq	164
PCInadeq (%)	2.28
TotalEDev (MWh)	1
MeanPCP Deviation (%)	32.7

3. Voltage control monitoring

3.1 Voltage control in Turkey

Voltage control is an ancillary service related to the provision of reactive power designed to maintain an adequate voltage profile within the transmission network. For this purpose, generators adjust the injection or absorption of reactive power in order to maintain the voltage at the point of connection to the transmission grid within admissible bands around the setpoint sent by the system operator. Voltage control is mainly affected by the reactive generation and absorption capabilities of the units, and by the reactive consumption of the step-up transformer that connects the synchronous generator to the transmission grid.

In Turkey, all generation plants connected to transmission or distribution grids shall participate in reactive power control. Upon the instructions of the System Operator (transmission or distribution), output power factor should be kept between 0.85 (over-exited limit) and 0.95 (under-excited limit). The Turkish Grid Code states that the reactive power output should be fully available within the voltage range ±5% at 380, 154 and 66 kV levels.

A generation plant has to sign a reactive power control agreement with either TEIAS or the relevant distribution company. Reactive power remuneration is based on the lost income due to active power reduction and is calculated according the formula stated in Ancillary Services Service Market Remuneration.

3.2 Description of voltage control monitoring

The monitoring of voltage control is based on a reference model using the same principle established for the reference model proposal of frequency control monitoring. The reference model fixes the desired voltage set point of the generating unit at the high voltage bus *HVref(k)* in each control cycle *k*, allowing a narrow band *VBand* around the desired response to allow for small deviations from desired. Measures of the voltage at the high voltage bus *HV(k)* and reactive generation at the low voltage bus *QGen(k)* every control cycle k should be obtained. Both signals should be filtered using a moving average function to allow for the removal of high frequency components, obtaining the filtered voltage *HVfil(k)* and the filtered reactive generation *QGenfil(k)*. If the filtered voltage signal is outside the admissible band, the filtered reactive output at the low voltage bus is checked to see if the generator is contributing to voltage control as specified by the mandatory reactive generation/absorption limits *QMax* and *QMin*. If the voltage *HVfil(k)* is under the minimum admissible voltage, the generating unit is not complying with the service if the filtered reactive power *QGenfil(k)* generated at the low voltage bus is under the mandatory reactive generation *QMax*; if the voltage *HVfil(k)* is over the maximum admissible voltage, the generating unit is not complying with the service if the unit is consuming less reactive at the low voltage bus than the mandatory reactive consumption *QMin*.

In a similar way as in frequency control monitoring, the behaviour of each unit is evaluated by means of the total number of samples with inadequate performance both in absolute value (*NInadeq*) and relative value (*PCInadeq*):

(5) $$NInadeq = \sum_{k=1}^{NSamples} PInadeq(k)$$

(6) $$PCInadeq(\%) = \frac{NInadeq}{NSamples} \cdot 100$$

where *NSamples* is the total number of samples during the monitored period, and *PInadeq(k)* corresponds to the flag indicating whether the response of the unit is inadequate in control cycle *k* (*PInadeq(k)*=1), or adequate (*PInadeq(k)*=0). In addition the total reactive energy deviation during the monitoring period (*QDevTot*, in Mvarh), and the percentage of the total reactive energy deviation (*QDevPer*, in %) with respect to the total maximum energy deviation (*QDevMaxTot*, in Mvarh) , indicate the quality of the unit response to voltage control:

(7) $$QDevTot(\text{Mvarh}) = \frac{T_S}{3600} \sum_{k=1}^{Nsamples} Qdev(k)$$

(8) $$QDevMax(k) = \begin{cases} QMax \ if \ \begin{pmatrix} HVfil(k) < HVref(k) - VBand \\ QMax > QGenfil(k) \end{pmatrix} \\ -QMin \ \ if \ \begin{pmatrix} HVfil(k) > HVref(k) + VBand \\ QGenfil(k) > QMin \end{pmatrix} \\ 0 \ \ in \ any \ other \ case \end{cases}$$

(9) $$QDevMaxTot(\text{Mvarh}) = \frac{T_S}{3600} \sum_{k=1}^{Nsamples} QdevMax(k)$$

(10) $$QDevPer[\%] = 100 \frac{QDevTot}{QDevMaxTot}$$

where *QDev (k)* is the reactive power deviation of the unit in control cycle *k*.

3.3 Application example

This section illustrates the central monitoring system of voltage control using real data of a hydro Turkish power plant G2.

G2 has a maximum reactive limit *QMax* of 87.72 Mvar and a minimum reactive limit *QMin* of -62.84 Mvar. Actual voltage control data was collected from 01:00:00 to 01:31:20 on the 19th February 2010, with measurements of voltage and reactive power every 10 seconds. Since the reference voltage was not known, an illustrative example assuming *HVref*= 400 kV and *VBand*=7 kV will be presented.

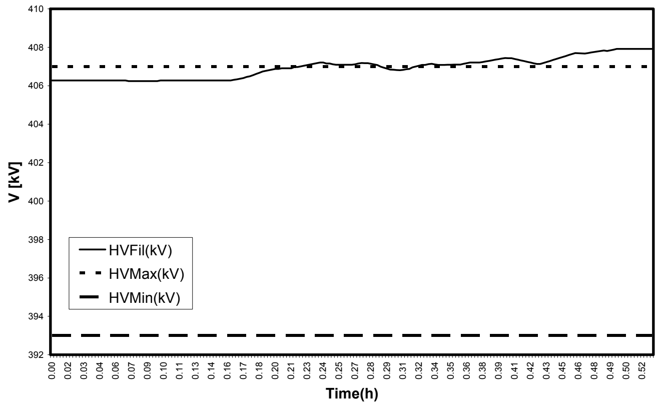

Fig 5: G2 filtered, maximum and minimum voltage assuming *HVref*=400 kV and *VBand* =7 kV.

Fig 5 shows the filtered voltage, together with the maximum and minimum admissible voltage. The filtered voltage is over the maximum admissible voltage in some cycles: in these cycles the reactive power at the low voltage bus is checked. As can be seen in Fig 6, since the unit does not provide the minimum reactive limit, there exist a reactive deviation which is the difference between the filtered reactive output and the minimum reactive limit. TABLE 2 summarizes the performance evaluation of the voltage control by the unit. The final value of samples with inadequate response for monitoring period is 100 samples (52.98 %). The total unserved reactive energy adds to 13.5 Mvarh, which represents 77.6% with respect to the maximum reactive energy deviation.

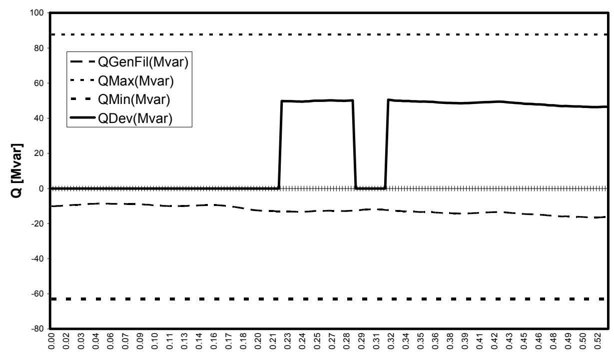

Fig 6: G2 filtered *QGenfil*, maximum and minimum reactive powers *QMax* and *QMin*, and reactive deviation assuming *HVref*=400 kV and *VBand* =7 kV.

Table 2. Summary of voltage control performance evaluation of hydro unit G2

NInadeq	100
PCInadeq (%)	52.9
QDevTot (Mvarh)	13.5
QDevPer (%)	77.6

4. Conclusions

Within the Turkish Power System, frequency and voltage control have been defined as mandatory remunerable ancillary services that are provided by generating units and managed by the system operator. This paper proposes a central monitoring system of frequency and voltage control of the Turkish Power System in order to validate the correct fulfillment by generating units.

Even though both services present different technical, time-scope and complexities by definition, the system proposed share the same intuitive approach: both frequency and voltage control monitoring is based on a reference model that compares the real operation of the generating units with the desired behavior established by the technical specifications of the Turkish grid code. A number of quantitative measures, based on the deviation between the real and the desired response are proposed to evaluate the adequacy of each unit behavior. Application examples of the central monitoring system are provided using real data of different Turkish power plants. It should be noted that the simple and intuitive central monitoring of frequency and voltage control proposed in this paper can be applied to any power system by just specifying the desired response based on the system technical requirements of the grid code.

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