Monitoring of generating units' contribution to Frequency and Voltage Control

P. Juston, F. Guy, S. Henry, P. Bertolini

***Abstract*--Ancillary Services (Frequency and Voltage Control) are very important for the electric system operation reliability. RTE (Réseau de Transport d'Electricité) has developed a monitoring tool aiming at analyzing measurements (active and reactive power, voltage) at the delivery point of the units. This tool computes indicators and supplies diagnosis information on conformity of the participation of units to frequency and voltage control. After about five years, the results are positive and RTE has gained detailed and precise information about the individual behavior of each generation unit.**

***Index Terms*--Ancillary-services, Frequency-Control, Voltage-Control, Monitoring**

I. Introduction

Frequency and voltage controls are one of the main components of the electric system operation reliability. RTE (Réseau de Transport d'Electricité), the French TSO, is the guarantor of safety for the French electricity system and as such must ensure that Ancillary Services are available. The stakes for the power system and the transmission system users are very high. Analysis of the European incident that occurred on 4th November 2006 highlighted the considerable importance of rigorous management of the generation units' primary and secondary frequency reserves. Reactive power management has been an important issue during 2003 blackout in the United States and Canada [1].

According to the law dated 10th February 2002 [2], [3], RTE ensures availability of the Ancillary Services (voltage and frequency control) and for this purpose negotiates the necessary contracts freely with the Scheduling Responsible Entities and the suppliers it has chosen.

Since 2003, RTE has developed an original performance monitoring procedure based on two key points:

- development of a diagnosis tool that enables continuous monitoring of all the generation units contributing to the load frequency and voltage control,
- and introduction into the Ancillary Services Participation Contract [4] of clauses giving producers incentives to guarantee the long-term availability and quality of the services purchased.

The present document describes the Ancillary Services Participation Contract (Part II); the diagnosis tool (Part III); and the benefits of the procedure (Part IV).

II. The Ancillary Services participation contract

The Ancillary Services Participation Contract describes the technical, legal and financial terms and conditions for RTE's acquisition of the contributions of generating units to frequency and voltage controls. The model contract, including current remuneration prices, is published on the RTE web site.

The Ancillary Services participation Contract, specifies in particular:

- the minimum performance expected from the generating units,
- the arrangements for remuneration of energy generators, fixed by RTE and not negotiable. They are based on the unit prices for each type of control. For frequency control the remuneration is based on primary control reserve (MW of control capability upwards) per hour of availability. In the case of a secondary control demand, the energy supplied in addition (MWh) is remunerated and the saved energy is reimbursed to RTE at the same price. For voltage control, the remuneration is based on the reactive capability of unit (Mvar) per hour of operation. In reactive power sensitive zones, some of the energy generator's investment costs (MVA per year) for a generating unit satisfying the criteria defined in order [2] are remunerated. The remuneration is increased by 50% if the unit participates in Secondary automatic Voltage Control.
- the consequences of failure to abide by the provisions,
- the mechanisms for returning to conformity if the performance levels stipulated by the contract are not achieved. These mechanisms include a sliding scale of financial penalties according to the scale and duration of the discrepancies.

III. Diagnosis tool

The CdP-Prod diagnosis tool (French acronym for "verification of generators performance"), developed by RTE since 2003, makes it possible to analyze the units' response to the natural surges of the controls and to compare this response

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to the performance expected within the contractual framework. This software analyses the measurements of frequency, active and reactive power and voltage at the connection point, computes the indicators and supplies diagnosis information concerning conformity of the participation in control. This diagnosis information is available subsequently, at D+1.

The tool makes use of various types of information originating from the RTE information system: scheduling, real time SCADA, metering, and does not require the installation of specific measurement equipment.

A. Monitoring of the unit's contribution to Frequency Control

1) Principle

The steady state response expected from a generating unit participating in primary control and secondary control is:

$$P(t) = P_0 + K.\Delta f(t) + N(t).P_r \quad (1)$$

where:

- P(t) is the active power supplied by the generating unit,
- P_0 is the active power declared by the energy generator with regard to the daily scheduling of its generating units,
- K is the unit's primary control frequency characteristic (in MW/Hz) declared by the energy generator as part of the contract [4],
- Δf(t) is the difference in frequency compared to the 50 Hz reference value,
- N(t) is the value of the secondary control signal sent by RTE ($N \in [-1, +1]$),
- P_r is the secondary control half-band declared by the energy generator with regard to the daily scheduling of its generating units.

Finally the response dynamic of the control system and turbine process is taken into account by applying a first order filter to signal Δf(t) and signal N(t). The response of the generating is then:

$$P(t) = \left(P_0 + K.\Delta f(t) + N(t).P_r\right) / \left(1 + T.s\right) \quad (2)$$

where:

T is the time constant of the process, and s the Laplace variable.

When the time constant is well known, the basis for monitoring is to identify the (P_0, K, P_r) triple by using the least squares method. The remote measurements (the generated power P, the frequency F and secondary control signal N) are available at the 10-second sampling period. The duration of the identification window must be at least 1 hour. The estimated values of (P_0, K, P_r) are validated if the estimation error is below a threshold.

The estimated values (P_0, K, P_r) are compared with the contractually expected values.

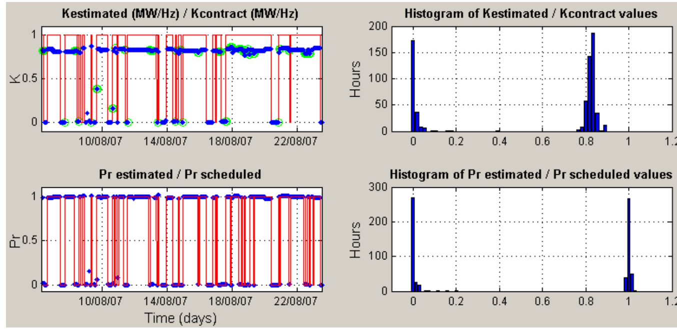

Fig. 1. Monitoring of a generating unit's contribution to frequency control for the month of August 2007.

The curves in the left part of Fig. 1 superimpose as a function of time:

- the contractually scheduled values of parameters K and P_r (solid thin red line). They equal either 1, when the unit is scheduled for control, or 0 when it is not.
- the estimated values for these same parameters, at a ten-minute pitch, normalized with the scheduled values (thick blue line).

The curves in the right hand part of Fig. 1 represent the histograms of the estimates for parameters K and Pr.

This type of presentation makes it possible to verify first whether a unit has contributed to control as per its scheduling, and second whether the values of the K and P_r parameters comply with the values declared by the energy generator.

2) Dynamic behavior identification

When the time constant is not known, the estimation process is extended to the quad (P_0, K, P_r, T) by using the equation:

$$P(t) = P_0 + K.\Delta f(t) + N(t).P_r - T.\frac{dP}{dt} \quad (3)$$

where dP/dt is the derivative of the active power.

This equation corresponds to the well-known time constant representation by state space model (Fig. 2).

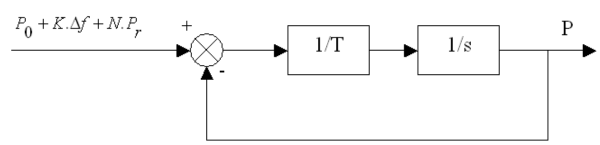

Fig. 2. Main time constant of process

3) A particular case: run of river power stations

For run of river power stations, there is no active power P_0 declared to the daily scheduling. To overcome this difficulty, P_0 is substituted by the low frequency component P_{LF} of active power P(t) which is calculated with the equation:

$$P_{LF}(t) = H(s).P(t) \quad (4)$$

where H(s) is a low pass filter.

The frequency signal F is filtered with the same filter to obtain the signal F_{LF}:

$$F_{LF}(t) = H(s).F(t) \tag{5}$$

The unit's primary control gain K is then estimated by using the equation:

$$P(t) = P_{LF}(t) + K.\left[F_{LF}(t) - F(t)\right]/(1 + T.s) \tag{6}$$

This method is equivalent to identify the primary control gain K in the "high" frequency domain (frequencies over the cut-off frequency of filter H).

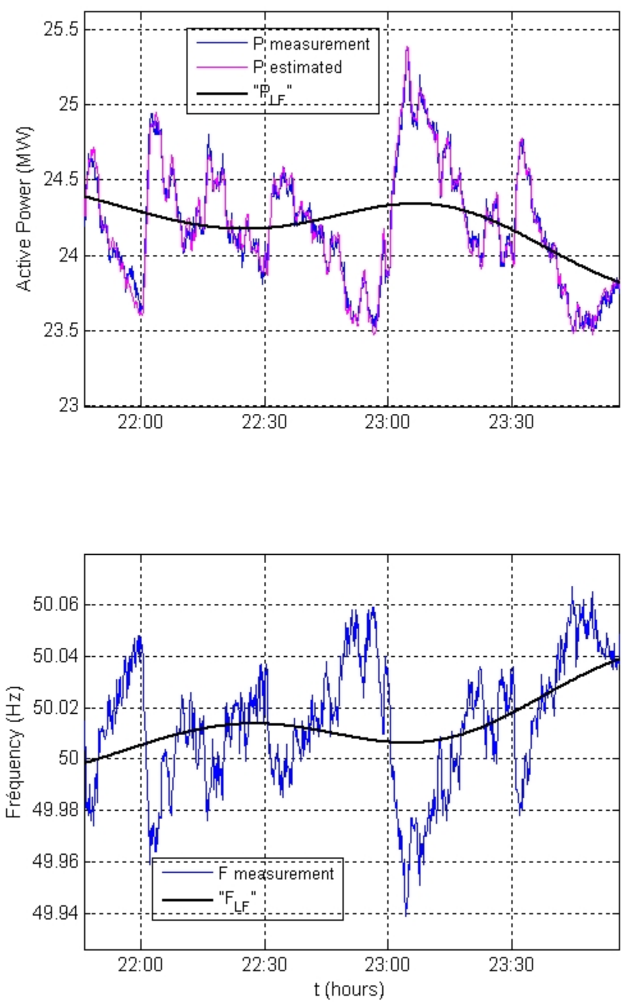

Fig. 3. Monitoring of a run of river unit

On Fig. 3 the solid thin black lines represent the low frequency component of active power and frequency signals. The blue curve represents the active power measurements and the magenta curve the estimated power. Active power variations around the "mean" active power are proportional to frequency variations around the "mean" frequency.

In this example, the low pass filter cut-off frequency was 0.00125 rad/s.

B. Monitoring of the unit's contribution to Secondary Voltage Control

1) Focus on the Secondary Voltage Control

The basic principle of the Secondary Voltage Control (SVC) is to share the EHV network into distinct control areas and to control the voltage profile within each area of the power system, by an automatic and coordinated action of dedicated generators, called "controlling units". This action is carried out so as to regulate the voltage of a dedicated node of the area, called "pilot node".

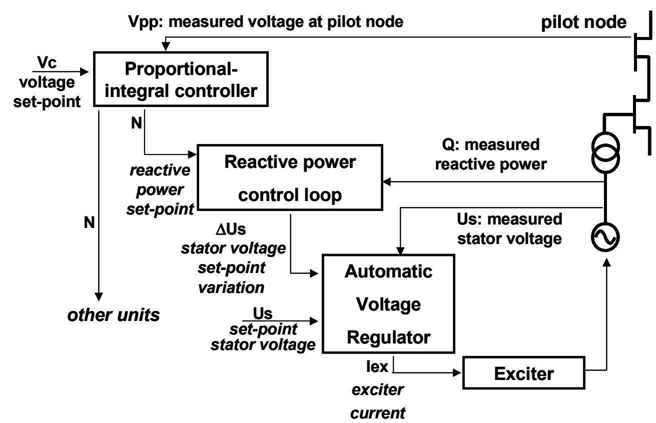

Fig. 4. Secondary Voltage Control loop

The technical principle of the Secondary Voltage Control is to maintain, in the area, the pilot node voltage V_{PP} equal to its set-point V_c, which has been set by the Regional Control Center. This regulation is based on a proportional integral law, which elaborates from the deviation (V_{PP}-V_c), the so called "area reactive level", N, N $\in$ [-1, +1], which indicates the need for reactive power generation or absorption within the area. This level N is calculated on a dedicated computer at the Regional Control Center and transmitted every ten seconds to each controlling units, where a local control loop tends to set the per unit reactive power of the generator equal to N, by a modification of the AVR set-point. Each controlling unit participates to the voltage control proportionally to its reactive power capacity. In steady state operation, reactive power generated by each controlling unit is "aligned" to the same relative value, N.

2) Focus on the Coordinated Secondary Voltage Control

An improved version of the Secondary Voltage Control, called "Coordinated Secondary Voltage Control" (CSVC) has been developed and implemented in the West of France. It has been described in [5], [6], [7]. Whereas the SVC system controls locally the voltage at a single pilot node, the CSVC system adjusts the voltage map for a whole region by controlling the voltages at a set of pilot nodes. In closed-loop mode, it computes fresh set-point values for the generator unit primary controls at 10-second intervals, by minimizing the following multi-variable quadratic function:

$$\begin{aligned} \min \Big\{ & \lambda_v \left\| \alpha(V_c - V_{pp}) - C_v \Delta U_c \right\|^2 \\ & + \lambda_q \left\| \alpha(Q_{ref} - Q\ ) - C_q \Delta U_c \right\|^2 \\ & + \lambda_u \left\| \alpha(U_{ref} - U\ ) - \Delta U_c \right\|^2 \Big\} \end{aligned} \tag{7}$$

where:

- α is the control gain,
- Vpp, Vc are the measured and set-point voltage values at pilot nodes,
- Q, Qref are the measured and set-point reactive power values at generating units,
- U, Uref are the measured and set-point stator voltage values,
- ΔUc is the vector of stator voltage variation,
- λv, λq, λu are the weightings for terms in objective function: pilot node voltage, reactive power, and generator unit stator voltage,
- Cv is the sensitivity matrix relating variations in pilot node voltage to variations in stator voltage (Network is modeled by sensitivity matrices for coordination between generating sites),
- Cq is the sensitivity matrix relating variations in reactive power to variations in stator voltage.

Concerning the monitoring, the main difference between SVC and CSVC is that the controlling variable is the reactive power in SVC mode and the terminal voltage in CSVC mode.

3) Participation to the Secondary Voltage Control

The terminal reactive power Q_{st} of a controlling unit participating to the Secondary Voltage Control (SVC) should be proportional with a constant factor Q_r to the N level transmitted by the Regional Control Center, according to the following static law:

$$Q_{st} = N.Q_r\,,\;\; N \in [-1, 1] \tag{8}$$

To perform a continuous monitoring, the deviation ε between the measured response of the unit and the set-point is computed as follows:

$$\varepsilon = |Q_{st} - N.Q_r| \tag{9}$$

The participation of the unit to the Secondary Voltage Control is considered as unsatisfactory as soon as ε is greater than a certain threshold during a significant time period. The threshold takes into account the dead band of reactive power control loop.

Fig. 5 illustrates the principle of the Secondary Voltage Control service monitoring. The deviation ε is plotted at the bottom of the figure. In this specific case, the behavior is satisfactory. The deviation does not exceed the threshold (red line).

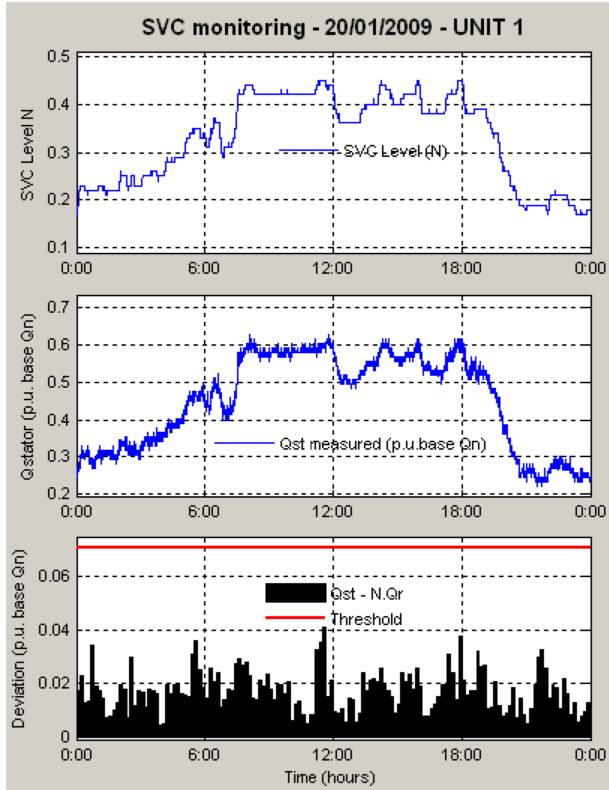

Fig. 5. Secondary Voltage Control monitoring

4) Participation to the Coordinated Secondary Voltage Control

The terminal voltage variations ΔU_s of a controlling unit participating to the CSVC should be equal to AVR set point variations ΔU_c sent by the Regional Control Center:

$$\Delta U_s = \Delta U_c \tag{10}$$

The monitoring is realized in two steps:

- First, identification of the interface gain G_i between Regional Center and AVR set point.
- Second, identification of the AVR gain.

The interface gain is estimated by the least squares method with the following equation:

$$U_{C\,k+1} - U_{C\,k} = G_i.\Delta U_{C\,k} \tag{11}$$

where Uc_{k+1} and Uc_k are samples of the AVR set point.

The identification of the AVR gain is more difficult. Some of AVR present a steady state error which can depend on the operating point of the unit (active and reactive power).

Therefore, the steady state response of AVR is represented by the equation:

$$U_s = K_u.U_c + K_0 + K_p.P \tag{12}$$

where P is the active power of the unit.

The (K_u,K_0,K_p) triple is estimated by the least squares method from measurements U_c, U_s, P (10-second samples).

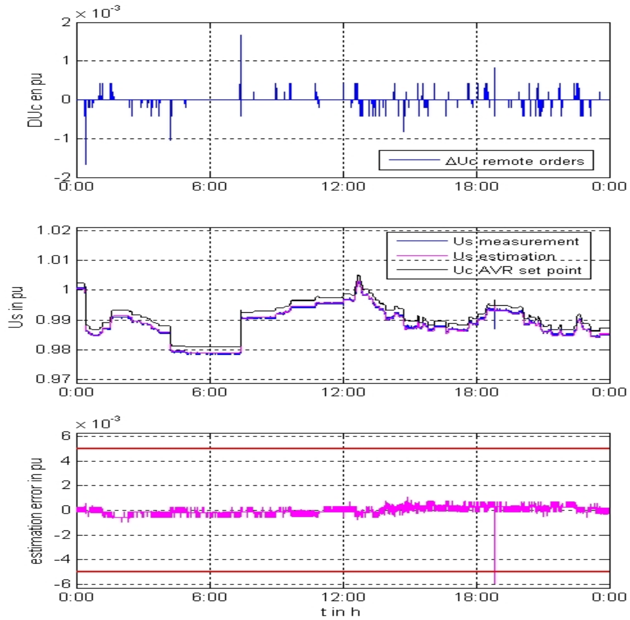

Fig. 6. Coordinated Secondary Voltage Control monitoring

The deviation between the estimation and the measurement of terminal voltage must remain below a threshold (Fig. 6). The control gain for CSVC is represented by the product $G_i.K_u$ and must remain close to 1 in pu.

Furthermore, the modification of AVR parameters can be detected by the observation of estimations over a long period (typically a few months).

5) Availability of the required [U/Q] domain

A generating unit can follow remote variations sent by the Regional Control Center, only if its operating point is not on a limitation (like over excitation limit for example).

To evaluate reactive power capabilities of a unit, the operating points at connection point are plotted in the [U-Q] domain for a fixed active power and compared with the capability curves given by the producer.

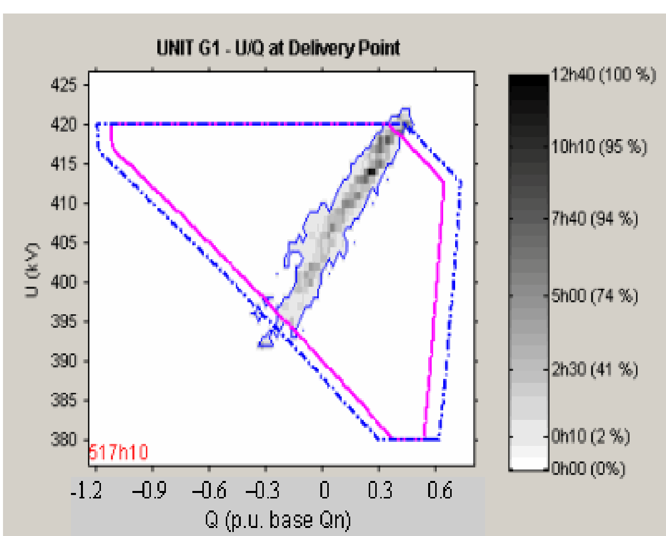

Fig. 7. Cluster of operating points, at the connection point, during 517 hours of running the unit (in U/Q plane)

On Fig. 7, the unit's normal operating limits are in blue dotted line and the pink line corresponds to a margin of error covering chart measurement and construction uncertainties.

In the case of Fig. 7, all the supply and absorption capabilities are available.

IV. Conclusion

RTE's assessment of the first few years during which this procedure has operated is a positive one. This procedure has supported the initial diagnosis of satisfactory overall contribution of the French generating system to frequency and voltage control. The diagnosis tool enables RTE to obtain more detailed and precise information about the individual behavior of each generation unit and to detect cases where generating technologies or particular units do not fully satisfy the performance criteria set by RTE. For example, the procedure has made it possible to show that for certain units there are delays compared to the required response times in the context of secondary control of frequency and voltage. For these specific cases, progress actions have been undertaken by the main French producers to improve their performance in order to respect the criteria required by RTE.

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