Implementation of Coordinated Voltage Control for the Swiss Transmission System

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Abstract—This paper outlines the organization of the ancillary service "voltage control and provision of reactive power" for the deregulated Swiss electricity market environment. A central voltage/reactive power management concept was elaborated and introduced with the respective operational procedures, from day-ahead planning to ex-post monitoring and accounting. Economic incentives were defined for all involved parties within Switzerland. This article describes the main features of the concept and its implementation. A conclusion summarizes practical experience and possible future improvements.

I. INTRODUCTION

Besides other major changes in the Swiss energy supply sector, the Swiss Electricity Supply Act of 23 March 2007 requires a set of ancillary services to be organized in a market-oriented, non-discriminatory, and in transparent manner [1]. Provision of reactive power/energy for transmission system voltage control is among the ancillary services which had to be re-organized before the corresponding provision entered into force on 1 January 2009. The Swiss national transmission system operator (TSO) Swissgrid took this opportunity not only to define economic incentives for the involved parties, but also to introduce a central voltage/reactive power coordination for the Swiss transmission system which includes the 220-kV and 380-kV levels.

This paper starts with a general outline of the involved parties and their roles on a system level. The main characteristics of the new concept are presented before the practical implementation is outlined. One of the key operational procedures, the so-called Day-ahead Reactive Planning, covers another section. Preliminary results after six months of operating experience ends off the paper.

II. INVOLVED PARTIES AND THEIR ROLES

Fig. 1 shows the parties that exchange reactive power with the transmission grid. Their roles in terms of voltage/reactive power management are outlined in the following paragraphs.

A. Transmission System

Voltage control is one of the major TSO tasks. Depending on the available infrastructure, TSOs organize their voltage controls in different ways [2]-[11]. Today, the only resources available for transmission system voltage control by Swissgrid are power plants directly connected to the transmission grid, and 220/380-kV transformers equipped with tap changers.
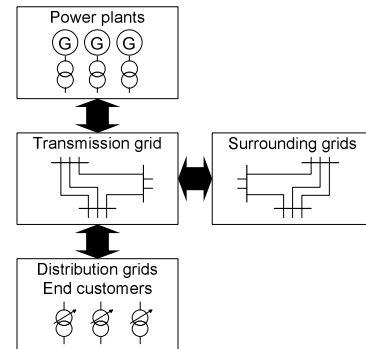

Fig. 1: Power exchanging parties.

Since there is no dedicated transmission system voltage control infrastructure available for Swissgrid, voltage control is planned and coordinated off-line based on forecasts. In real-time operation, the grid voltages are monitored and predefined set-points are corrected if necessary.

B. Power Plants

Power plants which are directly connected to the transmission grid are able to control their reactive power exchange with the grid and are thus used for transmission system voltage control. Most of the Swiss power plants control the voltage according to a static voltage/reactive power droop, and the set-point is often adjusted manually. The proportional control characteristic results in a permanent control deviation. Only a few hydro units are equipped with advanced voltage controllers. In Switzerland, transmission system connected power plants are not equipped with on-load tap changers, thus there is no possibility to control the voltage by changing the block transformers' tap positions.

C. Distribution Grids and End Customers

Distribution grids directly connected to the transmission grid influence the transmission system voltage according to their reactive power exchange, whereas controllability of reactive power is usually limited. Most of the transformers that connect the transmission grid with the distribution grids are equipped with on-load tap changers, which are usually operated manually for voltage control.

Transmission system connected end customers, such as the Swiss Federal Railways, exchange reactive power via their grid interfaces, which are either static or rotating converters (16.7 Hz to 50 Hz). The ability to control the reactive power flow depends on the technology of the interface.

D. Surrounding Grids

The Swiss transmission system is part of the European continental grid and strongly interconnected with the surrounding systems. Rules for reactive power exchange between control areas are defined in the Operation Handbook for the Entso-E Continental Europe interconnection (former UCTE) [15].

E. Previous Situation

In the past (i.e., before restructuring of the Swiss power industry) all power plants were operated on constant voltage set-points. Voltage and reactive power were not in the main focus of the plant operators because there were no compulsory agreements and reactive power/energy was not subject to economic considerations. There were no rules at all covering the reactive power exchange of directly connected distribution systems and end-customers with the transmission system. A fully responsible national TSO was not installed before 2009, and the central transmission coordination was not in charge of system operation. One result of this situation was that unacceptable voltages occurred frequently. Another result was high, uncontrolled reactive power exchanges with neighboring transmission grids. However, roles and duties of all parties were re-defined by the Swiss Electricity Supply Act. A new concept for voltage control had to be introduced in order to comply with the new regulatory framework.

III. BASICS OF THE NEW CONCEPT

The concept for a new voltage control and reactive power paradigm was developed based on the following assumptions that have been widely accepted among all involved experts:

- Economic incentives to be introduced, reflecting the value of reactive power exchanged with the transmission grid.
- Utilization of reactive power resources to be centrally coordinated and optimized by Swissgrid.
- The concept to be developed based on international best-practice [2]-[13].

Economic incentives were defined for all reactive power interfaces within Switzerland. Besides the above assumptions, three main goals of voltage control were defined that should be supported by the new concept [14], [15]:

1. Keeping voltages within operational limits at all nodes, at all times.
2. Compliance with the Operation Handbook of the Continental Europe interconnection.
3. Optimizing reactive power flows in order to minimize costs for i) active power transmission losses and ii) reactive power payments to the power plants.

A. Power Plants

Today power plants are the only reactive power resources that can be actively utilized for transmission system voltage control by Swissgrid. Yet there are no other means, such as static compensators, available. All power plants directly connected to the transmission grid have to participate at transmission system voltage control to some extent while receiving financial compensation. All generators in operation are obliged to support the voltage within their so-called obligatory reactive power range, which is defined as the possible reactive operating range of the generators at maximum active power. Operation within the obligatory reactive power range does not cause any opportunity cost for the generators. Power plants can also provide enhanced reactive power services beyond the obligatory service by concluding bilateral agreements with Swissgrid. These agreements allow Swissgrid to access additional reactive resources (today generators operating as synchronous condensers).

Inside Switzerland, the reactive energy provided by the power plants for the purpose of transmission system voltage control is compensated by a default payment rate (CHF/Mvarh). The precondition for this payment is that the reactive energy exchanged is actually supporting the hourly set-point voltage defined by Swissgrid. This condition is checked every 15 minutes based on voltage measurements and metering data (active and reactive energy). Thereby it can be guaranteed that only voltage-supporting reactive power delivery is compensated financially. If the reactive power exchange of a unit is counterproductive for achieving the set-point voltage, no compensation is assigned for the corresponding quarter of an hour.

B. Distribution Grids and End Customers

Distribution grids and end customers directly connected to the transmission grid have limited abilities to control the transmission system voltage. They are therefore only requested to limit their reactive power exchange with the transmission system. The incentive for such behavior is given by another default payment rate (CHF/Mvarh) which is charged for excess reactive energy exchanged beyond the 15-minute average power factor of 0.90. This proposes a more deliberate reactive power management in the distribution grids and more local reactive power compensation. After intensive discussions about this concept and a decision of the Swiss Federal Electricity Commission, excess reactive energy is charged as of 1 January 2010.

C. Surrounding Grids

For the European continental grid, the relationship between adjacent control areas in terms of voltage and reactive power control are defined in Policy 3 of the Operation Handbook [15]. A set of general standards and guidelines is mentioned that describes the main duties of the TSOs and how they should cooperate: "Extensive reactive power flows beyond the own consumption of the tie-lines are the result of the different voltage levels on each side of the boundary. In order to ensure a safe operation of the synchronous area, adjacent TSOs shall agree on common voltage ranges on each side of the border to ensure the continuous voltage control."

This is a very general formulation, there are no clear operational instructions for voltage control and coordination with adjacent networks. Also, there are no clear limits for reactive power exchanges between control areas. In fact, today

there is no clearly defined voltage/reactive power coordination between Swissgrid and the neighboring TSOs.

D. Central Coordination

Swissgrid is in charge of planning and coordinating all reactive power resources throughout the transmission system. Today there is no dedicated voltage control infrastructure available, therefore the coordination of the reactive resources has to be performed off-line. The main coordination task is to optimally dispatch the reactive resources and to determine and communicate the voltage set-point values for the power plants. Additionally, on-load tap changers of 220/380-kV transformers are available for controlling the transmission system voltage. These transformers have to be dispatched by Swissgrid. The related planning procedure is outlined in Section V.

IV. PRACTICAL IMPLEMENTATION

Implementation of a new voltage control concept requires the definition and introduction of new operational procedures. In order to guarantee that the new concept worked, test procedures had been performed before the whole concept was realized.

A. Testing

Before the new voltage control concept was introduced, a test concept was elaborated in order to gain experience with the performance of the power plants and the behavior of the whole system under the new operating paradigm. Defining such test procedures is a difficult balancing act. On the one hand, the test case should simulate the new situation as realistic as possible, otherwise the results are not meaningful. On the other hand, executing the test sequence must not jeopardize the security of the system. Therefore three consecutive test procedures were defined approaching the future conditions step by step.

Individual Tests: In order to verify the reactive power capacities of the power plants and their dynamic behavior in terms of voltage control, every plant individually performed a simple test procedure where all generators of a plant were operated at minimum and maximum reactive power output. After that, the plants performed steps of ± 1 kV from a given set-point to explore their step response and the voltage/reactive power sensitivity at the transmission system node. In order to minimize loss of generation risk, the plants performed this test in a consecutive manner. Larger plants completed the test individually for each machine unit. Time slots for these tests were agreed between each plant and Swissgrid in order to avoid experiments in critical situations.

Common 4-hour Test: For four hours, all plants synchronously realized predefined changes of the set-point voltages. Two sequences have been prepared. Sequence A was realized by all plants where the voltage was rather low when the test was started. These plants changed their set-point twice, first +1 kV from the previous value, and after one hour back to the previous value (-1 kV). Sequence B was dedicated to all plants where the voltage was high at the beginning of the test.

The voltage was changed twice as well, first -1 kV, and after one hour back to the previous value (+1 kV). Both sequences have been repeated once. This test allowed evaluating the reaction of the whole system when the voltage set-points of all plants are changed synchronously in a step-wise manner. The test was done during a period that is usually noncritical concerning voltage—on a Thursday afternoon. Fig. 2 shows an example of a hydro unit's 4-hour test result. The reactive power is controlled in order to comply with the set-point voltage defined by test sequence B. Against the background of measurement uncertainties, the test sequence is performed fairly well, with acceptable voltage deviation and only a few minutes delay.
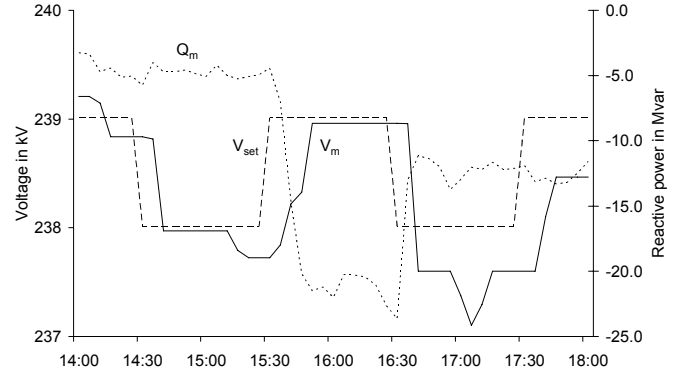

Fig. 2: Example of a 4-hour test result. V_{set} is the set-point, V_m the measured voltage, and Q_m the measured reactive power exchanged by the plant.

Common 24-hour Test: In this test the complete concept was realized for the very first time. Based on a day-ahead voltage schedule created by Swissgrid, the plants followed their individual set-point voltage profiles during 24 hours. The test was scheduled to start in a low-risk period but to end in a realistic, challenging situation: Sunday 12 a.m. until Monday 12 a.m.

After all tests have been performed successfully, the new voltage control concept was accepted and approved for realization.

B. Operational Planning

The main operational planning task is done in day-ahead mode, after the Day-ahead Congestion Forecast (DACF) is available [16]. Based on this forecast and other information, the so-called Day-ahead Reactive Planning (DARP) procedure is performed in order to determine the optimal set-point voltages for the power plants. Section V describes this procedure in detail. The core of DARP is a reactive optimal power flow computation that aims at minimizing

- the cost of active losses throughout the Swiss transmission system plus
- the cost of reactive energy payments to the generators

while ensuring a number of technical and operational constraints. As a result, a day-ahead voltage schedule, that

contains 24 hourly set-point voltages for all production nodes, is sent to the power plants.

C. Real-time Operation

In real-time operation, the voltages throughout the Swiss transmission system are monitored and supervised by the operational staff. A general monitoring screen shows all nodes of the system and marks them according to the voltage green, yellow, or red.

Besides the general voltage monitoring screens, a plant-based voltage/reactive power monitoring system has been created where every plant's operating point is shown in detail. The operators can see the actual reactive power production, limits of the obligatory reactive power, and possible enhanced reactive power capacities. Deviations of the actual voltages from the set-point voltages are shown as well as the compliance of each plant. The concept of voltage/reactive power compliance is outlined in the following section. Fig. 3 shows a screenshot of this monitoring system.

An operational emergency plan was elaborated that provides a number of procedures for the operators to keep voltages within operational boundaries. Intervention by the operator might be necessary if actual voltages exceed certain boundaries. This may happen if the forecast-based set-point voltages turn out to be inadequate and/or the plants are not able to keep the voltages close to the set-points due to unforeseen circumstances. The type of measure/procedure depends on the severity of the situation. One of the first measures is to advise the plants to fully utilize their obligatory reactive power in order to support the scheduled set-point. In a next step, the operators may order enhanced reactive power services by calling contracted generators to operate as synchronous condensers. As a last measure on a national level, all available units are called to synchronize to the grid and provide their full reactive power capacity while reducing their active power production to a minimum. Additionally, international redispatch procedures with the surrounding TSOs are available. These procedures have been defined primarily for reducing (n-1) loading, but they have also been triggered to solve transit-related voltage problems.
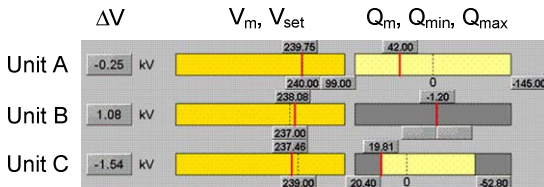

Fig. 3: Voltage/reactive power plant monitoring. ΔV is the deviation between measured (V_m) and set-point (V_{set}) voltages. Q_m is the measured reactive power (value above bars), Q_{min} and Q_{max} are the technically min./max. reactive power values, respectively (value below bars). The obligatory reactive power range is highlighted in the reactive power bar.

D. Ex-post Monitoring and Accounting

The reactive power exchanges of all power plants are reviewed in an ex-post monitoring and accounting process. An important measure for the quality of a voltage controlling resource is its monthly voltage/reactive power compliance.

This measure expresses whether the reactive energy exchanged by a plant was supporting the set-point voltage or not. Sufficient compliance is a precondition for financial compensation of the reactive power delivery of a plant.

Compliance is given if the voltage is above the set-point and reactive power is absorbed from the grid, or vice versa (see Fig. 4):

$$K = \begin{cases} 1 & \text{IF} \left(V \geq V_{set} - \Delta V_m \right) \text{AND} \left(W_Q \geq 0 \right) \\ 1 & \text{IF} \left(V \leq V_{set} + \Delta V_m \right) \text{AND} \left(W_Q \leq 0 \right) \\ 0 & \text{ELSE} \end{cases} \quad (1)$$

Here V is the 15-minute average voltage at the plant's injection node (measured), V_{set} is the predefined set-point voltage, ΔV_m is the voltage measurement uncertainty, and W_Q is the reactive energy exchanged ($W_Q > 0$ means that reactive power is absorbed from the grid).

The compliance K determines whether compensation is assigned for the relevant quarter of an hour or not:

$$C_i = K_i \cdot W_{Qi} \cdot T_Q \quad (2)$$

Here C_i is the financial compensation for the 15-minute period (i = 1, 2, ..., n), K_i is the compliance for period i, W_{Qi} is the net reactive energy exchanged by the plant in period i, and T_Q is the reactive payment rate. The monthly sum of C_i is paid to the plant if compliance of its reactive energy exchange is given in at least 70% of all operating periods of the month.
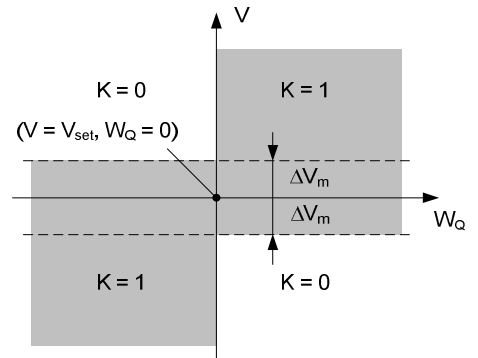

Fig. 4: Voltage/reactive energy compliance principle.

V. Day-ahead Reactive Planning

Since there is no dedicated closed-loop voltage control system available for the Swiss transmission system, the set-point values for the voltage controlling power plants have to be determined off-line based on forecast data. For this purpose, a so-called Day-ahead Reactive Planning (DARP) process has been introduced. The main result of the DARP process is the day-ahead voltage schedule for the power plants. This day-ahead schedule contains the individual 24 hourly set-point values for all transmission system production nodes. Besides that, DARP provides a fairly realistic picture of the voltage situation to be expected for the next day. Measures can be

prepared whenever voltage problems are foreseeable. Compared to the results of the Day-ahead Congestion Forecast (DACF) [16], which mainly focuses on active power issues, DARP delivers a more complete picture including voltage and reactive power phenomena, and delivering a reasonable estimation of active power losses. From this point of view, DARP can be seen as an extension of DACF.

A. Overview

Fig. 5 gives an overview of the DARP process. The main input data are the 24 DACF snapshots that contain the continental power flow forecast for the 24 hours of the following day. As mentioned before, the DACF models have been mainly developed for active power problems; these models are not suitable for evaluating voltages and reactive power flows. In order to achieve an appropriate model quality, the DACF models are completed with

- precise reactive power limits of power plants participating in voltage control, and
- precise models of 220/380-kV transformers with tap changers used for voltage control.

Various parameters for the optimization have to be defined as well.

All information—DACF files, reactive power capacities, transformer tap models, and optimization parameters—is merged into a complete Optimal Power Flow (OPF) model. The OPF is then performed in a consecutive manner for all 24 model snapshots. Main results of the OPF are the voltage schedule, the transformer tap position schedule, and active power grid losses.

The following sections give a more detailed outline of the DARP process blocks.

B. Data and Models

In the simplified DACF model, most power plants are represented by single generators (or negative loads). Since the reactive power capacity of a plant depends on the individual operating states of the generators, it is not clear from the DACF model how much reactive power the plant can deliver. Since this information is essential for voltage/reactive power optimization, it has to be included in the model. For DARP, information about the minimum available reactive power capacity of a plant is derived from its total active power exchange (including all generators), which is clear from the DACF model. For every plant, the minimum available reactive power is derived from its total active power production. The resulting look-up table is based on the worst-case operating state in terms of available reactive power (total reactive capacity of the fewest generators necessary for a certain total active power production). Fig. 5 sketches this estimation as "$Q_{lim} = f(P)$."

Another critical model detail for voltage/reactive power optimization concerns the tap-changing transformers between the 220-kV and 380-kV levels that are used for voltage control. These tap position data have to be carefully represented in the model in order to get meaningful results.
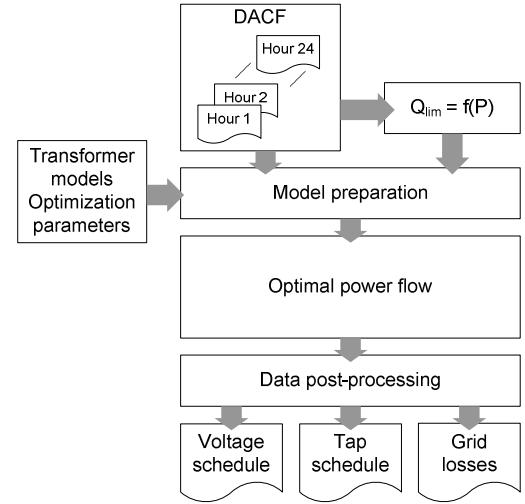

Fig. 5: Overview of the DARP procedure.

For the OPF, a number of additional parameters have to be defined. Most important for the optimization are the boundary conditions, the objective function, and the computation parameters. The following boundary conditions are included in the model:

- General voltage limits for each voltage level.
- Individual voltage limits for selected nodes.
- Voltage difference constraints between nodes.
- Reactive power flow branch group limits, per border (Austria, Italy, France, Germany) and for Switzerland in total.
- Transformer tap position limits.

Within the feasible region defined by these limitations, the OPF aims at minimizing the total cost for active power losses in the Swiss network plus reactive power payments to the Swiss generators supporting the voltage:

$$TC = \alpha \cdot P_{loss} + \beta \cdot \sum_k |Q_k| \qquad (3)$$

Here P_{loss} are the total active power losses throughout the Swiss transmission grid, and Q_k are the reactive power exchanges of all Generators (k = 1, 2, ..., m) that participate in voltage control. α and β are weighting factors that enable to express the two objectives as cost components. α represents the cost of active power losses in CHF per MW during an hour, and β represents the cost of reactive energy in CHF per Mvar during one hour. β thus corresponds to the constant default reactive energy payment rate, it is equal in all hours and days. α varies from hour to hour according to active power procurement cost.

Note that the terms of the objective function might be conflicting. In general, network losses decrease with increasing voltage. Depending on the state of the system, reactive power exchange of the generators may have to be increased in order to achieve higher voltages. Reducing the cost for losses by increasing voltages may thus lead to increased cost for reactive energy from the generators.

C. Optimization

After the model files are prepared, the optimization is performed sequentially for all 24 snapshots. The OPF aims at minimizing the total cost TC subject to the constraints defined by varying the plants' reactive power injections Q_k and the 220/380-kV transformers' tap positions. From a mathematical point of view, the problem can be classified as a nonlinear, mixed-integer optimization problem. A commercially available software tool with a specially developed Java-based user interface is used to solve the OPF problem [17]. The application enables the OPF to be run in semi-automatic mode.

D. DARP Results

The main results of DARP are the optimal nodal voltages to be realized by the power plants. Although the OPF reliably converges to mathematically correct and reasonable solutions, the results have to be analyzed and reviewed in a post-processing stage. Especially when limits are relaxed by the OPF, the results cannot be simply taken over to the voltage schedule for the power plants. A careful review by experienced operators is essential before the voltage set-points are realized by the power plants.

Other important results are the optimal tap positions of the 220/380-kV transformers. A tap position schedule is prepared for the operators as a guideline for tapping these transformers.

Since the DARP model includes precise reactive power information, the resulting active power losses are realistic and valuable for procurement of active power for compensating grid losses. In most of the cases these results are accurate enough to be understood as a reasonable forecast.

VI. EXPERIENCE AND CONCLUSIONS

A. General Experience

First conclusions after six months of operating experience show that the new voltage control concept works well. While severe voltage conditions occurred frequently in the past, it was only necessary a few times to utilize enhanced reactive power services after the new concept had been introduced. The economic incentive seems to be attractive for most of the power plants, they are seriously engaged in supporting the voltage schedule. The average monthly compliance is above 90%, although the control is done manually in most of the plants.

Analyses show that uncontrolled reactive power exchanges with neighboring control areas could be influenced as well. All in all, the median reactive exchange of the Swiss control area could be reduced by 49% during the first six months. This is a first achievement, but there is still some potential for decreasing these flows. Reactive exchanges could only be reduced on two of the four borders, the median value increased on the other two borders; but in total the exchanges were reduced.

B. Voltage Control Performance

The power plants are able to keep the voltage close to the scheduled voltage most of the time. As an example, Fig. 6 shows the typical situation at the transmission system

injection node of a large hydro unit on 10 June 2009. In this particular plant, the reactive power exchange is adjusted manually according to the difference between measured and set-point voltages. Within these 24 hours the median difference between measured and set-point voltages is 0.88 kV, with a standard deviation of 1.25 kV. Against the background of measurement deviations up to 3 kV, this is an acceptable voltage control performance.
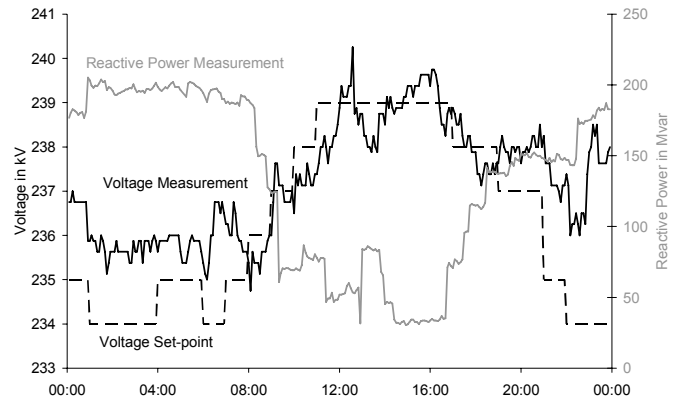

Fig. 6: Manually controlled hydro plant supporting the set-point voltage in the transmission grid.

Typical monthly compliance values of the plants' reactive power exchanges are in the range of 80 to 100%. Within the first six months of 2009, the average monthly compliance of the plants is almost 95%.

C. Outlook

Results after six months with the new concept are satisfactory. However, only little experience has been gathered so far and it is too early to conclude the topic. A number of possible enhancements have already been identified that should be addressed in the near future, for example:

- Active participation of directly connected distribution grids and end customers at transmission system voltage control. Besides power plants, these additional resources should be addressed for active transmission system voltage control as well.
- Better co-ordination with surrounding networks in terms of reactive power and voltage.

In the longer term, a central closed-loop voltage control system should be realized with direct on-line control of the plants' reactive power exchanges.

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