Improvement of Power Transmission Capacity in Power Networks Equipped with FACTS Devices and Wide Area Control Systems: A case Study

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Abstract— **The opening of the power market has generated more power flows in the European electrical grid and as a consequence congestions have appeared. Differences in energy prices in different regions can generate congestions which may give rise to differences in energy pricing. As the extension of the grid with new high voltage overhead lines faces most often the opposition of the population due to environmental issues, there are some solutions to be considered to reduce congestions : installing Flexible AC Transmission Systems (FACTS) devices and installing Wide Area Control Systems (WACS). But a coordinated, synchronized, and reliable control of FACTS devices is necessary at the system level covering a wide area. This contribution deals with the theoretical development of such a control for the Swiss HV network, aiming at preventing congestion in the north-south corridor across the Alps. The control algorithms are developed and implemented on a reduced scale physical model for experimental validation.**

Keywords : power systems, transmission lines, congestion, corridor, FACTS, WACS.

I. From WAMS to WACS

WAMS (Wide Area Monitoring System) is a technology aiming at preventing system wide disturbances that cannot be addressed by existing protections and controls. Such a system utilizes phasor measurement units (PMU) placed at suitable locations in the power system providing operators with real time information (indicators, events) that allow them to anticipate the counter actions to eliminate occurring disturbances and instabilities in the network. The principle of this technology is illustrated in figure 1.

Due to the application of the WAMS technology, the time of reaction in case of perturbations or instabilities is significantly shortened, but when several FACTS devices are installed, a real risk of uncoordinated control due to adverse interactions of the FACTS must be addressed.

In this configuration, the power grid, its measurements and control units including FACTS, works in open loop mode. The WAMS technology is upgraded into a WACS (Wide Area Control System) technology by closing the previous open loop: the settings of the FACTS (and eventually of the power generators) are changed automatically on the basis of the data provided by the PMUs.

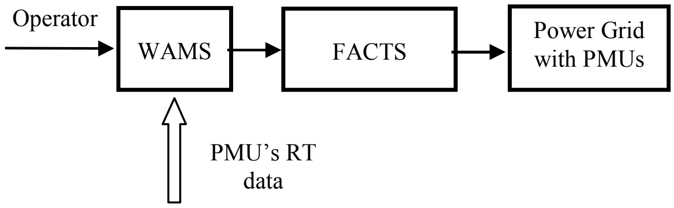

Figure 1. Block diagram of a WAMS

The corresponding control problem –which consists in developing the automatic controller - might be seen as an Optimal Power Flow, whose objective is to shape the load flow in order to meet the control requirements. In this paper an OPF based control method [1] is investigated and applied to the Swiss power grid.

It is well understood that this approach is today not fully verified for application to a real grid concerning the reliability aspects. The reliability in telecommunications linked to a WACS has been partially checked but the first results indicate that this issue will not be solved in short or middle term [2]. For example interferences emitted on site in parallel in the frequency band of the GPS antenna have disabled the PMUs. The rapid development and deployment of power electronics based devices like HVDC and other FACTS devices will call for an increased reliability of the WACS.

II Swiss WACS System Description

The European 400 kV power network contains in Switzerland an important corridor (figure 2) oriented north-south where the power congestion is sometimes a problem, as the power transit demand continue to grow while any extension of the grid is hard to implement due to environmental issues. This motivates a feasibility study of a WACS system aimed at preventing power congestion in the corridor and, simultaneously, to maintain the voltage in acceptable margins around the nominal value. The purpose here is to evaluate the effect of installing an HVDC line parallel to existing ac lines in the corridor as indicated in Figure 2.

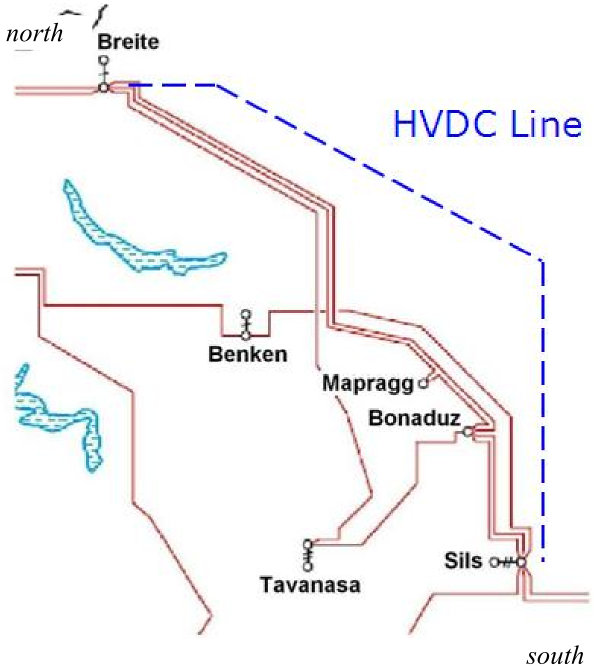

Figure 2. North-south Alp corridor with HVDC line

Basically, the congestion will be alleviated and the voltage regulation in the corridor will be performed by use of an optimal power flow (OPF) based controller as described in the next sections. Our purpose, in the following, is to show its formulation for the Alp corridor.

1. OPF based Controller

The OPF method consists, at first, in defining an objective function which allocates a positive, real value to every power flow distribution in the corridor. This function is defined so as to evaluate the gap between the targeted objectives and their realization in the real power flow, by using the measurements provided by the PMUs. Minimizing such a function – by monitoring the FACTS – leads to the optimal power flow. In addition, the power flow equations must be fulfilled, which implies that the minimization is done under the equality constraints that represents these equations.

Analytically, the objective function to be used is defined as follows, where i, j indexes the corridor lines and nodes, respectively.

$$f(\vec{x},\vec{u}) = \sum_i \overbrace{(a \cdot P_i^{loss}}^{(A)} + \overbrace{b \cdot \varepsilon_i}^{(B)} + \overbrace{c \cdot \eta_i) + \sum_j d \cdot (Vj - V_j^{ref})^2}^{(C)} \quad (1)$$

P_i^{loss} is the power dissipation in line i, V_j the voltage at node j, and V_j^{ref} the specified voltage reference.

The quantities ε_i and η_i are called "slack variables" [1]. They are introduced to softly handle violations of line transfer capacity:

- η_i : small exceed (in absolute value) of the maximum flow capacity of the line i, $\eta_i \geq 0$;
- ε_i : small exceed of 90% of the maximum flow capacity of the line i, $\varepsilon_i \geq 0$;

Maximum slack variables are defined by the user.

Minimizing (1) enables to reduce the power losses (term A), lines congestion (B) and voltage deviation (C). For that, the user specifies the weighting parameters "a" to "e" in order to fix the priorities of the optimization. The term (A, B or C) with high weighting parameter(s) will have a higher weight in the minimization, which means that the underlying objective is prioritized.

Vectors $\vec{x}$ and $\vec{u}$ contains the nodes voltages (module and phase), the FACTS settings ($\vec{u}_f$) and the slack variables ($\vec{u}_s$):

$$\vec{x} = \begin{pmatrix} V_1 \\ . \\ V_n \\ \theta_1 \\ . \\ \theta_1 \end{pmatrix} \qquad \vec{u} = \begin{pmatrix} \vec{u}_f \\ \vec{u}_s \end{pmatrix} \qquad (2)$$

To summarize, the OPF problem consists in minimizing (1) by taking into account the constraints set on the slack variables and on the settings of the FACTS. As stated above, the solution must also fulfill the load flow equations.

The optimization will be made iteratively: on the basis of the network model, the load flow and then (1) are estimated for each FACTS's settings combination. The solutions are the settings of the FACTS corresponding to the minimum of (1).

2. VSC-HVDC line

The FACTS device considered here is a VSC-HVDC line installed in the corridor (see figure 2). Main advantage of this technology is that active power transfer can be controlled, as well as reactive power on both sides of the line. To complete the formulation of the OPF method, one should define the physical setting variables of the VSC-HVDC and the relating constraints.

In the actual configuration (see experimental study), the VSC-HVDC line is connected to the slack node (see point 3.), and the active, reactive powers (P_{out}, Q_{out}) at the second node (node m) are effectively controlled by using vector control strategy [3].

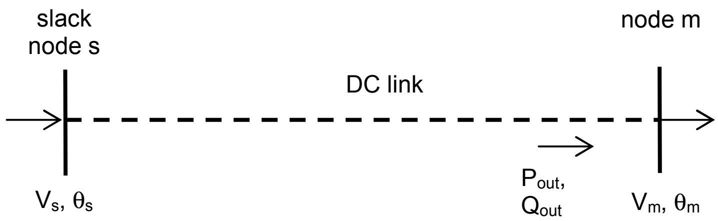

Figure 2. VSC-HVDC line

In controlling the power flow in the corridor, P_{out}, Q_{out} represents the effective influence of the VSC-HVDC line. So, their references values, P_{cout}, Q_{cout} are naturally defined as settings parameters, so that $\vec{u}_f = \begin{pmatrix} P_{cout} \\ Q_{cout} \end{pmatrix}$. The constraints on them are expressed by the two inequalities (P_{max} and Q_{max} are maximum rating values) :

$$\begin{aligned} -P_{\max} \le P_{cout} \le P_{\max} \\ -Q_{\max} \le Q_{cout} \le Q_{\max} \end{aligned} \quad (3)$$

As concerns the equality constraints, finally, the power flow equation at node m is expressed obviously in taking P_{out} and Q_{out} into account.

3. *Experimental Setup*

The OPF method described above is tested on laboratory equipment whose main piece is a 3 phases, 5 kVA analog simulator, comprising synchronous generators and loads (see figure 3). The following scaling factors have been defined:

- 400 V for 400 kV.
- 1 A for 1000 A.
- 1 VA for 1 MVA.
- 1 Ohm for 1 Ohm.

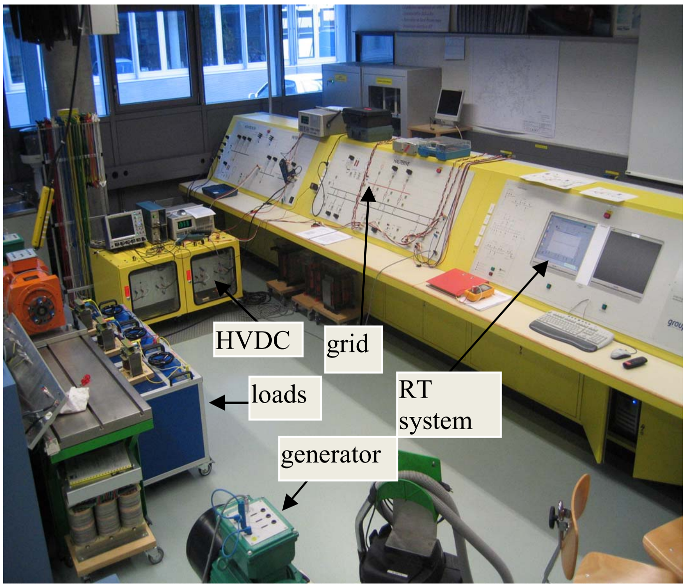

Figure 3. Analog simulator of the WACS system

The simulator is used to implement, in reduced scale, the north-south corridor with a slack node at the northern side Breite (see figure 2), and an equivalent (and variable) load at the southern bus Sils.

In this reduced scale model were embedded the measurement and actuating means that allow a real time control and supervision of the corridor: four PMUs and the VSC-HVDC line with maximum rating powers P_{max}=700 MW, Q_{max}=700 MVar, (see figure 4). Note that the two PST (Phase Shift Transformers) are actually bypassed.

Applying the OPF control method requires a model-based computation of the load flow in the corridor. So a suitable model should be selected. To this end, we use a comprehensive, validated model of the Swiss 400 kV, 17 nodes, which contain the corridor [4].

According to the OPF control method, the objective function is minimized iteratively, which will be performed on a periodical basis (sampling period of appr. 1 minute). The real time processing consists in the following operations:

- Interfacing the PMU's, which use a proprietary bus (ABB).
- Interfacing the VSC-VHDC, using CAN bus.
- Processing the HVDC settings (P_{cout}, Q_{cout}) according to the OPF control method.
- User interfacing.

The hardware/software used to perform these operations consists in a standard PC with embedded National Instruments I/O boards and LabView® 7.1 software. The OPF control method is programmed in LabView 7.1 with Matlab R2007a script in co-simulation, extending the available software resources.

III RESULTS

The weighting parameters defined in (1) are first chosen with the overall objective to maintain the nominal voltage of 400 kV. The parameter d is thus selected as much greater than the others, as shown in the following table:

TABLE I. WEIGHTING PARAMETERS

a	b	c	d
10	10	100	1000

With these parameters, the experimental WACS system is applied on the reduced scale model (of the corridor) whose equivalent terminal load is previously set to 1090 MW, 18 MVar. The resulting voltages at main nodes are shown in figure 5. They correspond to the powers P_{out} = 694 MW, Q_{out}=-700 MVar delivered by the HVDC line.

We observe a strong improvement of the voltage profile, obtained with the HVDC line actually used as a VAR compensator. Once the term C of (1) is minimized, the algorithm of the OPF control method begins dealing with the term A for losses reduction, which leads to a strong injection of the active power through the HVDC line, as a result of the fact that DC resistance of the latter is very low in comparison with the ones of the lines. As concerns the congestion (term B of (1)), there is no optimization since the lines are strongly under loaded.

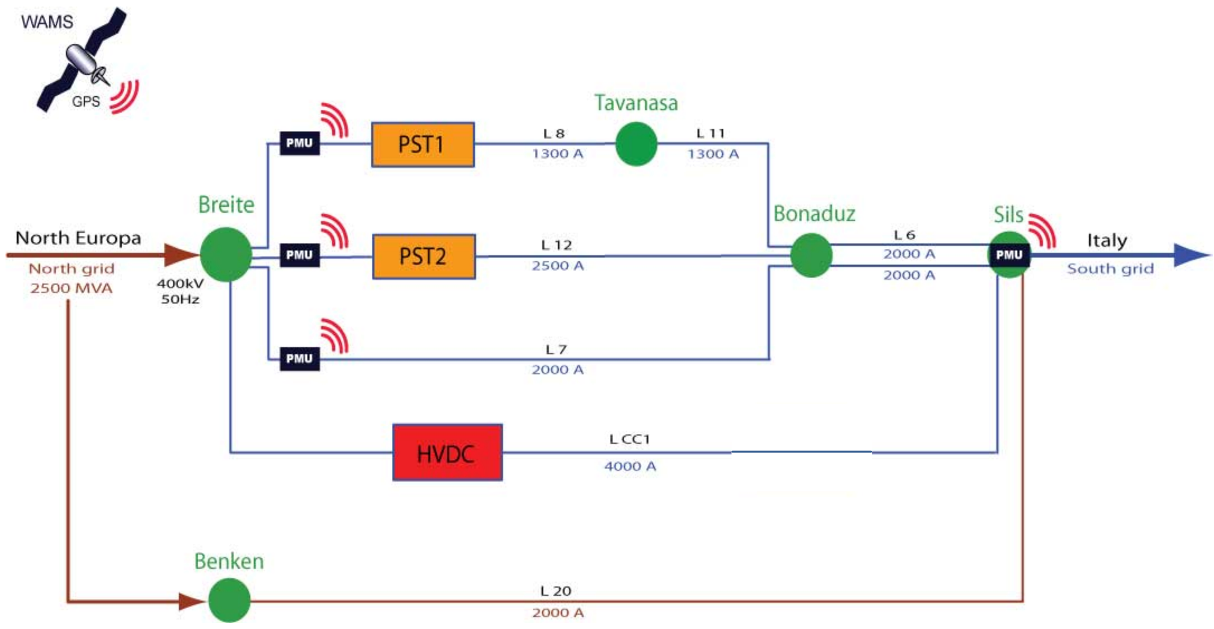

Figure 4. Reduced scale analog model of the alp corridor.

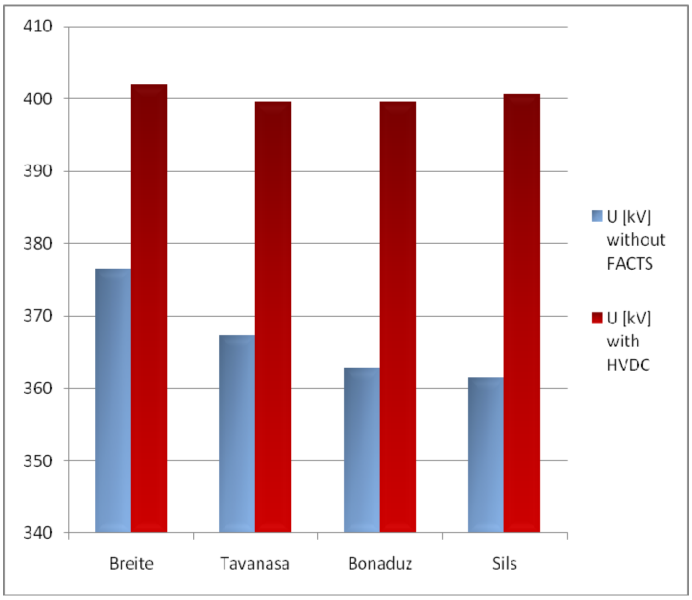

Figure 5. Voltage level at main nodes of the corridor.

In a second test, the weighting parameter c is over weighted in an attempt to maintain loads of lines L_7, L_8 and L_{12} under their maximum values of 560, 360 and 580 MVA, respectively. The chosen set is given in the following table:

TABLE II. WEIGHTING PARAMETERS

a	b	c	d
10	10	1000	1

The equivalent terminal load of the corridor is adjusted to 1351 MVA, a level at which one line (L_8) is at its maximum value when the HVDC line is bypassed, as seen in figure 6.

With the HVDC line active, the terminal load is increased until having, again, one of the three lines at its maximum capacity. This is achieved when the power flow is at its maximum P_{out}=700 MW, Q_{out}=-100 MVar in the HVDC line and of 1403 MVA in the three lines together (see figure 6). Operating in such a way enables an evaluation of the effect of the HVDC line on the power flow distribution in the corridor.

Although not as obvious as for the voltage, there is an improvement of power distribution in the corridor, which contributes not only in preventing any congestion, but also in increasing the transfer capacity in the corridor, of 50 MW in this test. Moreover, all the node voltages are kept within the specified tolerance interval of ±10%.

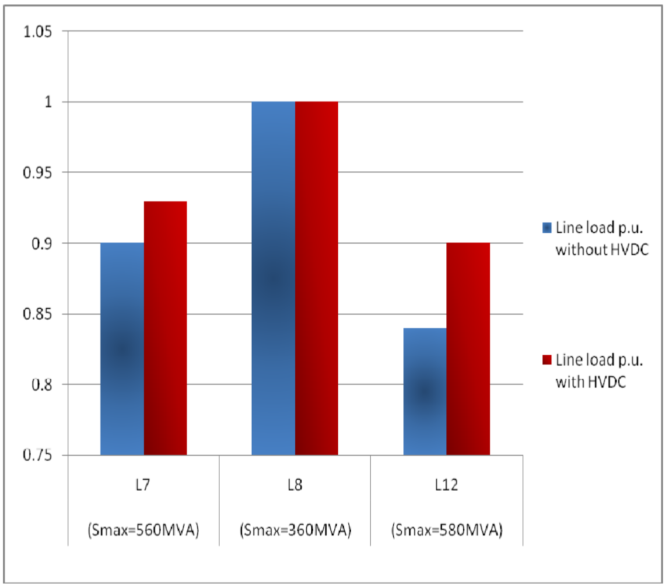

Figure 6. Load distribution in the corridor.

The setting of the reactive power Q_{cout} is adapted also in order to maintain the voltage level, which is done at best considering the congestion priority.

IV CONCLUSION

FACTS devices and particularly HVDC lines are excellent means to reduce congestions in critical grids. If PSTs are well known and introduced in many places, the return on investment for HVDC lines is less obvious for local projects. But the other advantages offered by the HVDC should increase more and more their number.

WAMS are becoming more popular in the world. To promote this technology even more, protection relays with time reference could look like PMUs and push the use of this technology. In this case, the question of accuracy will remain. Only the presence of data with voltage and current phasors (magnitude and phase angle) amplifies the control of the grids, especially with the use of hybrid state estimators [5].

WACS needs more reliable telecommunications [2]. Time is not come to link the control of power FACTS in closed loops where quantities of MVA would be dependent on the data transfer. This is a call for more research in this sense.

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