POWER SYSTEM OPERATION WITH WIDE AREA CONTROL INCLUDING REAL TIME ATC CALCULATION AND POWER FLOW CONTROL

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Abstract – This paper outlines practical experiences from the application of a wide area monitoring and control system in a real network environment. After outline a general architecture for system control, results of application for power flow optimization based on ATC calculation will be given. The network studies have been carried out utilizing different power system simulation tools and have been implemented in a real-time network model in laboratory scale.

Index Terms – *wide area measurement, wide area control, ATC, power flow control, HVDC, phase shifting transformers, real-time, optimal power flow*

I. INTRODUCTION

During the last years phasor measurement unit (PMU) based wide area monitoring systems (WAMS) have been evolved far beyond basic protection functions [1]. Today WAMS technology is seen as a powerful technology platform enabling dozens of new application in power system control and operation (e.g. [2]-[5]).

Many results of case studies and results of first prototype applications have been published during the last years. The next step towards an overall control system is to operate the WAMS in closed loop mode in order to control network controllers like phase shifting transformers, FACTS devices or HVDC schemes. This yields a wide area control systems (WACS) which is seen as a centralized instance in energy management systems to ensure safe and reliable system operation in case of multiple network controllers (see also [6]).

Consequently, the WACS technology can be seen as a platform for more secure operation of interconnected power systems. On top of the aforementioned applications, the WACS can be taken to setup a supervisory system that allows for the next generation of higher energy management system functions. In particular, this applies to those areas, which are supervised by different SCADA/EMS systems within an interconnected power system.

To further develop approaches for coordinated control of network controllers for power flow control (Power Flow Controller, PFC) a WACS has been setup within a reduced scale model of a part of the Swiss transmission grid (see Figure 1). In addition, this model comprises two phase shifting transformers (PSTs) and a High Voltage Direct Current (HVDC) scheme for power flow control purposes from *Breite* to *Sils*. The entire corridor is referred to as the *alpine corridor*.

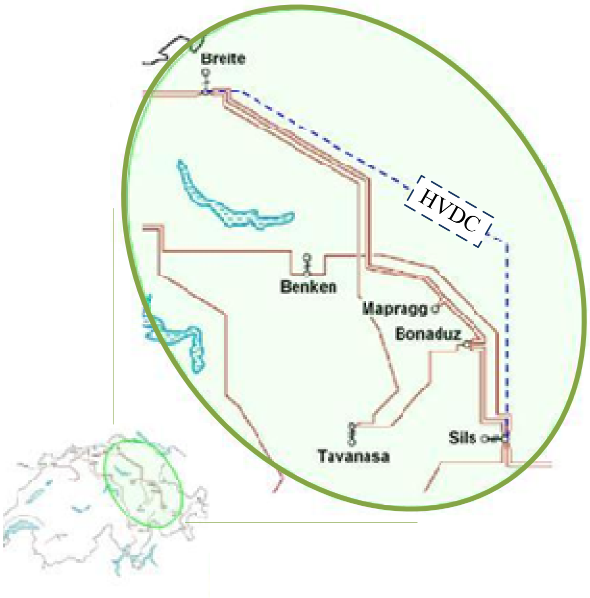

Figure 1: Considered part of the Swiss transmission system

This paper outlines the general approach of WACS architecture suitable to fulfill the coordinated control requirements based on optimal power flow as central instance. The practical realization focuses on the implementation with an objective function that comprises control for node voltage deviations and branch losses. After a general description of the approach an extended objective function is proposed that allows optimizing the available transfer capacity (ATC) in a given corridor. The general setup is aligned with a three layer approach considering primary equipment, secondary equipment and economic boundary conditions at the same time [7]. Results of lab tests will be given and discussed. They result from prototype implementation of the control functions covering the above mentioned objectives.

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II. NETWORK CONTROL APPROACH

A. General Approach

The operation of network controllers in interconnected power systems is a very complex task in three dimensions: control structure design, control objective definition and data availability. With respect to comprehensive system control all dimensions are of equal importance. Control structure design and control objective definition strongly depends on the application area. If it comes to applications in interconnected power systems a coordinated operation is of utmost importance. Most of the approaches have been based on the assumption of an ideal functioning of the network control system (data availability) and the existence of suitable objective functions. Today the control objectives are subjected to rapid changes. In the light of power market deregulation the power flow objectives may change from loss minimization to maximum import capacity from one operation cycle to another. A typical decomposition of control tasks in interconnected power system follows a three-layer-perspective where the layers interact with each other with respect to holistic system operation architecture (see Figure 2):

- Network layer reflecting the power system view from a macro-perspective
- Economic layer describing the economic perspective of a power system. This consideration ranges from market prices for electricity to corridor capacity allocation.
- Measurement layer representing the device level and corresponding measuring devices.

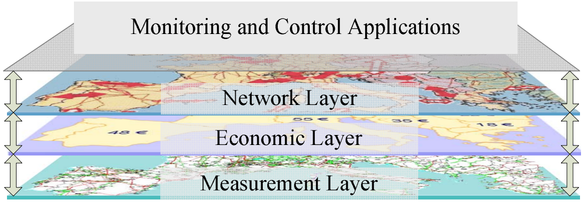

Figure 2: Arrangement of the three layer perspective in power system operation

Methods for the coordinated control of power flow controlling devices (optimal power flow, OPF), as introduced by Hug-Glanzman [8], can be associated with the network layer. For the integration of the economic layer into the network layer the OPF algorithm can be extended in two different ways. Firstly, the objective function can be extended by a certain expression that describes the "economic" value of a transmission path. The second possibility is to adapt the formulation of the optimization constraint. A possible third way however would be the combination of both.

In a first step the objective function will be extended by a term that comprises the actual loading of the controlled corridor. Eq. (1) describes the resulting objective function, which has to be minimized by adjusting the control variables in the utilized power flow controlling schemes in the network.

$$f(\boldsymbol{x},\boldsymbol{u}) = \sum_{\forall ij}\left(a\, p_{loss,ij} + b\,\varepsilon_{ij} + c\,\eta_{ij}\right) + \sum_{i=1}^{n_n}\left(d\left(u_i - u_i^{ref}\right)^2 + e\,u_i\right) + \sum_{\forall kl}\left(f\,\frac{s_{kl}}{s_{\max,kl}}\right) \tag{1}$$

In this objective function *ij* denotes the index of the lines *i* denotes the index of the nodes and *kl* denotes the index of those lines in the system which are subjected to be included into corridor loading optimization (e.g. the lines within the *alpine corridor*). The weighting factors *a* to *f* are utilized to adjust the importance of each criterion (Table 1).

Table 1: Overview on weighting factors

Factor	Objective
a	minimization of active power losses
b	keeping line loadings below 90%
c	keeping line loadings below 100%
d	minimization of voltage dev. from references
e	keeping bus voltages within acceptable limits
f	Weighting the loading of the controlled corridor

B. Adaptation for Corridor Control with HVDC

The network model that has been derived for real time simulation represents the power grid as North-South transmission in the eastern part of the Swiss transmission grid (Figure 1 and Figure 3 for a detailed network representation).

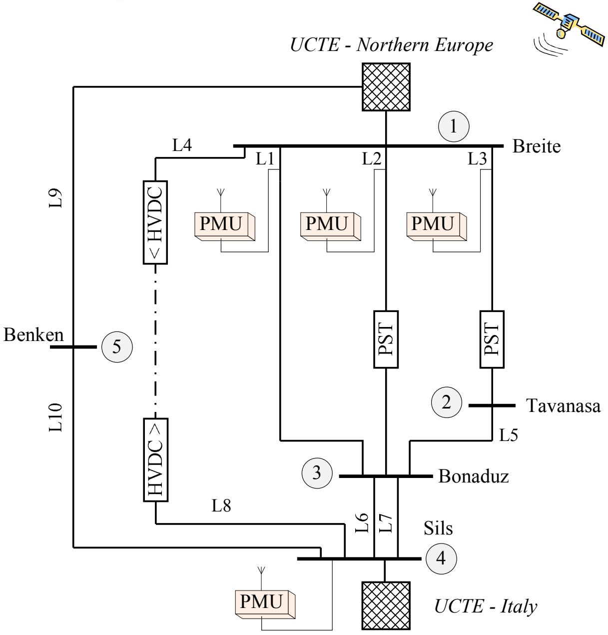

Figure 3: Topology of the transmission network

The interconnections to the UCTE grid have been modeled by voltage sources with corresponding internal impedances. Power flow control capabilities have been installed be means of one voltages source converter based HVDC (700 MVA) and two phase-shifting transformers, so that the power flow capability of the corridor between *Breite* and *Sils* (*Bonaduz*) is fully determined. The adjacent network has been modeled as an equivalent parallel line. The HVDC control capabilities have been considered in terms of nodal voltage sources providing active as well as reactive power at both ends of the scheme. The PSTs are represented by the additional voltage injection capability in the control vector.

The constraints for the optimization are defined starting from the evaluation of the branch power flows. With the HVDC one adds active and reactive power injections into the network at different places. For the node equations the following constraints have to be added:

$$p_{bus} + p_{load} - p_{gen} + p_{HVDC} = 0 \qquad (2)$$

$$q_{bus} + q_{load} - q_{gen} + q_{HVDC} = 0 \qquad (3)$$

The losses of the HVDC scheme have been added as separate constraint according to eq. (4):

$$\Delta p_{converter} = p_{DC,loss} \qquad (4)$$

C. Extension to ATC Calculation

The concept of net transfer capacity (NTC) and available transfer capacity (ATC) is used by network operators to schedule the network operation and identify congestions in transmission paths. The “day-ahead” determination of the ATC is based on notified and confirmed physical flow one day ahead of operation (see Figure 4).

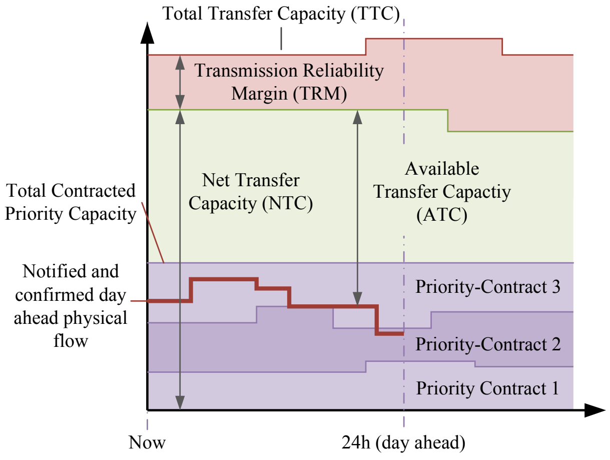

Figure 4: Graphical representation of the definition of the available transfer capability according to [9]

For each defined point in time, for example one hour, all the parameters are given in order to be able to organize the daily exchanges of power. When the transaction volume has been allocated and confirmed, the operator of the network guarantees the transactions and manages physical flows.

For most effective network utilization it is beneficial to maximize the ATC. With respect to the day ahead approach of ATC an OPF that determines the setpoints of power flow controllers can help to fulfill this requirement. Therefore the OPF equations need to be extended by an expression that takes the ATC into account [10]. The optimization variables will be extended by a factor λ according to eq. (5):

$$\boldsymbol{x}_{\mathrm{ATC}} = \left[\boldsymbol{x}^{\mathrm{T}}, \lambda\right]^{\mathrm{T}} \; ; \; \lambda \geq 1 \qquad (5)$$

The factor λ is used to scale the load at the receiving end of the corridor (*Sils*). During the case studies it has been shown that λ needs no limitation in the constraints. Hence, the constraints as formulated in eq. (2) and (3) need to be extended with respect to the scaling of the loading at the receiving end of the line:

$$\lambda\left(p_{load} - p_{gen}\right) + p_{bus} + p_{HVDC} = 0 \qquad (6)$$

$$\lambda\left(q_{load} - q_{gen}\right) + q_{bus} + q_{HVDC} = 0 \qquad (7)$$

It is assumed that the load factor cos φ remains constant at those load busses that are subjected to be scaled during ATC calculation. Finally, the objective function needs to be re-written taking into account a fourth term that comprises the nodal load balance at nodes which are relevant for ATC calculation. A new weighting factor *g* adjusts the importance of this criterion within the objective function:

$$f(\boldsymbol{x},\boldsymbol{u}) = \sum_{\forall ij}\left(a\, p_{loss,ij} + b\,\varepsilon_{ij} + c\,\eta_{ij}\right) + \sum_{i=1}^{n_n}\left(d\left(u_i - u_i^{ref}\right)^2 + e\,u_i\right) + \sum_{\forall kl}\left(f\,\frac{s_{kl}}{s_{\max,kl}}\right) + \sum_{\forall ATCi}\left(g\,\Delta p_{ATCi}\left(\lambda - 1\right)\right) \qquad (8)$$

III. SYSTEM SETUP

A. Network Model

This analogue simulation environment has already been utilized for various WAMS and WACS application studies [7], [11], [12].

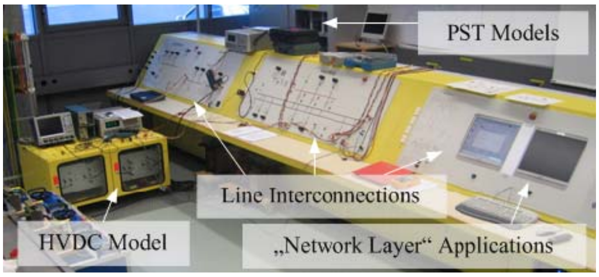

Figure 5: Picture of the laboratory setup

The network comprises two interconnections to the UCTE system which have been modeled as ideal network interconnections. For system studies typical faults can be applied to the system at each node and / or on the lines at predefined locations. The scale of the model is 1 kVA for 100 MVA and 400 V for rated voltage of the original system. In order to study the behavior of embedded HVDC one scheme has been integrated into the network. As reference for a parallel operation, a HVDC transmission line has been integrated between *Breite* and *Sils*. This is referred to as a model of a potential DC based *alpine corridor*. The HVDC scheme is based on voltage source converter technology. The PSTs have been modeled by series connected voltage sources that are fed out of shunt branches.

B. Wide Area Control System

For the supervision and control of the network model four PMUs have been used. They are integrated in the network and synchronized by a conventional GPS signal. The data processing is based on the software PSG by ABB [12], [14]. The phasor information is provided to an application and control server, where the control algorithms and general analysis functions are executed (Figure 6).

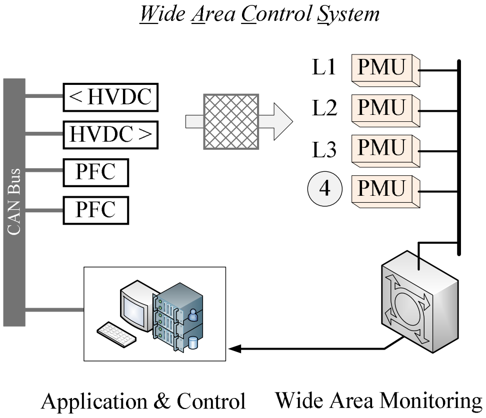

Figure 6: General structure of the wide area control systems

The lab control is realized by LabView software; higher analysis and control applications are utilizing a MATLAB environment. The control signals are distributed to the network controllers via a controller area network bus (CAN Bus). In the lab environment the PMU deliver the actual loading status of the network (see Figure 7).

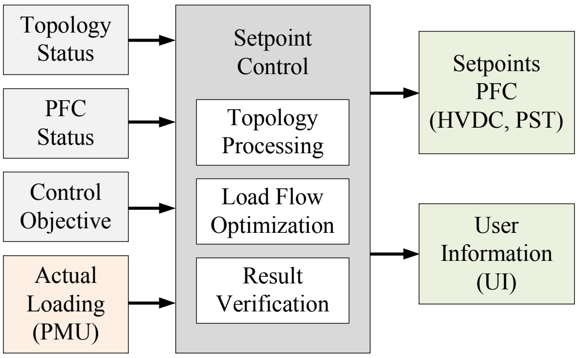

Figure 7: Overall structure of the coordinated control realization as realized in the lab environment

Topology status, network controller status and control objectives are manually pre-adjusted. This models the real application frame, where the operator defines the actual control target. By extracting data from the SCADA system, topology status and PST and HVDC status can be derived automatically. Based on this information the set point optimization comprises a topology processor, the OPF instance and a module for result verification.

In the utilized setup these routines have been realized in MATLAB. I.e. the OPF implementation provides a set of setpoints for the HVDC and PST controllers. Based on this set point the WACS utilizes the PMU information in order to realize the closed loop control.

IV. APPLICATION STUDY

As simulation scenario a reference loading situation from January 2007 has been chosen. The parameter set for the OPF calculation has been adjusted according to earlier studies to:

$$a = 10^6,\ b = 10^3,\ c = 10^5,\ d = 10^4,\ e = 5\cdot 10^2,\ f = 0,\ g = 1$$

The first calculation has been performed in order to validate the MATLAB implementation of ATC calculation. Therefore a network model has been implemented in two well known power system simulation tools, namely NEPLAN [15] and PowerWorld [16]. For this steady state calculation the HVDC scheme has been represented as load / injection model.

As indicated in Figure 8 the results are almost equal. The small differences between the results are caused by policies on power measurement and differences in the implementation of the network elements.

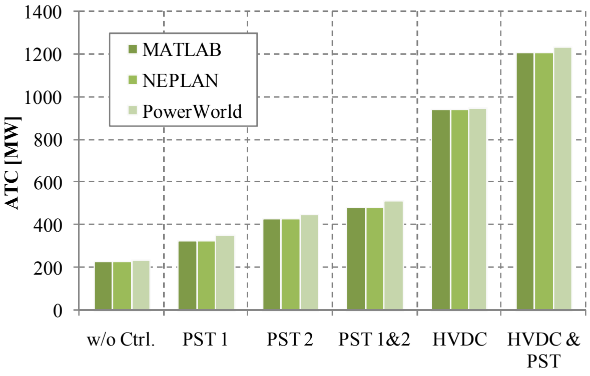

Figure 8: Results of ATC calculations with different tools

With HVDC control, the ATC increases considerably. This is quite natural since new transmission capacity is added. With all the PST used, the limits of existing lines are reached.

In a second simulation run it has been investigated how precise the online calculation of the ATC appears to be. For this purpose the base case scenario has been setup with the analogue simulator. Here the power that is injected into the node *Sils* (P_{Sils}) almost remains the same for all controller actions when the load is assumed to be constant at each simulation run. By activating the ATC optimization for the different power flow controlling devices the ATC increases.

In order to validate the proposed ATC calculation, the loading in the node *Sils* has been increased until one of the transmission devices was reaching its operational limits (P_{Sils}”).

This equals an experimental determination of ATC. Only very small differences between the calculated the measured ATC could be achieved (see Figure 9).

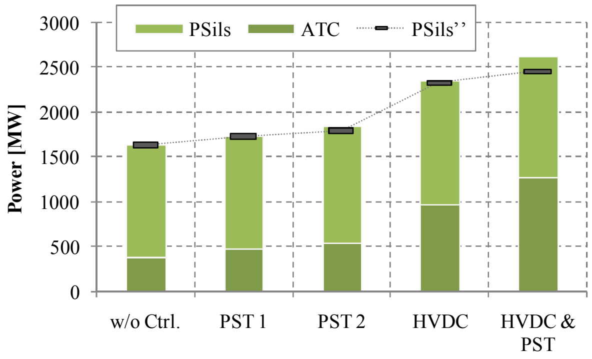

Figure 9: Increase of ATC by means of power flow control and comparison to "measured" ATC

When the resistive load is increased, the voltage at the node *Sils* will decrease. This effect impacts a bit the calculation of ATC.

V. CONCLUSION

In a reduced scale power system setup one application area of WACS has been analyzed: Coordinated control of network controllers with OPF with respect to increase the ATC of a transmission corridor. Therefore a well known approach for the coordinated control of power flow controllers has been adopted and extended by a term representing the ATC of a transmission corridor. The OPF serves as central controller instance that determines the setpoints for network controllers.

The investigated system represents a part of the Swiss transmission grid, namely the north-south-corridor in the eastern part of Switzerland. In order to show the control properties of the proposed controller setup two phase shifting transformers and one voltage source converter based HVDC scheme have been installed. A wide area control systems comprising four PMU serves as power flow control system for the corridor. The setpoints for the wide area control system are computed by an optimal power flow.

The basic functionality of the system has been demonstrated and validated by lab simulations and comparisons with simulations based on well known software simulation packages. The online calculation of the ATC has been shown to be very precise. This was validated by a measurement of ATC by means of continues load increase in the laboratory setup.

Future work has to be carried out, to further investigate the robustness of such an approach and to improve the response time if it comes to real applications where network controllers operate at remote installations.

VI. ACKNOWLEDGEMENT

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