

Possibilities of Multifunctional FACTS Application in the European Electric Power System under the Changing Conditions of the Liberalized Electricity Market

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1 INTRODUCTION

Competitive markets play a key role in modern industrial society. In many European countries, politicians set the stage for an open electricity market to facilitate competition with full access to grids. This has led to changes in load-flow patterns in transmission networks. The grid access is accompanied by large power transits even over long distances and unpredictable short-term changes of system conditions.

In particular interconnecting lines between different grids have been built for better reliability and efficiency through co-operation in case of faults. However, bulk power transport over long distances, as the present situation in Central Europe already shows, has not been the primary objective of connecting the transmission grids. A number of interfaces between national grids, as well as internal transmission elements like lines or transformers were not designed with sufficient capability reserve to fully meet the demand caused by the present trading transactions among market players. Since bottlenecks in the grids cannot be removed in short time, the Transmission System Operators (TSO) have to set up procedures and rules for allocating Net Transfer Capacity (NTC) for market actors.

Obviously open access has led to high uncertainty about capacity utilization and makes planning and operation of networks more difficult. Building new lines against uncertain future transmission needs is usually not possible in view of environmental aspects and economical consequences. However, the TSO are committed to eliminate existing trade restrictions in the course of their network reinforcement measures.

Therefore, one of the main challenges in the large European open access system is handling congestions in the grid. Another important aspect is system flexibility and

the ability to control or channel power flows for a maximum capacity utilization of the existing networks.

In this context, the conditions for the benefits of Load-Flow Controllers (LFC) like FACTS devices or Phase Shifting Transformers (PST) will change. The advantage of FACTS devices is the possibility of simultaneous application for additional control demands like voltage control, power oscillation damping or enhancing the transient stability. However there exist separate and sometimes conflicting design criteria for each application, e.g. favorable locations or necessary ratings, corresponding to Fig. 1.

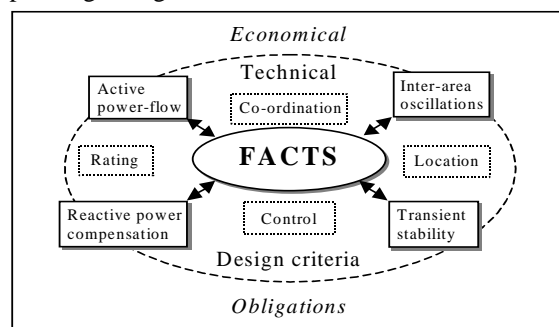


Fig. 1. Application and design criteria of multifunctional FACTS devices

For a multifunctional use of FACTS devices, comprehensive criteria for all desired applications are necessary, considering both the technical and the economical importance of the control functions. In the following, basic estimations of the present and future possibilities of FACTS application under the new market conditions will be highlighted.

2 PRESENT USE OF FACTS DEVICES

FACTS devices are used shunt connected like the Static Var Compensator (SVC) in Fig. 2a, in series connection to a line (Thyristor Controlled Series Compensator

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(TCSC)) in Fig. 2b or in combined shunt and series connection like the Universal Power Flow Controller (UPFC) in Fig. 2c.

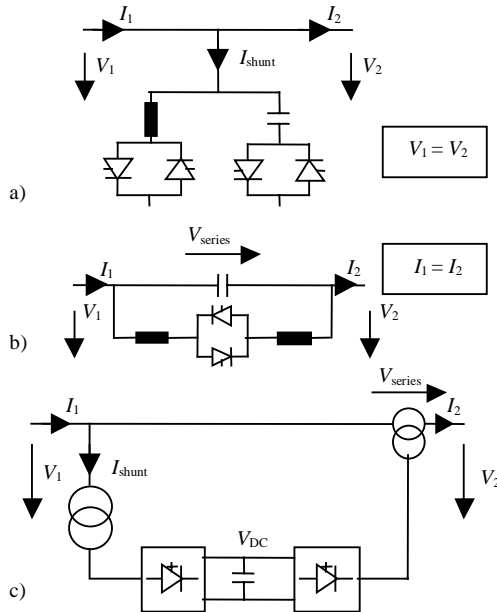


Fig. 2. Basic connection schemes of some FACTS devices
a) shunt connected: SVC
b) series connected: TCSC
c) shunt and series connected: UPFC

SVCs are used since many years for improving AC systems. More recently TCSCs reached commercial application. FACTS devices based on voltage source converters like the UPFC are the most modern solutions with only a few pilot projects. Major examples of FACTS application presently in operation are:

- Relocatable Static Var Compensators (RSVC): Penn and some more substations, UK
The RSVCs normally control the terminal bus voltage and thus contribute to maintain the network stability and power transmission capability. In addition, they can be used for power oscillation damping. If the network configuration changes permanently they can be relocated within short time to other substations where they can operate more efficiently [1].
- TCSC: Kayenta, USA
To allow increased loading of transmission lines the TCSC is controlled to maintain either a fixed line impedance or to regulate the transmission line current or power flow [2].
- TCSC: Stoebe, Sweden
The TCSC was implemented in a complex system involving several series compensated transmission lines. It efficiently reduces the risk of subsynchronous resonance and thus allows an enhanced use of the transmission lines above the limits imposed previously [3].
- UPFC: Inez, USA
The UPFC was installed in the Inez area because of its critical need for increased power transfer capability and voltage support. The UPFC contributed to improve the network as expected [4].

3 LOAD-FLOW CONTROL POTENTIAL

3.1 PARALLEL FLOW REDUCTION

During the bilateral agreed power exchange, the power partly flows over third party networks according to the network impedances. These parallel flows can be undesirable if several control areas, which are involved in transactions, are affected. Fig. 3a shows the natural flow in a part of Germany where three TSO adjoin. The loop flow is caused by the constellation of power plant locations, the network impedances and the centers of demand.

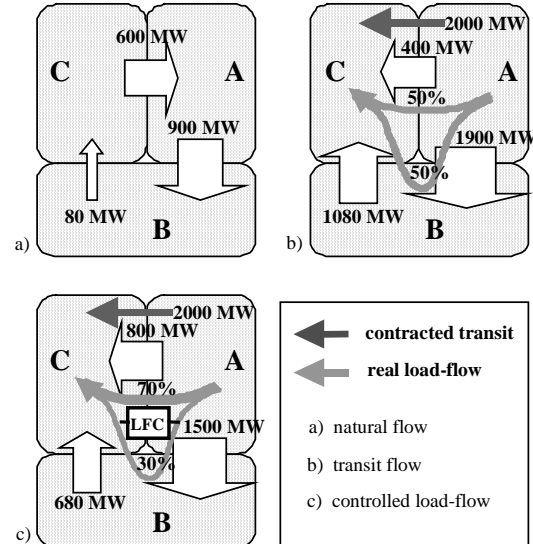


Fig. 3. Congestion management with LFC

In Fig. 3b a superposed transit has been assumed from control area A to C. However, 50 % of this transit spread over network B, thus leading to a higher loading of the interconnecting lines between A-B and B-C as well as on the network elements in B. The losses in network B increase significantly.

Apart from conventional network reinforcement measures, LFC like PST or series connected FACTS devices constitute a conceivable alternative to decrease the parallel flow. Fig. 3c shows the assumed transit scenario with a LFC on the interconnecting line A-C. As this load-flow control enables an increase of the direct transit between the networks A and C, the parallel flow across network B is distinctly reduced to 30 % of the transit power. If this does not give rise to congestions in A or C, their trade volume can even be increased by this measure. However, the losses and the need of reactive power increase. Usually for European grid conditions, this need can be satisfied with the reactive power output of existing power plants.

3.2 SYSTEMATIC INCREASE OF THE NTC

Due to the distinctly increasing power exchange in the European electricity market and the limited NTC, demanded power transits have to be evaluated regarding their feasibility and their effects on the reliability. If bottlenecks prevent a reliable system operation under consideration of contingency cases, these demanded transits must be rejected. However, in areas with a mul-

titude of expected transit scenarios LFC can be implemented to increase the NTC and therefore enable the demanded transits.

A systematic assessment of LFC locations requires quantitative criteria for the aptitude to increase the NTC for the evaluated scenario. A sensitivity analysis based on the DC load-flow provides constant and therefore comparable dependencies of the load-flow deviations independent of the operating point of the power system and is therefore suitable for fast and extended optimization algorithms.

The constant dependencies between the power shift from one line to the surrounding lines are based on the Generation Shift Distribution Factors (GSDF) [5] and can be derived from the inversion of the sparsed nodal admittance matrix. The automated alteration of this matrix in combination with a fast re-inversion based on the Woodbury formula enables the determination of superimposed power shifts caused by various LFC, which are automatically sited at favorable locations by an optimization algorithm.

The NTC between areas of a power system can be estimated with the lowest margin of all lines between the actual loading and the respective current limit combined with the summarized sensitivities to all increasing and decreasing power injections. Its possible enhancement with a certain number of additional LFC, their locations and the NTC for the maximum capacity utilization of the controlled system can also be determined, as well as the restrictions considering contingencies.

A detailed description of these procedures can be found in [6]. As the DC simplifications only affect the determination of the necessary number and favorable locations of LFC, but not the load-flow calculations, its use is not a restriction of accuracy.

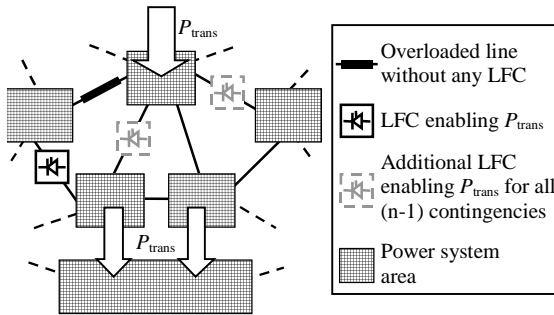


Fig. 4. LFC demands for a transit scenario in the UCTE

For the example in Fig. 4 of an additional offshore wind power injection of $P_{trans} = 2500$ MW at a strong node near the coast of the UCTE and a transit demand to the southern tie lines of the power system, its feasibility and the additional transfer capacity will be discussed.

In the uncontrolled scenario, one transmission line exceeds its maximum permissible loading. In this example, one LFC is able to unload the bottleneck, because the power shift does not lead to additional overloaded branches. Therefore the scenario is feasible with one LFC. The evaluation of contingency cases leads to a demand of two additional LFC to fulfill the (n-1) crite-

rium for all lines and generators in the power system area, though this additional expense could be reduced by tripping the transit in the worst contingency cases.

Without outages, the transfer capacity in addition to the evaluated transit power P_{trans} is about 50 MW. If an additional LFC is used, it can be further increased by about 720 MW. A second additional LFC leads only to an increase about 90 MW. Because a further power shift from the resulting bottleneck is not possible, the maximum capacity utilization of the power system is therefore reached for this transit scenario with three LFC and a total transfer capacity of about 3360 MW.

Nevertheless, a practical installation of LFC demands an evaluation of various power system utilization scenarios with an assessment of alternative solutions to increase the NTC.

3.3 HANDLING OF INCREASING WIND POWER INJECTIONS

Beside the problem of undesired parallel flows over third party systems and the limited NTC for the trade with electrical energy, the handling of the future wind power injections seems to be a highly demanding challenge. In all probability the off-shore technology will be able to generate and supply wind power in large scale into the German transmission grid.

An enormous increase of the installed wind power has taken place especially in the North of the German transmission network. The installed wind power capacity in Germany has increased over a period of the last five years from 1 400 MW to an amount of 6 300 MW until the end of the year 2000. For the year 2005 an installed capacity of 12 500 MW is expected. Corresponding to the available areas in the North Sea and the Baltic Sea a sum of additionally 10 000 MW installed off-shore wind farm capacity is possible. These planning figures in relation to the current peak load in Germany of about 80 000 MW form the framework conditions for the future transmission and distribution network development.

In any case a reinforcement of different voltage levels with new transmission lines is required to handle the high additional loading of the power system and integrate the wind power generation in Germany. However, the installation of LFC can provide an additional alternative to prevent network congestions. The use of FACTS devices as LFC can be advantageous for the dynamic and hardly predictable wind power injections especially from on-shore wind farms.

Investigations have shown that the reactive power output of the existing power plants reduced to the technical active power minimum is high enough to maintain the voltage stability in the transmission and the involved distribution networks connected to the on-shore wind farms. Therefore compensators are generally not required to produce reactive power for wind power transportation.

However, off-shore wind power utilization requires the installation of an economic sea cable transmission sys-

tem. The application of both DC and AC technology is possible. The economic break-even point depends on the distance between the off-shore wind farms and the network connection node. If an AC application is chosen a reactive power compensation at the off-shore as well as at the on-shore side is absolutely essential. Shunt connected FACTS devices can be useful to provide an adapting reactive power consumption according to the varying wind power injection.

3.4 COMPARISON OF REINFORCEMENT MEASURES

If the investment for a network reinforcement with additional transmission lines is feasible from the authority approval point of view, this measure is generally preferential compared with an implementation of LFC. Otherwise the installation of power shifting devices can provide an interesting alternative, particularly if an increase of the NTC is demanded in short time. Moreover LFC can be a temporary alternative to improve the network until the reinforcement measures can be carried out. For rarely changing steady state load-flow control, normally PST are reasonable LFC. However, series FACTS devices can be demanded for fast and frequent power shift requirements according to high wind power deviations.

To justify the application of LFC, the TSO balances the value of the increased transmission capacity and the grid flexibility against the resulting investment costs. Several characteristics of PST or FACTS devices as control speed, removability, shunt or series connection or load dependency can be decisive for identifying the most appropriate LFC. However, the examples in chapter 2 provide evidence that different FACTS devices can be applied economically under special grid conditions. To ensure an economic capital investment, further applications of FACTS devices like power oscillation damping should be scheduled and considered in the economic valuation.

Clearly, detailed budgetary cost information can only be obtained from specific decision-making studies including specified offers from manufacturers. However, a detailed estimation of specific costs for existing installations can be found in [7].

4 DYNAMIC STABILITY IMPROVEMENT

4.1 INTER-AREA OSCILLATIONS IN THE UCTE/CENTREL

The interconnected operation of many national energy grids enables an exchange of large amounts of energy over long distances and undoubtedly provides economic advantages. However, the physical nature of synchronous power systems causes significant dynamic interactions between the subnetworks and power plants.

Inter-area oscillations are low frequency rotor swings between remote groups of generators. They are a common problem world-wide in extended power systems. Many TSO experience an increased loading in parts of their transmission system, which can and sometimes do

lead to poorly damped inter-area oscillations in the range of 0.2 - 0.8 Hz. This subject has been treated intensively for a long time for power systems with stability problems caused by network extensions or high transmission loadings.

Inter-area oscillations can even severely restrict system operations by requiring the curtailment of power transits as an operational measure. If the power swings lead to cascading outages of transmission lines, widespread system disturbances like the black-out in western North America on August, 10th of 1996 can occur.

Therefore the understanding of the global stability behavior of large interconnected power systems is an important aspect for system planning and operation. After the expansion of the UCTE to the CENTREL (Poland, Czech Republic, Slovakia and Hungary), recordings of the Wide Area Measuring System (WAMS) have shown significant changes of the dynamic system behavior, as shown in Fig. 5. This was principally predicted by simulation studies carried out before, where poorly damped inter-area oscillations were indicated. Without further damping measures, future power transits can be restricted due to the significant influence on the stability.

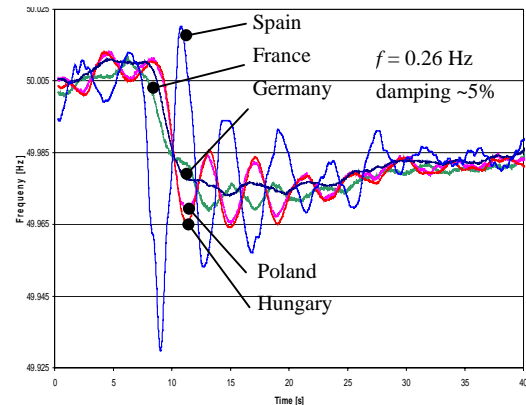


Fig. 5. Inter-area oscillation in the UCTE/CENTREL after a power plant outage of 900 MW in Spain

In near future, the South East European Network will be connected to the UCTE, consisting of the temporarily disconnected areas of Greece and the former Yugoslavia as well as the areas of Bulgaria, Romania and the West Ukraine (Burshtyn-Island), which are currently under investigation and in test operation. Further synchronous connections with the areas of Turkey and the Mediterranean Ring are currently under discussion. All these network extensions demand detailed considerations of the small signal, the transient and the voltage stability to guarantee the stability of the future Trans European Synchronously Interconnected System (TESIS).

4.2 GLOBAL POWER SYSTEM MODELING WITH DYNAMIC EQUIVALENTS

A reliable examination of power swing phenomena in the current and future TESIS and the siting and optimization of additional damping measures require a dynamic model of the entire power system. Currently, dynamic simulations are carried out by different utilities

based on different network models. However, data exchange does not take place regularly, though the consideration of the whole system based on up-to-date data is necessary for detailed investigations.

Despite of the increasing performance of modern computers, dynamic simulation studies are very time consuming. Particularly, the use of controller design techniques requires smaller system models.

In many cases, dynamic equivalents provide sufficient accuracy for the investigations. Furthermore, the system size is smaller with the advantage of a better simulation time performance and less data requirement. In the competitive electricity market TSO are not interested in sharing important data. In this situation, dynamic equivalents provide the possibility to cover information and therefore prevent the direct access while their effect can still be considered.

Recently, the association of the German transmission system operators (DVG) started a research project about equivalencing methods [8]. The objective of this project was to develop special methods for producing equivalents for each subsystem separately, which can be composed to a whole system model. Each operator of a subsystem could prepare an equivalent for his part, which will then be used by other TSO (Fig. 6).

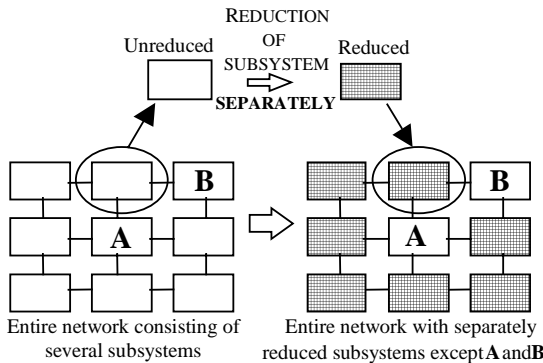


Fig. 6. Dynamic equivalents by reducing subsystems separately

It has been shown, that with the new equivalencing techniques developed in the project, the system size can be reduced up to 50 % without considerable losses of accuracy. Because the critical system modes remain, controller design can be carried out based on the reduced model.

4.3 EIGENVALUE ANALYSIS

Based on an accurate dynamic power system model, inter-area oscillations and the damping potential of advanced Power System Stabilizers (PSS) or FACTS devices can be observed by simulation in the time domain. However, pure time domain analysis is a non-systematic, time and cost intensive method. From the time domain curves it can often not be determined which generators are involved in a particular mode of oscillation and how it can be damped effectively.

A systematic approach for the solution of these problems is the eigenvalue analysis. The advantage of this method is the representation of the oscillatory behavior of the complex power system in one single calculation.

However, the eigenvalue analysis is only valid for small perturbations around the steady state equilibrium point of the linearization. For large perturbations, a combination of eigenvalue analysis and time domain simulation is required. In order to get reliable results for all relevant system conditions, different characteristic load-flow scenarios must be taken into account.

A complete overview about the theory of eigenvalues can be found in [9]. The basics for the determination of inter-area oscillations and the siting and design of PSS or FACTS controllers are summarized in the following.

Each linearized dynamic system can be represented by the state space matrix equations in (1), where \underline{x} is the state vector, \underline{y} the output vector, \underline{u} the input vector, \underline{A} the state matrix, \underline{B} the input matrix, \underline{C} the output matrix and \underline{D} the feedforward matrix.

$$\dot{\underline{x}} = \underline{A} \cdot \underline{x} + \underline{B} \cdot \underline{u} ; \quad \underline{y} = \underline{C} \cdot \underline{x} + \underline{D} \cdot \underline{u} \quad (1)$$

The eigenvalues λ_v of the system can be calculated from the characteristic equation (2), where \underline{I} is the identity matrix.

$$\det(\underline{A} - \lambda_v \underline{I}) = 0 \quad (2)$$

The system modes are complex eigenvalues $\lambda_v = \sigma_v \pm j\omega_v$, where ω_v characterizes the frequency $f = \omega_v/2\pi$ and σ_v the damping behavior of the oscillation. For a stable power system it is required that all eigenvalues show negative real parts σ_v . Moreover, it is desired that all electromechanical oscillations are damped out as quickly as possible. The common index for system damping is the relative damping in (3).

$$\zeta_v = \frac{-\sigma_v}{\sqrt{\sigma_v^2 + \omega_v^2}} \quad (3)$$

In its physical meaning a relative damping ratio of 5 % indicates, that after five periods of oscillation the magnitude is damped to approximately 20 % of the initial value. Eigenvalues with $\zeta < 5$ % are considered to be weakly damped. All oscillations in a power system should have a minimum relative damping ratio between 3 and 5 %.

4.4 FAVORABLE LOCATIONS FOR DAMPING CONTROLLERS

Eigenvalue analysis not only determines damping and frequency of the oscillations but also allows an assessment of mode observability and controllability.

$$\underline{A} \cdot \underline{\phi}_v = \lambda_v \cdot \underline{\phi}_v ; \quad \underline{\psi}_v^T \cdot \underline{A} = \lambda_v \cdot \underline{\psi}_v^T \quad (4)$$

The right eigenvector $\underline{\phi}_v$ to a given eigenvalue λ_v is calculated with (4) and describes the magnitude and the phase angle of a particular mode in the system states and thus its observability in the corresponding generators. The left eigenvector $\underline{\psi}_v^T$ measures the efficiency of controller actions effecting different oscillations. Therefore, the left eigenvector can be utilized for the determination of controller siting.

$$p_{iv} = \underline{\phi}_{iv} \cdot \underline{\psi}_{iv} \quad (5)$$

The association of a generator with a particular inter-area mode is measured with the participation factor

p_{iv} in (5), which is defined as the participation of the generator state x_i in the mode λ_v .

Better indicators for the siting of a damping controller are the residues of the transfer function matrix $G(s)$ which can be calculated directly from the matrices of the state space equations [9]. This method considers the individual transfer functions of the different types of damping controllers. For example the most suitable transfer function for a SVC is shown in (6), because the SVC changes its reactive power ΔQ_{SVC} and therefore modulates the node voltage ΔV_{node} . Equivalent transfer functions can be defined for other types of damping controllers.

$$G(s) = \frac{\Delta V_{node}}{\Delta Q_{SVC}} \quad (6)$$

Eigenvectors, observability and controllability information of a specific mode can be visualized in bar, phasor or geographic diagrams. As an example, an expected rotor mode shape of an European inter-area oscillation after the connection of the South East European Network is shown in Fig. 7. It visualizes the elements of the right electromechanical eigenvector plotted at the locations of the corresponding generators on a geographical map and provides an overview of the direction and intensity of generator swings referring to the selected mode. Furthermore, swing nodes and antinodes can be easily identified providing information about favorable controller locations.

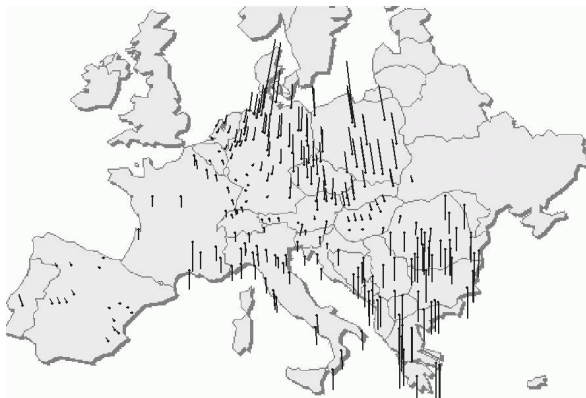


Fig. 7. Rotor mode shape plot of an European inter-area oscillation

Similar diagrams of relevant transfer functions show suitable locations for a particular type of damping controller. This method is reliable and proven and was applied for a number of system planning projects all over the world. Some examples can be found in [10].

Generally, inter-area oscillations can be characterized with a high amplitude of frequency deviation in the outlying areas and a low frequency deviation at the oscillation node in the inner area according to Fig. 5. Therefore, the location of generators for advanced PSS or shunt connected FACTS devices is the most favorable in the outlying areas.

The main task of a series FACTS device normally is the steady state load-flow control. In these cases the location will strongly depend on its power shift potential

according to chapter 3.2. However, optimal locations for the damping of inter-area oscillations can also be determined with the eigenvalue analysis. Unlike the frequency, the amplitude of power deviations caused by inter-area oscillations reaches its maximum at interconnection lines in the middle of the power system. If load-flow controlling FACTS devices are located in series to these interconnection lines for enhancing the NTC between the inner grids, they can be also quite effective for power system damping.

4.5 CASE STUDIES FOR THE DAMPING OF THE FUTURE TESIS

The stability study concerning the connection of the South East European Network provided by the DVG in 1999/2000 has shown the demand of a sufficient strengthening of the network coupling [11]. At least three independent interconnections are necessary for a reliable inclusion of these areas. The determined frequencies of the inter-area oscillations have values down to 0.22 Hz or even lower with a critical low damping ratio.

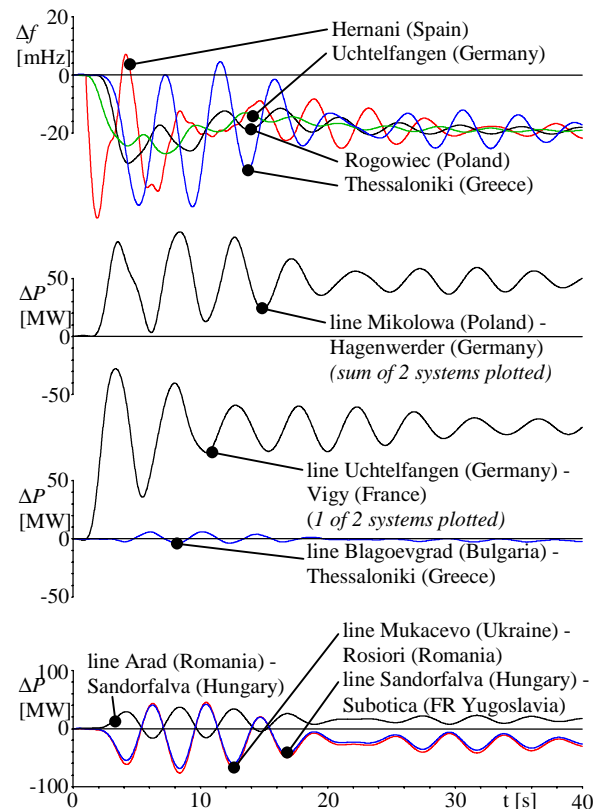


Fig. 8. Oscillation of the South East Network connected to the UCTE after a power plant outage of 1000 MW in Spain

Fig. 8 shows the frequency and power oscillations at various locations after a generator outage of 1000 MW in Spain. An acceptable relative damping of these oscillations in the range of 3 to 5 % with PSS can only be reached by advanced controllers with various input signals [12]. The effect of several PSS with frequency and power deviation inputs at favorable locations in the areas of Spain and South East Europe is shown in Fig. 9 [13].

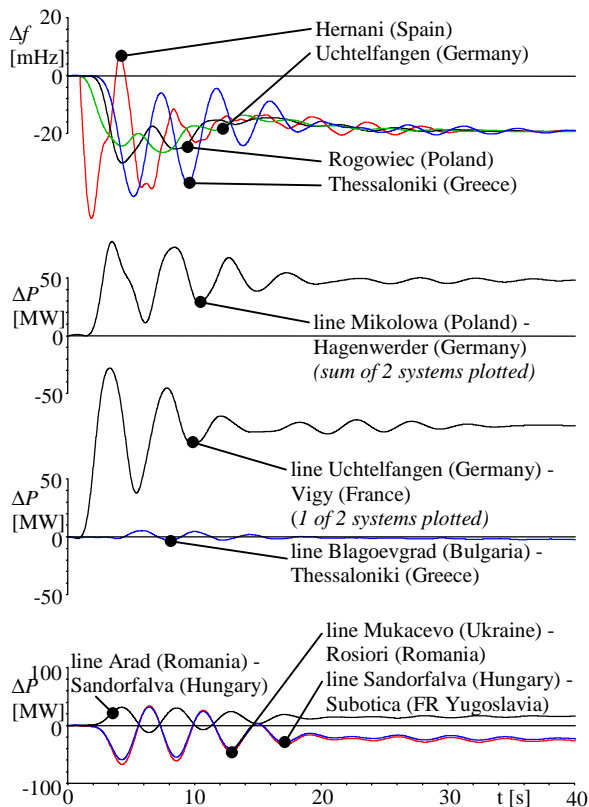


Fig. 9. Damping improvement with advanced damping controllers

Similar results have been achieved with shunt connected FACTS devices in the Eastern part of the power system. Examinations with series FACTS devices located in the center of the grid also show good damping potentials.

If the frequency of the oscillations will decrease significantly below 0.2 Hz, FACTS devices clearly become more advantageous because of their direct generation of the damping power in the correct phase, while PSS only have an indirect influence over the exciting system and the voltage controller of the generator.

Moreover, former investigations of the phenomena of inter-area oscillations have shown a high influence of the voltage level of the power system to the frequency and the damping of power swings [14] [15]. Thus for improving the dynamic system behavior measures to stabilize the voltage level are also effective.

4.6 CO-ORDINATION REQUIREMENTS

In contrast to the planning stage, the real operation requires a robust and autonomous controller response to contingencies and changing load-flow patterns without the need of current global system state information. According to the restricted availability of real-time measured values, controllers exclusively using local measurable values are necessary. Multifunctional series connected FACTS devices need to simultaneously support steady state load-flow control, power swing damping and the exchange of control power for frequency control.

The power system control center should only define the control tasks of the FACTS devices and transmit the

setpoint values. However, pre-determined parameter adjustments according to long-term topology or load-flow changes can enhance the damping potential.

5 CONCLUSION

The changing conditions in the liberalized electricity market provide new possibilities for FACTS application in the European transmission system. The increasing demand of NTC between different grids according to wind power injections and energy trade can be satisfied with the installation of additional transmission lines and LFC. The more expensive FACTS devices can be an interesting alternative to the conventional PST, if frequent adaptations of the load-flow are necessary.

The decreased damping of inter-area oscillations according to the extensions of the TESIS can be improved by advanced PSS, series FACTS devices or dynamic voltage stabilizers like shunt connected FACTS devices. Alternatively the multifunctional use of load-flow controlling FACTS devices can be utilized, if the devices are sited at favorable locations for both applications.

Generally, a consideration of multifunctional FACTS devices beside conventional reinforcement measures can be worthwhile for the future operation of the European power system.

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