Proceedings of the Sixth IASTED International Conference
EUROPEAN POWER AND ENERGY SYSTEMS
June 26–28, 2006, Rhodes, Greece

MODELLING AND APPLICATION OF FACTS DEVICES AT THE INTERCONNECTED SOUTH EAST EUROPEAN REGION

Dr Nikolaos Athanasiadis, Senior Engineer, Hellenic Transmission System Operator, Asklipiou 22, Krioneri, 145 68, Athens, nathanasiadis@desmie.gr

Professor Dimitrios Bandekas, Technical Educational Institute of Kavala, Department of Electrical Engineering, Agios Loukas, Kavala, kavala12000@yahoo.gr

Magafas Likourgos, Senior Lecturer, Technical Educational Institute of Kavala, Department of Electrical Engineering, Agios Loukas, Kavala

Efstathios Athanasiadis, Energy Consultant, Leonidou 23, Xarilaou, 54250, Thessaloniki, Greece, efstathios_athanasiadis@yahoo.co.uk

ABSTRACT

This paper presents FACTS controllers that can be used for effective congestion management under the consideration of liberalized European Electricity markets. The main steps of a complete congestion management process are presented including preventive, correcting and reacting congestion management systems and series FACTS controllers are applied to real network conditions in the South East European region. By taking advantage of these devices it is shown that congestion management can be a major area for the application of power flow controllers while at the same time system security can be better maintained.

KEY WORDS

Modelling, simulation, FACTS, Congestion, South Europe

1. Introduction

The liberalisation of the European Electricity Market brought major changes and new challenges to the Transmission System Operators (TSOs). In this new context, each producer and consumer wishes restrictions on trade to be reduced as much as possible. Power flows become higher and more dynamic while a significant increase in congestion arises on the European grid when transmission line capacities cannot always cope with energy flows.

The ongoing liberalization that requires the unbundling of production, transportation, trading and distribution of electricity markets results in a continuous increase of power flows in the grid that become difficult to predict.

Due to physical constraints in meshed power systems, transmission lines are often only utilized at a fraction of their individual limits. To improve customer benefit one possibility would be to add to the value of the transmission lines by increasing the amount of transported energy over the lines.

Flexible AC Transmission System (FACTS) devices are capable of electronically controlling the power flow along a transmission line, by handling electrical parameters as nodal voltage, nodal angular difference and line series impedance.

Flexible AC transmission systems allow the increase of the overall utilization of an electrical power network by controlling the power flow.

It is well known that transmission system power capabilities, such as the Available Transmission Capacity (ATC), can be directly influenced by series compensation. In this paper the operating principles of major connected FACTS devices (Solid State Series Compensators-SSSC, Unified Power Flow Controller UPFC) will be analyzed and implemented using real case scenarios to control the power flows in the second UCTE zone and to secure the operation of the power systems in this area under the N-1 criteria.

The paper addresses the issue of a complete congestion management process that includes various ways of congestion elimination such as preventive, correcting and reacting congestion management and presents results of implementing controllable devices in a liberalized electricity market.

2. The value of FACTS controllers in power systems

FACTS technology is very young. FACTS devices are now being installed in many places all over the world since they offer an economic way to flexibly compensate long lines interconnecting distance regions. For FACTS devices- such as unified power flow controller (UPFC) or controlled series capacitors-there will definitely be an increasing demand in the new electricity transmission systems. The overall value of such devices can easily be linked to the gained transfer capacity between the interconnected regions. In highly meshed grids e.g in continental Europe the added value of a FACTS device is more difficult to determine.

Not many publications can be found in the literature with a view of demonstrating the value of a FACTS device in congestion management systems. There are several publications on the ideal placement of devices with specific objectives:

[1] and [2] are using different indices to show ideal placement options to reduce total system power losses, which will decrease loop flows. In the above the results differ depending on the objective function chozen. In [3] the special case where FACTS devices are used to optimise a hydrothermal coordination problem is discussed concluding that overloaded lines are not always the best candidates for installing controllable devices. [4] and [5] set up FACTS models and simulated them using the EMTP simulator. [6] discussed the capabilities of the UPFC and [7] introduced UPFC in voltage stability studies.

These examples show clearly that there are not many contributions in the literature to determine the value of a FACTS devices for congestion management purposes. This should help decision makers to get an integral view over the different areas where FACTS devices can have in modern power systems.

Static VAR compensation is already widely used and other fields will become more important as the liberalization of transmission systems advances further and the TSO or ISO have no longer direct control over generation.

To control power flow for increasing transfer capability the thyristor controlled series capacitor (TCSC), the Solid State Series Compensator (SSSC) or the unified power flow converter (UPFC) are best suited. The UPFC is of course the most versatile device and can be used for all areas, but can also be the most expensive since it needs series and parallel transformers [4-8].

In table 1, we provide an overview of most used FACTS devices and their typical applications. The decision of what device to install has to be made depending on the system configuration and the actual needs of an ISO or TSO.

FACTS	Static stability	Dynamic stability	Increasing transfer	VAR compensation
SVC	+	+		+
STATCOM	+	+		+
SSSC	+	+	+	
TCSC	+	+	+	
UPFC	+	+	+	+
IPFC	+	+	+	

Table 1

3. Congestion management systems

Congestion management systems can be classified in three different time ranges [9] as seen in figure 1 and descibed in the following graph

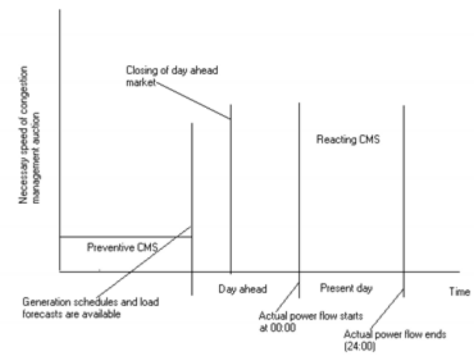

Figure 1

3.1 Preventive Congestion Management Systems

The preventive Congestion Management Systems (CMS) may be subdivided into long-term and short-term CMS. Both kinds of preventive CMS aim to avoid the development of generation schedules which could lead to congestion situations.

Long-term preventive CMS refers mainly to power system planning. Short-term preventive CMS are measures which are usually taken on a day ahead basis like market splitting or auction market. With an increasing deregulation of electricity markets, fixed structures with long-term contracts etc. disappear and the markets become more flexible. Thus, it becomes increasingly uncertain and difficult to perform some of the preventive CMS measures. Therefore, it will be more important in the "completely-deregulated" future to correct the generation schedules by means of correcting CMS.

3.2 Correcting Congestion Management Systems

In liberalized electricity markets it seems to become common that on the day ahead of the actual power flow the pattern of the generator power feeding and the pre-dicted load arc known to the network operator. After this point of time up to the actual power flow, it is possible for the network operator to perform security calculations and if necessary to avoid congestions. In this case congestion means the violation of thermal and voltage limits under consideration of (n-l)-contingencies in the system.

The cost free actions (operating costs are not taken into account), which can be taken by the network operators to solve the congestion problems, are as follows:

- Topology change
- Changing of transformer tap position
- Operation of conventional compensation devices
- Set-point variations for FACTS

If these actions are not sufficient to solve the congestion problem, it is necessary that the network operator spends money for advanced measures.

The network operator has to pay the power plants for the energy delivery. Also normally the power plants have to pay the network operator to reduce their energy delivery. It is quite obvious, that the power plant is just willing to pay as long as the price has not reached his generation costs, where he starts to realize profits. It is in general the task of the network operator to guarantee by other means the power supply of the customers of the power plant who has reduced his energy delivery.

3.3 Reacting Congestion Management Systems

Reacting CMS are those measures which are taken on the day of service immediately after a congestion has occurred due to e.g. network faults, disturbances, major schedule variations. In order to avoid a critical situation for the entire network, it is neccesary that the network operator has the right to use all technical possibilities to solve the problem. This includes those measures which have been available before the deregulation (e.g primary and secondary reserve, re-dispatch etc.) The main thing which has changed is the financial side of the transactions.

After a stable operating point has been reached again, it is possible to strart the same measures as for the correcting CMS, if there is the danger of a permanent congestion situation.

4. Basic operating principles of FACTS controllers

4.1 Solid State Series Compensator (SSSC)

The SSSC controller consists of a solid-state Voltage Source Converter (VSC) with several GTO thyristor switches, or any other semiconductor switches with intrinsic turn-off capability valves, a dc capacitor, a transformer, and a controller [11]. The number of valves, and the various configurations of the transformer depend on the desired quality of ac waveforms generated by the SSSC. A frequent approach involves PWM-controlled VSCs where the quality of the ac output waveforms depends on the switching frequency.

The line side transformer winding is connected in series, placing the VSC alsoeffectively in series with a transmission line, and thus allowing series compensation of the line. The SSSC is used to generate or absorb reactive power from the line, and hence can be utilized as a transmission line power flow controller. Basically, it generates on its output terminals a quasi-sinusoidal voltage of variable magnitude in quadrature with the transmission line current, if the SSSC losses are neglected. Thus, the line injected voltage emulates a capacitive or an inductive reactance in series with a transmission line, which increases or decreases the total transmission line reactance, resulting in a decrease or increase of the power flow in the transmission line.

In general, the SSSC can be viewed as analogous to an ideal synchronous voltage source as it can produce a set of three-phase ac voltages at the desired fundamental frequency of variable and controllable amplitude and phase angle. It also resembles a synchronous compensator, as it can generate or absorb reactive power from a power system and can, independently from the reactive power, generate or absorb real power if an energy storage device instead of the dc capacitor is used in the SSSC.

The SSSC is typically restricted to only reactive power exchange with the nearby ac system, neglecting the small amount of real power used to cover the circuit and switching losses, because of the relatively small SSSC capacitor. If the dc capacitor were replaced with an energy storage system, the controller would be able to exchange real power with the ac system and compensate for the transmission line resistance.

Figure 2 shows a functional model of the SSSC where the dc capacitor has been replaced by an energy storage device such as a high energy battery installation to allow active as well as reactive power exchanges with the ac system. The SSSC's output voltage magnitude and phase angle can be varied in a controlled manner to influence power flows in a transmission line. The phase displacement of the inserted voltage Vpq, with respect to the transmission line current Iline, determines the exchange of real and reactive power with the ac system.

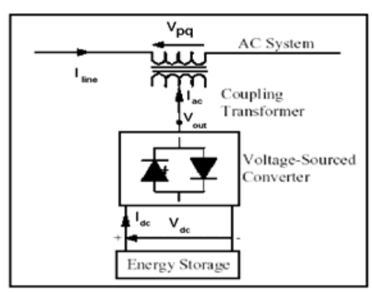

Figure 2

The SSSC output voltage phase angle is correlated to the line current phase angle by plus or minus few degrees for example, to account for changes in the dc voltage. It has to be noted that the injected SSSC voltage Vpq is different from the SSSC output voltage VSSSC, due to the voltage drop or rise across the series transformer reactance. This voltage difference between the injected and output SSSC voltage can be small in the case of small transmission line currents, but it can be significant in high loading conditions.

Considering that the angle between the SSSC output voltage and line current is approximately 90 degrees, the SSSC real power should be small compared to the reactive power. This is expected, since the real power going into the SSSC is used only to cover for the losses and charging of the dc capacitor.

The losses in the SSSC circuit are due to the transformer windings and due to the switching of the GTO valves.

4.2 Unified Power Flow Controller (UPFC)

This paragraph is concerned with the UPFC controller where two synchronous VSCs employed in combination are used for dynamic compensation and real time control of voltage and power flow in transmission systems.

DC terminals of both converters are connected to a common dc capacitor. The basic three-phase UPFC scheme is shown in Figure 3 [11]. Figure 3 shows that if the series branch is disconnected, the parallel branch comprised of a dc capacitor, VSC-1 and a shunt connected transformer corresponds to a Static Compensator or STATCOM. Since the STATCOM can generate or absorb only reactive power, the STATCOM output current is in quadrature with the terminal voltage.

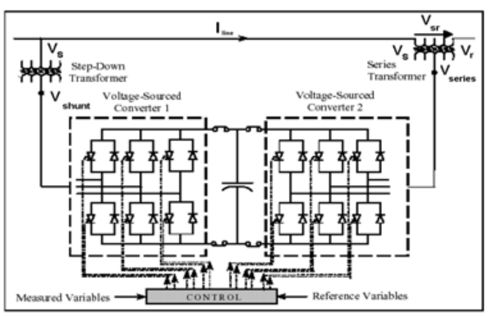

Figure 3

If the parallel branch is disconnected, the series branch comprised of a dc capacitor, VSC-2 and a series injected transformer corresponds to a SSSC. The SSSC acts as a voltage source injected in series to the transmission line through the series transformer; the current flowing through the VSC is the transmission line current, and it is a function of the transmitted electric power and the impedance of the line. The injected voltage VSR is in quadrature with the transmission line current Iline with the magnitude being controlled independently of the line current. Hence, the two branches of the UPFC can generate or absorb the reactive power independent of each other.

If the two VSCs are operating at the same time, the shunt and series branches of the UPFC can basically function as an ideal ac to ac converter in which the real power can flow in either direction through the dc link and between the ac terminals of the two converters. The real power can be transferred from VSC-1 to VSC-2 and vice versa, and hence it is possible to introduce positive or negative phase shifts between voltages Vs and Vr The series injected voltage VSR can have any phase shift with respect to the terminal voltage VS. Therefore, the operating area of the UPFC becomes the circle limited with a radius defined by the maximum magnitude of VSR, i.e., VSR,max.

The VSC-2 is used to generate the voltage VSR at fundamental frequency, variable magnitude and phase shift. The harmonic content in the voltage VSR depends on the design and control of the VSC. This voltage is added in series to the transmission line and directly to the terminal voltage VS by the series connected coupling transformer. The transmission line current passes through the series transformer, and in the process exchanges real and reactive power with the VSC-2. This implies that the VSC-2 has to be able to deliver and absorb both real and reactive power.

The shunt-connected branch associated with VSC-1 is used primarily to provide the real power demanded by VSC-2 through the common dc link terminal. Also, since VSC-1 can generate or absorb reactive power independently of the real power, it can be used to regulate the terminal voltage VS; thus, VSC-1 regulates the voltage at the input terminals of the UPFC.

Another important role of the shunt UPFC branch is a direct regulation of the dc capacitor voltage, and consequently an indirect regulation of the real power required by the series UPFC branch. The amount of real power required by the series converter plus the circuit losses have to be supplied by the shunt converter. Real power flow from the series converter to the shunt converter is possible and in some cases desired, in this case, the series converter would supply the required real power plus the losses to the shunt converter.

The UPFC's rating and hence, the amount of the real and reactive power that can be exchanged with the power system are determined by ratings of its shunt and series converters. The UPFC rating is basically a sum of the shunt and series converter ratings.

As the possible UPFC role and performance depend on its power rating, it is important to distinguish between the functional control capabilities and the related rating requirements. For example, a UPFC that has as its primary role the control of power flow will certainly have a different rating than a UPFC used for damping.

The power rating of a converter is derived from the product of the maximum continuous operating voltage and maximum continuous operating current The series converter maximum voltage is determined based on the function that the UPFC is designed to perform. It could be power flow control in the transmission line or power oscillation damping. The maximum current is usually taken to be the thermal line current limit, which basically implies that the converter switches have to be designed to withstand that level of current to be compatible with line.

The shunt converter has two functions: one is to supply real power to the series converter and the other one is bus voltage control. The maximum continuous rating should take into account the amount of reactive power needed for voltage control at the point of connection with the ac system.

5. Example and test results

One aspect of how FACTS devices can improve inter-regional transmission capacity and eliminate congestions will be illustrated by an example based on a real case scenario. The scope is to get the set point values of the installed FACTS devices which allow to decrease the overloadings present in the system. A graphical representation of this network configuration is illustrated in Figure 4.

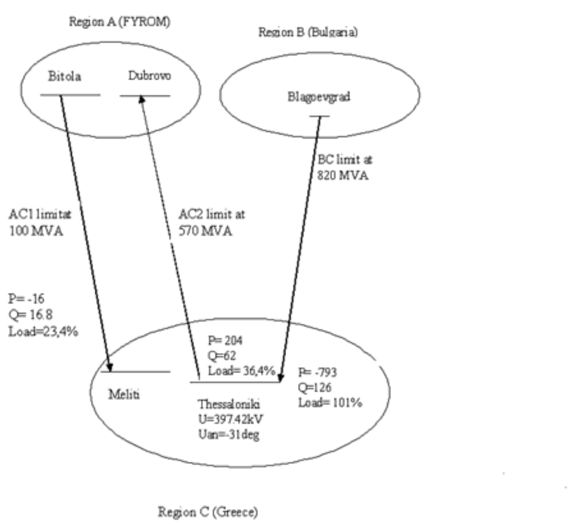

Figure 4

In region B (Bulgaria) there is a large amount of nuclear power generation installed leading to low electricity prices. Region C (Greece) has high prices due to a deficit in generation. Starting condition is the base case, without any FACTS controllers installed and the ratings for the interconnected lines are the ones considered in table 2. In order to test the security of the zone and to check the profitability of the proposed devices a major 400kV line for the stability of the whole South European region region, the Nis-Kosovo was considered out of operation (critical N-1 point in the region).

We will show how the installation of controllable devices make possible to control the power flows imported into region C without decreasing security limits. This will increase the overall market efficiency since trading will be less constrained by unavailable transfer capacity.

Line	Dubrovo-Thess	Blagoevgrad-Thess	Meliti-Bitola
Rating	570	820	100

Table 2

In figure 4 the base case of the system is presented. Region C is connected through a 400kV line with region B (the line Blagoevgrad-Thessaloniki or BC) and with a 400kV line (the line Dubrovo-Thessaloniki or AC2) and a 150 kV line with region A, FYROM (the line Bitola-Meliti or AC1). In the presence case 605 MW are imported into region C.

Since the strongest link represents the two 400kV lines connecting region C with A and B it is evident that placing a FACTS device at the bus Thessaloniki of region C leads to good results.

The PSS/E power systems analysis software is used for the load flow studies with and without the FACTS controllers. In table 3, we can see the results of the analysis where in the base case, the line Blagoevgrad-Thessaloniki line without any FACTS controllers installed, reached 101% of the line limit. The total import of area C is 605 MW. In the same table, we can see the results of the analysis using a UPFC in the line Dubrovo-Thessaloniki. The objective of the UPFC is to control the power flow at 83.3 MW for the line Thessaloniki-Dubrovo The result of this UPFC implementation is done by using for the shunt part of the UPFC 100.6 MVA reactive compensation (to control the voltage at Thessaloniki substation) while additionally there is a 29.6 power transfer though the DC link.

Case	**LINES**		
	AC-1	**AC-2**	**BC**
Base case			
Load	23.4%	36.4%	101%
Trans (MW)	16	-204	793
UPFC (set point of series part at 83.3 MW in Dub-Thess)			
Load	42%	23%	93%
Trans (MW)	-29	-83	729
SSSC (set point of series part at 83.3 MW in Dub-Thess)			
Load	43%	14%	92%
Trans (MW)	-28.8	-83.2	729.0
UPFC (set point of series part at 20.0 MW in Dub-Thess)			
Load	74%	5%	88%
Trans (MW)	-74	-20.0	699
UPFC (set point of series part at 652 MW in Blag-Thess)			

SSSC (set point of series part at 83.3 MW in Dub-Thess)			
Load	41%	16%	83%
Trans (MW)	35	-83.1	652.3

Table 3

The voltage of the series transformer of the UPFC is rated at 24,4% of the rated transmission line voltage (400kV the Dubrovo-Thessaloniki). The ratings of the shunt and the series connected parts of the UPFC were 120 MVA and 40 MVA respectively.

Moreover due to the high cost of the UPFC we can use a SSSC instead, with the series connected transformer voltage of its model rated at the 23,7% of the 400 kV rated transmission line. A Thyristor Controlled Series Capacitor (TCSC) with an equivalent reactance of 0,2844 p.u will have the same results with less cost. So, instead of the expensive UPFC, we can use a SSSC rated at 40 MVA or a TCSC rated at 40 MVA inductive and 80 MVA capacitive rating. Of course, for the final decision, we have also to take into account the superior performance of the UPFC over the SSSC and the risk of ferroresonance problems that the TCSC may develop.

The above results illustrated the cases where the setpoint of the series transformer was 83.2 MW. In table 3 there is also the case using a value of 20 MW for the series transformer. In this case for the UPFC the series voltage equals 36% of the rated one (the 400kV). Also at the same table it is shown that we can use both UPFC (in Blagoevgrad-Thess) and SSSC (in Dubrovo-Thess). The power flow results were illustrated in table 3 where we used series voltage of 4% for the SSSC and 52% for the UPFC (of the rated 400kV).

In all cases, the total import of country C was 605 MW. From the above results it can be noticed that the objective has been reached by the FACTS devices: the overloadings have been eliminated in a (n-1)-criteria analysis.

6. Conclusion

This paper discussed the concept of implementing FACTS controllers in a complete congestion management process. While market based techniques, such as market splitting and auctions can be used before the day ahead, FACTS controllers can be applied in transmission networks in order to eliminate congestion at the day ahead stage (correcting congestion management). In this paper, the application of FACTS devices in the South East European region for real case scenario was illustrated and various results from the analysis taken were shown.

FACTS devices constitute different advantages for different stakeholders, e.g generators, TSOs, consumers and it is the aim to include all these into a unique congestion management process.

Acknowledgements

The authors want to thank the Greek Ministry of Education and the European Union for funding the research though the Arximidis II, ΕΠΕΑΕΚ II program. The research was sponsored by the European Union.

References

[1] C Canizares, Z Faur, Analysis of SVC and TCSC controllers in voltage collapse, *IEEE Transactions on power systems, vol 14, No 1 , 1999, pp 158-165.*

[2] C Canizares, Power flow and transient stability models of FACTS controllers for voltage and angle stability studies, *IEEE Panel on Modeling, Simulation and Applications of FACTS controllers, Singapore , 2000*

[3] E. I Oliveira, I.W Marangon, K.C De Almeida , Allocation of FACTS devices in hydrothermal systems, *IEEE Transaction on Power Systems, vol 15, 2000,pp 276-282.*

[4] X Lombard, P. G. Therond, Control of Unified Power Flow Controller: comparison of methods on the basis of a detailed numerical model , *IEEE Transaction on Power Systems, vol 12, No 2, 1997, pp 824-830.*

[5] L Gyugyi, C. D Schauder, S. L Williams, T.R Rietman, D.R Torgerson, A. Eldis, The Unified Power Flow Controller: A new approach to Power transmission Control , *IEEE Transaction on Power Delivery, No 2, 1995, pp 1085-1097.*

[6] F D Galian, K Almeida, M Toussaint, J Griffin, D Atanackovic, B T Ooi, Assessment and Control of the impact of FACTS devices on power systems performance, *IEEE Winter meeting, Baltimore USA, 1996, pp 256-258.*

[7] N Dizdarevic, S Amborg, G Anderson, Possible alleviation of voltage stability problem by use of Unified Power Flow Controller, *UPEC 97, Manchester, pp 975-978.*

[8] N Athanasiadis, 1999, Modelling, Control and Design of FACTS, Custom Power devices and variable speed drives for transmission and distribution system architectures, *PhD thesis, University of Strathclyde, Glasgow, UK.*

[9] J Brosda and E Handschin, C Leder, Hierarchical visualization of network congestions, *Proc of the 14th Power Systems Computation Conference, Sevilla, Spain, June 24-28, 2002.*

[10] D Dr Zimmerman, K Dr Imhof and M Emery, 2002, Modular Day Ahead Congestion Forecast as a first step of a Congestion Management process, www.etrans.ch

[11] E Uzunovic, 2001, EMTP, Transient Stability and Power flow models and controls of VSC based FACTS controllers, *PhD thesis, University of Waterloo, Canada.*

[12] J Brosda and E Handschin, Sequential quadratic programming and congestion management, *Electrical Enginnering, Vol 83, Springer, 2001, pp 243-250*

[13] L Gyugyi, K Sen, C.D Schauder, The interline power flow controller concept: A new approach to power flow management in transmission systems, *IEEE Summer meeting, San Diego, 1998.*