

Use of Facts Devices for Congestion Management in a Liberalized Electricity Market

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Summary - This paper presents an overview over different areas where Flexible AC Transmission Systems (FACTS) devices can improve transmission system efficiency especially under the consideration of liberalized electricity markets. Furthermore, a network example, based on realistic data, is shown where the installation of a thyristor controlled series capacitor (TCSC) increases the transfer capacity into a region considerably while maintaining security margins. This can help to reduce or even eliminate congestion in a transmission network.

Keywords - FACTS, congestion management, liberalized electricity market, available transfer capability (ATC), TCSC.

1. INTRODUCTION

In a liberalized electricity market, the transmission capability of a transmission system is of an economical value to the network company. This company has a natural monopoly combined with the commission to maximize the benefit for its customer while giving a reasonable profit to its owners. Due to physical constraints in the surrounding network, the 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 these lines. Additionally, there will be a gain in overall market efficiency since more energy trading can take place between competing regions with different price structures. Flexible AC Transmission Systems (FACTS) devices allow the increase of the overall utilization of an electrical power network by controlling the power flow. Since installations of FACTS devices require huge investments with costs similar to new transmission lines

(see [1]) the effect of higher transfer capability only, can not necessarily justify these new installations. Therefore, it is evident that one has to consider all possible aspects, that add to the value of FACTS devices in a transmission system: static and dynamic stability, increased transfer capability, increased system reliability, regained controllability over the power flow for Independent System Operators (ISO) or Transmission System Operators (TSO) in a liberalized electricity market, and the possibility of relocation.

The paper is divided into three sections: First, we will give a systematic overview over all areas where controllable devices such as FACTS can contribute to the value of an electric transmission system. Second, the aspects of congestion relief will be illustrated in an example based on a “real-world” problem in the field of inter-regional electricity transmission. In the third section the *results* of the analysis of the problem described in the example will be given. Apart from the quantitative simulation results, we will also discuss qualitative issues that may add to the *value* of controllable devices. The paper presents results of an ongoing research project in the area of the value of controllable devices in a liberalized electricity market. Finally, we discuss the future work to be carried out on this topic.

2. THE VALUE OF FACTS DEVICES

Except for static VAR compensators (SVCs) FACTS technology is very young. SVCs are installed in many places all over the world since they offer an economic way to flexibly compensate long lines interconnecting distant regions. But even if not many of the other FACTS devices - such as unified power flow controller (UPFC) or controlled series capacitors (CSC) - are installed today there will definitely be an increasing demand for controllable devices in the new electricity

transmission systems. Today there are a few installations which help smoothing operations mainly in countries with long distance interconnections (e.g. Brazil, USA, Scandinavia, UK): They help to increase the transfer capacity of the congested links. The overall value of such a device 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. Each case has to be evaluated individually [1]. To justify the investments, it will be necessary to include not only one, but all aspects such as increased stability considerations into the investigations. Furthermore, the liberalized electricity market will make it increasingly difficult for ISOs or TSOs to operate their system in an optimal way since they no longer have the means to redispatch or control (e.g. the reactive power output) generation units. FACTS devices can help ISOs to regain control over the power flow in their system.

Not many publications can be found with an integral view on the value of a FACTS device. However, there are several publications on the ideal placement of devices with specific objectives:

[2], [3], and [4] are using different sensitivity indices to show ideal placement options to reduce either real power flow over a particular line or total system power losses, which will decrease loop flows. It is evident that the results differ depending on the objective function chosen.

In [5] 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.

These examples show clearly that a methodology to determine the value of a FACTS device is needed. This methodology should help decision makers to get an integral view over the different areas where such a device adds value to an existing system.

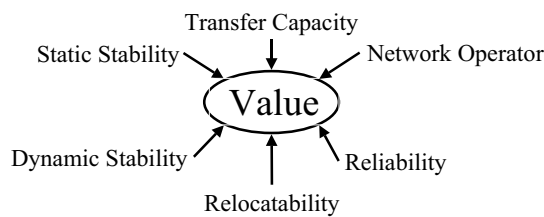


Figure 1 - Areas that add to the value of FACTS

In the following we will discuss the five main areas: *Static stability* - retrieve line overloading, *dynamic stability* - improve damping of system oscillations, *transfer capacity* - increase transfer capacity over certain links, *reliability* - reduce risk of loss of load or generation, *added value for ISO* - provide ancillary services, and *relocatability* - the possibility to move a FACTS device to a new location.

2.1. Static Stability

Today, electric distribution systems are normally designed based on a (n-1)-security criterion. Meaning that the system must have enough security margins to operate even if one of the elements, e.g. a transmission line, fails. With congested inter regional links this normally leads to the maximum allowed transfer capacity being considerably below the maximum power flow physically possible.

In [6] the use of TCSC to relieve line overloads during contingencies and thus increasing the static stability of the whole system is proposed. They show the feasibility with different configurations on a 14-bus network. However, they make also clear that not only network configuration and parameters influence functionality of the controllable devices but also load and generation patterns. Therefore, accurate load and generation forecasts will be an important part in the decision to invest in FACTS devices.

Another way to increase the static security is given in [7]: By installing a TCSC or an UPFC at one end of a parallel path, the security of the system can be increased considerably, especially the loss of load probability.

2.2. Dynamic Stability

Surprisingly, there are more publications in the area of increased dynamic stability by FACTS devices.

In [8] is shown that the voltage stability can effectively be improved in a three-machine system by installing an UPFC. Especially the shunt branch of the FACTS device contributes to stability even if only local signals are used.

[9] also shows that it is possible, with the help of control Lyapunov functions, to use series devices for system damping only by using locally measurable signals.

On the other hand, it is suggested in [10] that UPFC controllers using global information are more effective for power system damping enhancement than those using local information. They are arguing that global information has stronger observability for power system oscillations than local information. It has to be shown with more practical test systems whether local signals are adequate to improve dynamic stability with controllable devices.

An example of a typical installation is shown in [11]: Since early 1999 two small (6% controllable compensation of the lines) TCSCs installed at both ends of the Brazilian north-south interconnection (500 kV, 1,020 km) damp effectively the 0.18 Hz interarea oscillation mode.

FACTS can also be used to improve power quality such as reducing voltage dips, phase shifting etc. In [12] there is a good overview with simulation results where an UPFC is used to reduce voltage dips and harmonics at the node.

2.3. Transfer Capacity

In the new world of liberalized electricity markets system operators have no longer direct means - neither in short nor long term - to control the power flow by generator dispatch, since generating companies can decide on how and where energy is produced independently of the system operator. This implies changes in the geographic generation-load pattern and result in the necessity to change network topology since certain paths will get congested, and consequently traded transactions cannot always take place. For the system operator there are two fundamentally different solutions: Either reinforce the network by building new transmission lines or add flexible devices to leverage and control power flow. Building new lines especially in highly populated regions is due to environmental concerns often not feasible.

As shown in [13] and [14] it is possible to use FACTS (CSC or UPFC) to improve network performance and thus reduce load or generation curtailments and, at the same time, reduce system losses by minimizing loop flows.

2.4. Reliability

Electric power distribution system reliability is defined as the ability to deliver uninterrupted service to customers. In [15] it is shown that it is possible to increase reliability for the consumer considerably by installing TCSCs at the distribution delivery point without increasing short circuit current levels.

The same authors suggest in [7] a method to determine the change in loss of load probability and loss of load expectation. They show that the installation of an UPFC in one of two different parallel transmission lines significantly improves the reliability for the network fed by those two lines.

2.5. Added Value for ISO/TSO

In today's interconnected electric transmission systems the problem of load frequency control is often solved by automatic generation control (AGC): Electro-mechanical machines change their electric power output automatically if the system frequency or tie-line powers deviate from desired values in order to restore scheduled operation. Even if the time constants are quite long (more than ten seconds), this worked quite well until today: The reasons are, among other things, that loads are mostly frequency and voltage dependent and that tap-changing transformers have a long response time to voltage changes in the feeding network.

But the trend moves into another direction: Due to increased use of power electronics in medium and low voltage systems the loads will be less sensitive to changes in frequency and voltage which will decrease stability margins. In addition, in some countries (e.g. Denmark) a considerable amount of energy is produced by renewable power generation (e.g. wind power), which often does not provide mechanical inertia to help stabilizing the system.

Also damping of inter-area oscillations will be considerably decreased in future liberalized systems since transmission paths will be loaded at a higher level.

The network operator (ISO, TSO) has to cope with these emerging problems. FACTS devices will be one opportunity to provide short time active power to stabilize the system ([16]).

2.6. Relocatability

Today there are various commercially available FACTS devices that are relocatable: the main parts are built into movable containers that can easily be transported to other locations in a network. This makes it possible for operators to reconfigure their network according to actual needs: e.g. seasonal changes, changed load pattern.

Looking into the future relocatability leads to new business opportunities: Individual companies will be able to provide the service of installing a FACTS device in a already existing system in a very flexible way.

2.7. Concluding Remarks

In the preceding paragraphs, it was shown that FACTS devices could be used in a wide area of applications. 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.

The different types of FACTS devices can be used for different applications. While the static VAR compensator (SVC) can be used for stability improvements, it is not well suited for increasing transfer capacity over a congested link. However, as the name implies, it is normally used for shunt compensation of long transmission lines. To control power flow for increasing transfer capability the thyristor controlled series capacitor (TCSC) 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 it is also the most expensive since it needs a series and a parallel transformer. (See [17])

3. EXAMPLE

3.1. Introduction

One aspect of how a TCSC can improve inter-regional transmission capacity will be illustrated by an example based on a "real-world" problem. A graphical representation of this network configuration is illustrated in Figure 2: In region A there is a large amount of nuclear power generation installed leading to low electricity prices. Region C has high prices due to a deficit in generation. Since the link between B and C is crucial for secure operation of region C, a (n-2)-security is maintained by the authorities. This means that even if two lines fail the scheduled transmission power can still be maintained without overloading any lines.

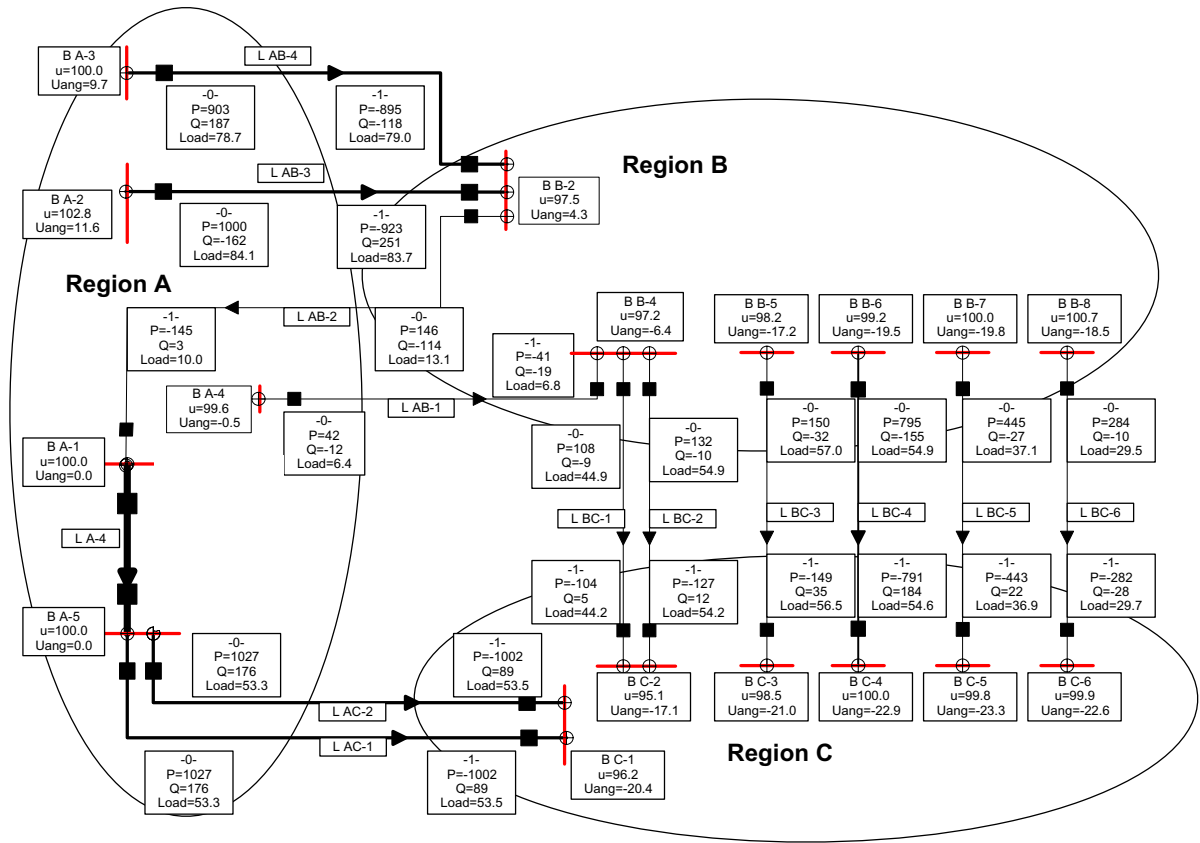


Figure 2 - Base Case without FACTS: Lines are loaded only around 50% to maintain (n-2)-security.

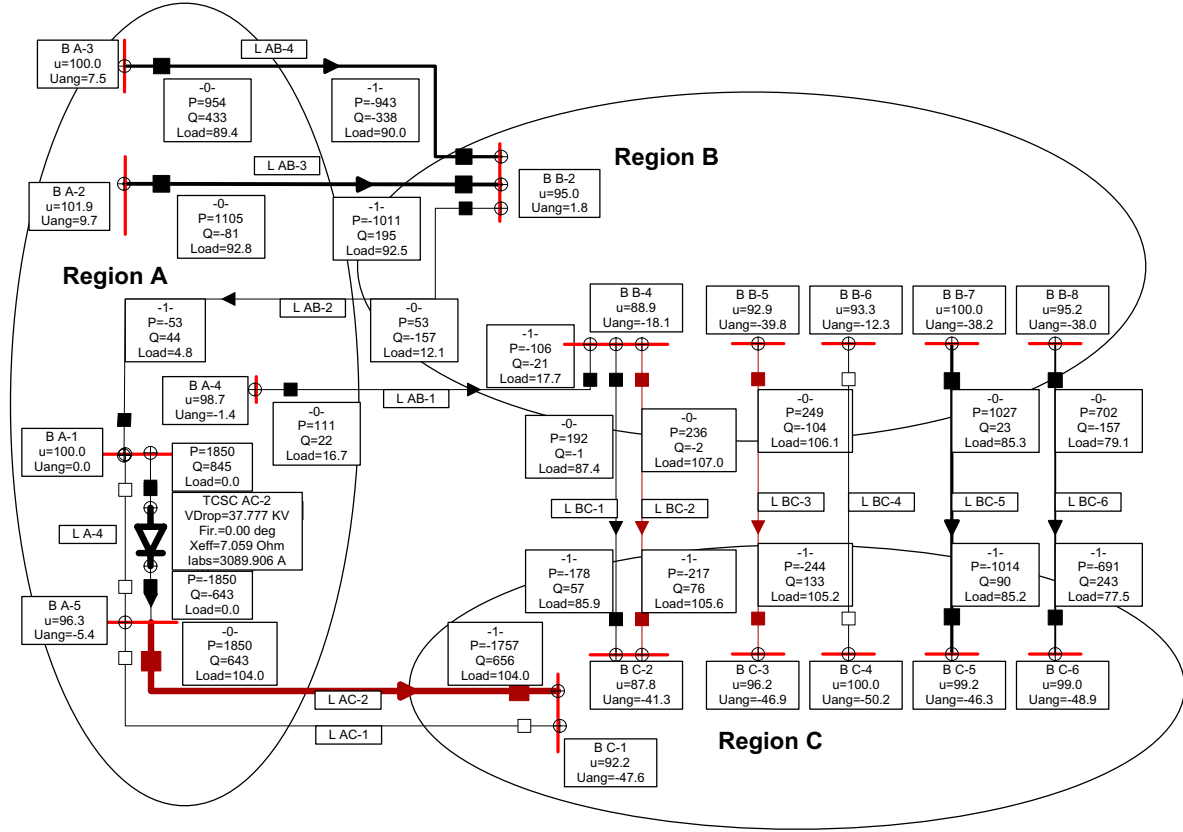


Figure 3 - One line tripped in each link to region C with TCSC: No overloads above 105% with higher import in Region C vs. base case.

We will show how the installation of a controllable device in this configuration makes it possible to increase the maximum power imported into region C without decreasing the security limits. This will increase the overall market efficiency since trading is less constrained by unavailable transfer capacity.

The data used for lines and generation and load characteristics is chosen to match a realistic scenario.

3.2. Description of example system

In Figure 2 the base case of the system is represented. All lines are in operation. Region A is connected to region C through two high capacity parallel lines at 380 kV (AC-1 and AC-2). Region B is connected to C through six lines of different capacities where line BC-1 to BC-3 is at 220 kV and lines BC-4 to BC-6 are at 380 kV. In the presented case 3900 MW are imported into region C. This is the maximum amount allowed if the (n-2)-security criterion is to be maintained meaning that if any two of the lines BC-1 to BC-6 fail, there will be no major overloads.

Since the strongest link represents the two parallel lines connecting region A to C (AC-1 and AC-2) it is evident that placing a FACTS device at the sending bus (A-5) shown in Figure 3 leads to good results (see above).

4. RESULTS

We used a power system analysis software ([18]) to do the analysis of the static load flow with a TCSC of the example system described above. We compared the base case where a maximum of 3900 MW can be imported into region C to the case, where a TCSC is installed in region A at the feeding bus for lines AC-1 and AC-2. In both cases, we did an analysis of the system running under normal operation and when lines BC-4 and BC-5 between region B and region C fail. The latter is a worst-case scenario since those two lines are feeding the most power from region B to C. The results are represented in Figure 2 (base case), and numerically in table 1 for all cases.

In the base case lines are loaded well below the physical limits with a maximum of 56.5 % for line BC-3 at a total of 3900 MW imported into region C. TSOs can't transfer above this value since lines would be overloaded if two lines fail. If lines BC-4 and BC-5 fail, line BC-3 is loaded 93 %, which is almost at the physical limit. This shows clearly that it is impossible to import more power into region C without any additional means like line reinforcement or installation of a FACTS device.

If a TCSC is installed at the mentioned position in region A, the maximum possible transfer power can be augmented to 4800 MW, an increase of about 23 %. We can see from the results (last section of table 1) that even if we import 4800 MW into region C we can keep line loads at a reasonable rate (maximum 102 % at line BC-6) during a double line failure if the TCSC is installed.

Table 1 - Results: Failure in link B-C

Case	Lines							
Base Case	Import Region C: 3900 MW							
Normal Op.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	53.5	53.5	44.2	54.2	56.5	54.6	36.9	29.7
Trans.[MW]	1002	1002	104	127	149	791	443	282
Base Case	Import Region C: 3900 MW							
Dbl. line fail.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	71.2	71.2	69.1	84.9	93.1	0.0	0.0	82.1
Trans.[MW]	1297	1297	153	186	229	0	0	738
TCSC	Import Region C: 4800 MW							
Normal Op.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	65	65	43.4	53.1	60.5	69.7	47.8	42.8
Trans.[MW]	1214	1214	102	124	158	1008	573	407
TCSC	Import Region C: 4800 MW							
Dbl. line fail.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	91.4	91.4	63.9	78.5	95.5	0.0	0.0	102.0
Trans.[MW]	1679	1679	142	172	233	0	0	896

Table 2 - Results: Failure in both links to region C

Case	Lines							
Base Case	Import Region C: 3900 MW							
Normal Op.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	53.5	53.5	44.2	54.2	56.5	54.6	36.9	29.7
Trans.[MW]	1002	1002	104	127	149	791	443	282
Base Case	Import Region C: 3900 MW							
Dbl. line fail.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	0.0	105.2	77.5	95.2	95.4	0.0	74.4	65.5
Trans.[MW]	0	1820	166	202	228	0	888	596
TCSC	Import Region C: 4100 MW							
Dbl. line fail.	AC-1	AC-2	BC-1	BC-2	BC-3	BC-4	BC-5	BC-6
Load [%]	0.0	104.0	85.9	105.6	105.2	0.0	85.2	77.5
Trans.[MW]	0	1757	178	217	244	0	1014	691

This also results in a better overall utilization of the transmission path during normal operation. E.g. the loading of line BC-4, the line transporting the most energy from region B to C, increased from 54.6 % to 69.7 %.

If we want to maintain the (n-2)-security on both links to region C we can show that the TCSC can still improve the maximum transferable energy, even if the increase is considerably lower: In the second case in Table 2 ("Dbl. Line fail.") we see that using the maximum allowed transferred energy of 3900 MW results in a load of line AC-2 at 105% if AC-1 and BC-4 trips. This shows that the (n-2)-criterion is met.

How can the TCSC installed at the same location improve the situation in this case? The results are shown in Figure 3 and numerically the last case in Table 2: Only 4100 MW can be imported into region C if the lines are not loaded above 105%. This is still a 5% increase. With peak energy price being very high as in recent times in Europe, even an increase this small could justify the investments.

5. CONCLUSIONS

FACTS devices can help ISOs or TSOs to increase the efficiency of the network in various ways: To improve static and dynamic stability, to increase transfer capacity over congested links, to reduce the risk of loss of load etc. All these fields have to be defined as ancillary services to the network customers such as generation companies or load aggregators.

The results of the simulations show clearly that the installation of just one TCSC can considerably increase the available transfer capacity over a congested link. However, it is important to have an overall view over the network configuration of the inter-connected regions since otherwise sub-optimal solutions might be found. Due to the same reason, TSOs of different areas will need to work in a partnership: If a congestion occurs between two regions it is sometimes more efficient to install devices in a third region to achieve good results.

On the economic side it will be necessary that cross border tariffs are well defined in order to determine the value of a new installation. It is not enough to define prices for net transfers since often transfer assets of one region (see region B in example above) are used to transmit energy between two other regions.

The question is: What is the value of transactions that cannot take place due to congested inter-connections? The answer to this question gives important input to evaluating the value of FACTS devices. However, it gives also important information when designing a congestion management system that is fair and gives the right signals to the different actors on the market.

6. FUTURE WORK

This paper has reported the first results from a project aiming at developing a systematic method to evaluate the value in various aspects of FACTS devices in an open electricity market. FACTS devices constitute different advantages for different stakeholders, e.g. generators, TSO/ISO, consumer, and it is the aim to include all these into a "global" assessment.

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