New types of FACTS-devices for power system security and efficiency

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Abstract **-- This paper provides an overview of new types of FACTS devices. These devices are considered for applications in real network cases in Europe and China. The value of these FACTS is the improvement of security and efficiency of power transmission networks. Fast controllability in emergency situations provides increased flexibility and therefore stability and security advantages. The flexibility in control allows operating closer to stability limits and improves the efficiency of existing networks.**

The considered devices are dynamic power flow controller (DPFC), fault current limiter (FCL), Static Synchronous Compensator (STATCOM) with energy storage and Voltage Source Converter based HVDC (VSC-HVDC).

The application scenarios are taken from UCTE (Benelux, Austria) and China (Shanghai). The studies are based on public available simplified network data.

Index Terms **-- Power control, Power system control, Power system economics, Dynamics, Power transmission, Congestion management, FACTS, Energy markets, Power Flow Control**

I. INTRODUCTION

INCREASE of the volume and volatility of cross-border and cross-network power exchanges occurs almost everywhere across the world due to the liberalization or fast growing electricity demand [1]. Transmission System Operators (TSOs) are striving to increase the capacity of existing lines, because the installation of new transmission lines is often politically unacceptable to residents and faces legal and environmental challenges.

Several new technologies are available to solve or at least to mitigate these problems [2][3]. Better network supervision with Wide Area Monitoring Systems (WAMS) is more and more accepted. Phase Shifting Transformers (PST) are implemented to increase the power flow controllability, for instance in Netherlands, Belgium, France and Austria. Underground transmission, particularly with Voltage Source Converter based HVDC (VSC-HVDC) is applied to feed power into huge city areas, like for example around New York.

Beyond these existing technologies several new ones have been developed recently. The combination of a PST with Thyristor switched series elements in the Dynamic Power Flow Controller (DPFC) provides dynamic power flow capabilities.

The STATCOM is a well established device since a couple of years for dynamic reactive power provision and power quality improvement. To face growing network volatilities for example by wind power injection, additional energy storage functionality can easily be integrated.

The technically feasible short circuit level will be exceeded soon in parts of the world due to growing load demands, for instance in Chinese mega-cities like Shanghai. A fault current limiting device based on a fast triggered protection device and inductance and capacitor arrangements is a simple and efficient solution.

Figure 1 gives an overview of nowadays available network controllers and FACTS-devices [4][5].

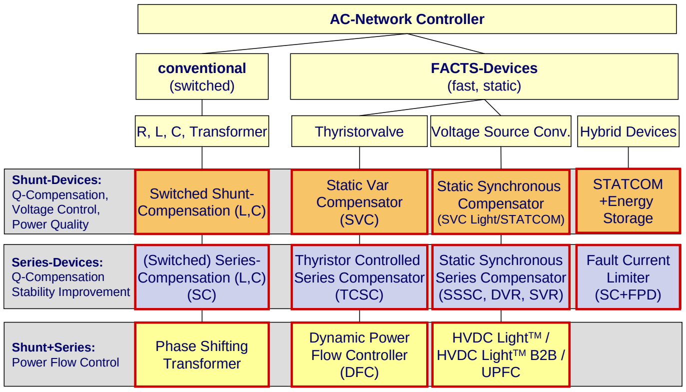

Fig. 1. Overview of compensation devices, network controllers and FACTS

II. NEW TYPES OF FACTS-DEVICES

A. *Dynamic Power Flow Controller*

The DPFC is a hybrid device consisting of a standard PST with a tap-changer, a number of series-connected Thyristor Switched Capacitors, Reactors (TSC/TSR) and a mechanically switched Shunt Capacitor (MSC). The latter is optional depending on the system reactive power requirements. A functional single line diagram of the DPFC is provided in Fig. 1. All the components of the DPFC are well known in practice. The TSCs and TSRs are similar to standard SVC components.

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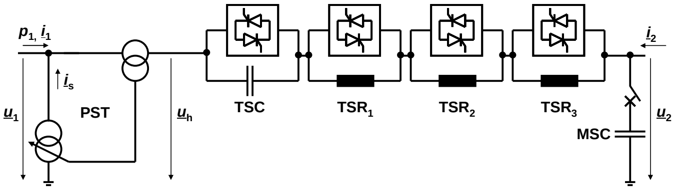


Fig. 2. General configuration of a DPFC

The reactance of reactors and capacitors is selected based on a binary basis to result in a desired stepped reactance variation. If a higher power flow resolution is needed, a reactance equivalent to half of the smallest one can be added. The switching of series reactors occurs at zero current to avoid any harmonics. In general, however, the principle of phase-angle control used in TCSC is also applicable for continuous control. The operation of the DPFC is based on the following rules:

- TSC/TSRs are switched when a fast response is required.
- The relief of overload and operation in stressed situations is first handled by the TSC/TSRs.
- The switching of the PST tap-changer should be minimized, particularly for currents higher than standard load.
- The total reactive power consumption of the device can be optimized by the operation of the MSC, tap-changer, and the switched capacities and reactors.

Due to its hybrid setup a DPFC provides fast controllability with considerably reduced costs compared to other FACTS-devices like UPFC.

The load flow model of the DPFC can be formulated based on the following equation in p.u.:

$$\begin{bmatrix} \underline{i}_1 \\ 0 \\ \underline{i}_2 \end{bmatrix} = \begin{bmatrix} \underline{y}_{PST} & -\underline{\tau}\,\underline{y}_{PST} & 0 \\ -\underline{\tau}^{*}\underline{y}_{PST} & \underline{\tau}^{*}\underline{\tau}\,\underline{y}_{PST} + \underline{y}_{TSC/R} & -\underline{y}_{TSC/R} \\ 0 & -\underline{y}_{TSC/R} & \underline{y}_{TSC/R} \end{bmatrix} \begin{bmatrix} \underline{u}_1 \\ \underline{u}_h \\ \underline{u}_2 \end{bmatrix} \qquad (1)$$

where $\underline{\tau} = 1 + \mathrm{i}(\Delta\tau \cdot t)$ with $t \in \{-3,-2,-1,0,1,2,3\}$ and $\underline{y}_{TSC/R} = 1/\left(a_{TSR1}\underline{z}_{TSR1} + a_{TSR2}\underline{z}_{TSR2} + a_{TSR3}\underline{z}_{TSR3} + a_{TSC}\underline{z}_{TSC}\right)$ with the switching variables $a_{TSR1}, a_{TSR2}, a_{TSR3}, a_{TSC} \in \{0,1\}$. y_{PST} is the admittance of the PST and $\Delta\tau$ is the incremental tap ratio of one PST tap.

The principle of the DPFC control scheme is shown in Fig. 3. The limiter output is quantized to select the reactance of the TSC/TSRs from the 16 binary combinations of the four elements. When one of the upper or lower four combinations is selected, the PST's up-tapping or down-tapping is initiated. The PST tapping brings the dynamic TSC/TSR part closer to its midpoint in order to maximize the dynamic control range.

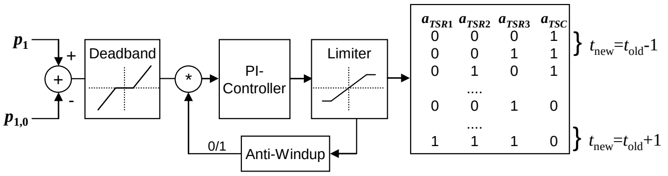


Fig. 3. Control scheme of a DPFC

B. Short Circuit Fault Current Limiter

The short circuit fault current limiter (SCFCL) concept is a series combination of a series reactor and a series capacitor. The circuit is tuned to the fundamental frequency and thereby eliminates the problems of a pure series reactor, like influence on system stability, the load sharing problem and the voltage profile problem. A single line diagram is shown in Figure 4 .

When a short circuit is detected the series capacitor is immediately bypassed by a fast protective device (FPD) and the short circuit current is limited by the series reactor.

The FPD consists of a combined Arc Plasma Injector and Fast Closing Contact for speed and reliability. Both units are fully encapsulated for maximum reliability also in adverse climate conditions.

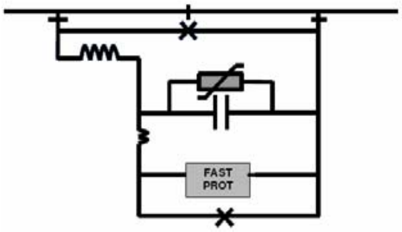


Fig. 4. Single line diagram of the short circuit fault current limiter

C. VSC-HVDC

HVDC with Voltage Source Converter (VSC-HVDC, HVDC Light) are well known and will therefore not be explained in detail. The advantage is underground transmission with fast controllability of active power flow and independent provision of reactive power at both ends. The reactive power improves the performance in terms of voltage quality and losses of the surrounding AC power system at both ends. The active power flow controllability avoids cascaded outages, because the system is prevented from being overloaded.

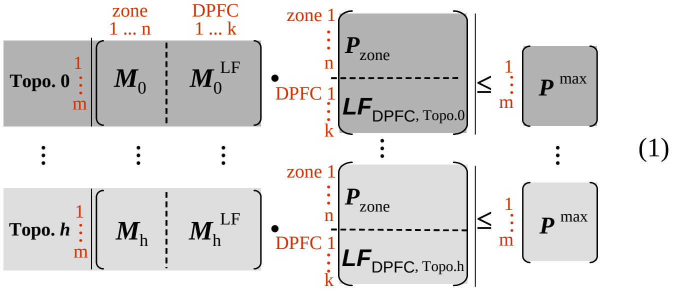
D. STATCOM with Energy Storage

A STATCOM is mainly a Voltage Source Converter connecting a capacitor as shunt element to the power network. The capacitor itself is an energy storage with very limited energy capacity. Therefore the STATCOM provides only reactive power. If for instance a battery is connected in parallel to the capacitor, additional active power capability is added and the device can operate in an almost circular area of the PQ-operational diagram for a certain time interval.

The benefit of such a device is for power quality improvement for example together with volatile power generation like for instance large wind parks. Short term active power variation can be buffered and together with the reactive power disturbances to the main grid can be mitigated effectively.

III. ASSESSING THE BENEFITS OF FAST POWER FLOW CONTROLLERS

The value of a fast load flow controller in an electricity market is gained from reduced congestions together with a reduction of system losses. In this section, we describe the basic properties of a special infinitesimal Power Transfer Distribution Factor (PTDF) model based on zonal balances and discuss how fast dynamic power flow controllers like DPFC or VSC-HVDC can be included [6][7]. The difference between 'slow' and 'fast' power flow controllers is that the latter can be shifted to an individual setting after each contingency. The DPFC would use its fast control range given by the TSC and TSRs. This means that for each topology each DPFC may have an individual setting and influence $\boldsymbol{LF}_{\text{DPFC, Topo.j}}$ according to (1). For the normal operation the DPFC settings $\boldsymbol{LF}_{\text{DPFC, Topo.0}}$ can be chosen for a loss optimal operation. This can be done separately by an OPF after the generation dispatch is settled by the market. In each post-contingency case, the power flow controllers are changing their settings immediately to fulfill the topology specific post-contingency requirements.



$$\begin{array}{l}
\text{Topo. 0}\begin{bmatrix} \boldsymbol{M}_0 & \boldsymbol{M}_0^{\text{LF}} \end{bmatrix} \bullet \begin{bmatrix} \boldsymbol{P}_{\text{zone}} \\ \boldsymbol{LF}_{\text{DPFC, Topo.0}} \end{bmatrix} \le \begin{bmatrix} \boldsymbol{P}^{\max} \end{bmatrix} \\
\qquad \vdots \qquad\qquad \vdots \qquad\qquad \vdots \\
\text{Topo. } h\begin{bmatrix} \boldsymbol{M}_h & \boldsymbol{M}_h^{\text{LF}} \end{bmatrix} \bullet \begin{bmatrix} \boldsymbol{P}_{\text{zone}} \\ \boldsymbol{LF}_{\text{DPFC, Topo.h}} \end{bmatrix} \le \begin{bmatrix} \boldsymbol{P}^{\max} \end{bmatrix}
\end{array} \qquad (1)$$

In addition, the combination of the power flow settings $\boldsymbol{LF}_{\text{DPFC, Topo.j}}$ with the zonal balances may allow for higher usage of the existing interconnections between the zones.

The scenario in Fig. 5 is developed to evaluate the increase of transmission capacity with a fast power flow controller. Area 1 is an exporting area with generators which are interconnected without network limitations. The exporting corridor is divided into three lines L_1, L_2 and L_3. These lines are feeding into area 2 which is an importing area. The corridor is limiting the export from area 1 to area 2. A power flow control device can shift the power flow between the lines to use the corridor in an optimal way.

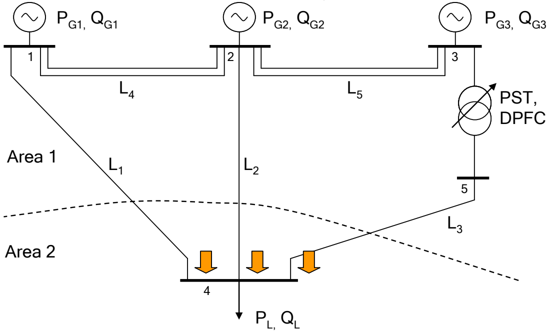


Fig. 5. Scenario for the evaluation of power flow control benefits

If only one PST or DPFC is used, it has to be installed in a line with lower transmission capacity than the other lines, otherwise the simultaneous outage of a high capacity line and the control device would always be the most severe N-1 case. Fig. 6 visualizes the N-1 outage cases of the lines L1, L2 and L3 as maximum corridor loading $P_{L,max}$ over a range of tap positions. The control range of the DPFC is recalculated into discrete tap positions. The lines in this case are limited by their thermal capacity. From the theoretical point of view other stability limits would show equivalent qualitative results.

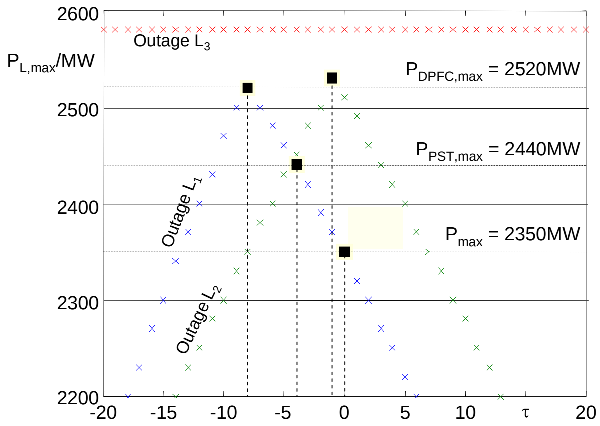


Fig. 6. N-1 outage cases for the network situation in Fig 5 with PST, with DPFC and without power flow control device

If no power flow control device is in use, the tap position is zero and the outage of L_1 limits the maximum flow according to N-1 criterion to P_{max} = 2350 MW. If a slow power flow controller is implemented a fixed tap setting is selected, which is the intersection between outage of L_1 and outage of L_2 in the diagram. The power flow can be increased to 2440 MW. If a fast power flow controller is implemented it provides the capability to react individually on the outages after their occurrence. This means that for outage of L_1 and the outage of L_2 the tap setting can be chosen differently. The maximum transmission capacity is 2520MW doubling almost the benefit in comparison to a PST.

Based on the model above the loss reduction and increase of transmission capacity can be assessed. During operation a simplified optimization, e.g. based on linear optimization and DC-load flow, can be performed to find the settings of the load flow controllers [8]. In cases of large networks which are distributed over different TSO areas, a rule based emergency control would be beneficial. In [4] it is shown how such an autonomous control for post-contingency actions can be implemented.

IV. EXEMPLARY RESULTS

A. *UCTE - Benelux region*

After the recent blackout of parts of the UCTE system in November 2006 the system has proven to be vulnerable to system instabilities. Especially loop flows through the Benelux countries are facing congested network situations. PSTs are already in operation at two substations (Meeden and Gronau) at the Dutch-German border. The goal of a system study is to evaluate the additional benefit of DPFCs instead of the existing PSTs. Fig. 7 outlines an overview of the principal transmission lines in the area mentioned. A more detailed description of the congestion situation can be found in publicly available EU studies [1].

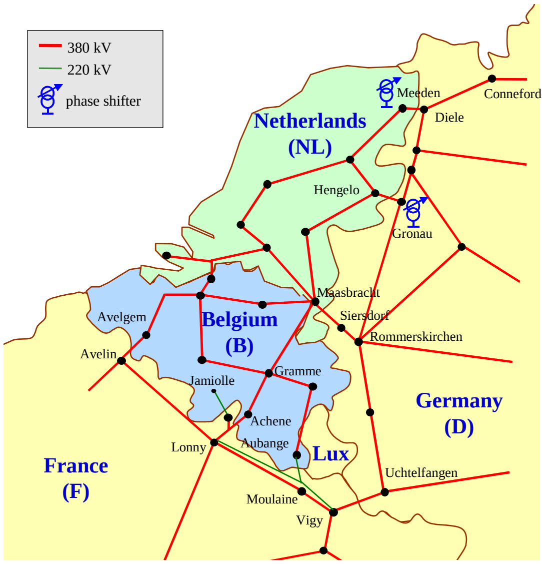


Fig. 7. Overview of the transmission network in the vicinity of Belgium and the Netherlands

As previously stated, the idea of the DPFC is to operate in a loss optimal way during undisturbed situations. This means that the DPFC could operate close to the neutral position or easily follow an hourly schedule. In emergency situations the DPFC would immediately adapt its setpoint to the new situation and prevent the system from overloads.

The DPFCs assumed in this case shall be an alternative for the existing PSTs. The question is whether the additional investment into DPFCs would pay off from improved operations. The assumed DPFCs have the same throughput power as the PSTs and are designed to provide a similar control range of +/-28 and +/-25 degrees, respectively. The design is such that the phase-shifting parts of the DPFCs have power consumption of half the original PSTs. The number of taps is only +/- 3, which drastically simplifies the PST. The dynamic range from the TSC/TSR is +/- 130 kV for Gronau and +/- 120 kV for Meden. This results in a control range that is similar to the original PSTs but has a much shorter reaction time. Investment in such a device can be assumed to be max. 80% higher than for a PST. With PST prices of around 8,000 Euro/MVA the DPFC would cost max. 14,600 Euro/MVA. The additional costs for one DPFC in Gronau and two in Meden compared to the existing PSTs are estimated to be 23 million Euro.

The next step is to quantify the loss costs under certain practical conditions. For the monetary assessment we have assumed a loss price of 34 Euro/MWh. Fig. 8 shows the yearly loss reduction by using DPFCs instead of PSTs. With full admissible tap range (i.e. the entire tap range is used for capacity maximization), the loss reduction by replacing the PSTs in Gronau and Meeden with DPFCs is 265 GWh/a in total for all countries. This constitutes a total monetary benefit of 9.0 million Euro/a.

With the additional investment of 23 million Euro and a discount rate of 10% over 12 years, the discounted cash flow calculation results in a payback time of 4.1 years with a Net Present Value (NPV) of 32 million Euro and an Internal Rate of Return (IRR) of 38%.

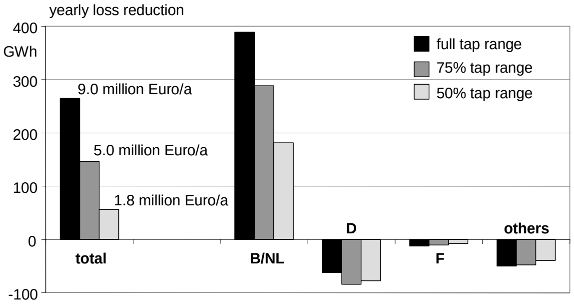


Fig. 8. Yearly loss reduction through DPFCs (instead of PSTs) in Gronau and Meeden for different tap range restrictions

The simulation results also indicate a strong dependency of the loss reduction on tap range restrictions. This means if the TSOs do not use the full range of a PST or DPFC exclusively for increasing the transmission capacity, the benefits are significantly smaller. For example, if only 50% of the total tap range is used, it results in a decrease of the loss cost reduction of up to 80%, meaning a drop to 1.8 million Euro/a. But it is clear that with the reduction of the used tap range for capacity increase the overall benefit of either PSTs or DPFCs in the energy market is significantly decreased and the installation would follow other criteria.

B. Shanghai Region and City Supply

The main structure of the grid in the Shanghai region is defined by a 500-kV-double loop. To decrease the short circuit current, the 220-kV-system is divided into several sub-areas. However, the three phase fault current of several 220-kV-buses still exceeds 50 kA and that of several 500-kV-buses exceeds 55 kA. Because of the splitting, two 220 kV sub-areas without large capacity generators are lacking dynamic voltage support. As a result, the voltages will not recover when severe faults occur.

In this paper two basic requirements for the solutions are defined as follows. The short circuit current of the 500-kV-bus is lower than 50 kA and that of the 220-kV-bus is lower than 42 kA. The voltage of sub areas shall recover to more than 0.8 pu after clearing the fault within 1 second. In addition, the power grid that adopts the proposed solution should satisfy the N-1-criteria. As solutions different configurations based on new technologies are proposed. One example is shown in Fig. 9 comprising of VSC-HVDC and Fault Current Limiter.

The splitting of the 500-kV-AC-loop decreases the short circuit current level significantly because the channel of the reactive current, main component of the short circuit current, is cut off. According to the circuit theory, the AC loop is isolated by the controllable VSC-HVDC. As a consequence, the equivalent impedance between each generator and fault point increases. This means, that the short circuit currents of all buses decrease below the required values. The effect is similar to the existing measure of tripping one or two lines of the 500-kV-double-loops. But the VSC-HVDC solution does not affect the reliability of the power grid. Another benefit of this pattern is the dynamic voltage support provided by the converters for the weak sub networks.

The SCFCL is in series with the 500-kV/220-kV-transformer on the 500-kV-side to limit the contribution of a group of generators in 220-kV-sub-area when the fault occurs.

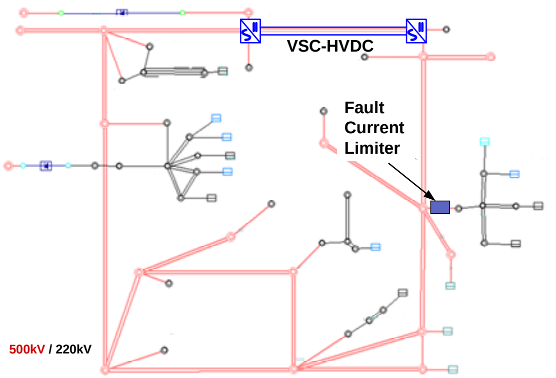


Fig. 9. 500-kV-ring around Shanghai and city infeed with 220 kV extended by VSC-HVDC and SCFCL (solution 1)

Table 1: Parameters of solution 1

Component	Item	Value
VSC-HVDC	S_n	360 MVA
	Cos Ψ	0.89
	Voltage	+/- 150 kV
	Reactive Power Control	Constant AC-Voltage
SCFCL	Reactor	8 ohm
	Capacitor	-8 ohm

Another case uses a STATCOM and Fault Current Limiters as options. The configuration of this solution 2 is presented in Fig 10. Three SCFCLs are inserted into the 500-kV-double loops to reduce the short circuit currents of both the 500-kV-system and 220-kV-system. Some 500-kV-substations are split by the SCFCLs. This does not only decrease the short circuit current of the 500-kV-system but also decreases the 500-kV- system contribution to the 220kV short circuit level drastically. The STATCOM is installed on the 35-kV-side of the 500-kV/220-kV/35-kV-connection-transformer in the northern part of the system. The capacity of the STATCOM is ±200 MVA which is the minimum value to meet the voltage stability requirements. The parameters of the solution 2 are listed in table 2.

Table 2: Parameters of solution 2

Name	Voltage	Inductance	Capacitance
SCFCL1	500 kV	25 ohm	-25 ohm
SCFCL2	500 kV	10 ohm	-10 ohm
SCFCL3	500 kV	10 ohm	-10 ohm
Name	Voltage	Capacity	
STATCOM	35 kV	±200 MVA	

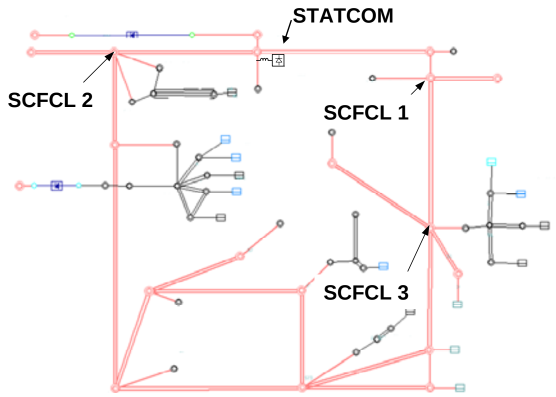


Fig. 10. 500-kV-ring around Shanghai and city infeed with 220 kV extended by SCFCLs and STATCOM (solution 2)

The comparison of the two solutions in Fig. 11 shows that the short circuit level can be limited below the required values.

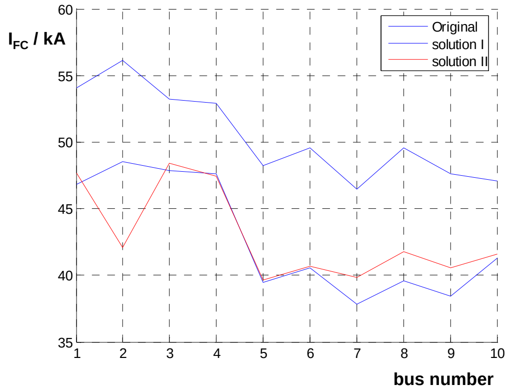


Fig. 11. Comparison of solution 1 and 2 regarding short circuit current levels of selected buses

The second criterion is the dynamic voltage recovery after severe faults. Sever faults are simulated in two sub-areas shown in Fig. 12. The settings of the scenarios are listed as follows. In sub-area 1 one 500-kV-line in the left trips, a three phase to ground fault occurs near the bus and it is cleared after 0.1 second. In the city center, a three phase to ground fault occurs at a 220-kV-bus. And it is cleared after 0.15 second.

In the simulation, the generator model considers sub-transient inductance, exciter and governor. Half of the total load is modeled as inductive motor and the other as constant impedance, which simulates the load during the summer peak. The voltage response curves are shown in Figure 13.

It can be seen from the figures that the voltage of the sub-areas can not recover and are lower than 0.8 pu finally for the original base case. Both solutions 1 and 2 meet the requirements recover the voltage appropriately.

The results show that both solutions are effective for the short circuit current reduction and voltage stability. Moreover, the performances of solution I and II are approximate the same in terms of short circuit current and voltage stability. A cost comparison shows that life cycle cost over a period of 30 years are comparable. In comparison to HVAC cables which could be required in city areas, the break even length for VSC-HVDC lies at approximately 20 to 40 km under the given requirements. More details can not be presented because of confidentiality.

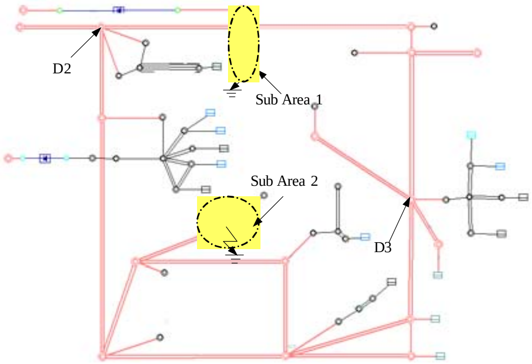


Fig. 12. Simulated faults in two areas of 500-kV-ring around Shanghai and city infeed with 220 kV

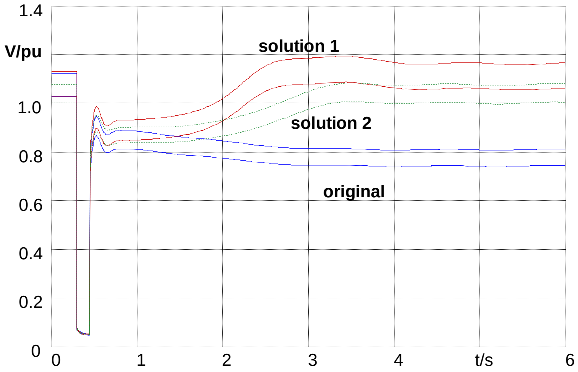


Fig. 13. Dynamic voltage response on city bus with faults in area 1 (upper curves) and area 2 (lower curves) for original case and solution 1 and 2

C. *Austrian Power Grid Situation*

In the Austrian Power Grid (APG) situation according to Fig. 14 there is a huge power transfer from North to South. Thermal and voltage limitations occur in the system. The 380-kV-ring is not closed, which is marked as dotted line in the South-East. PSTs are installed in two of the 220-kV-lines from North to South to mitigate overload situations or the loss of N-1-stability. This solution gives full power flow controllability in this area to using the existing lines to their maximum. To speed up the adaptability to different emergency cases the presented DPFC could be considered as an alternative similar to the presented case A from Benelux.

One option for closing the open 380-kV-ring is with a VSC-HVDC as an underground line. This technology would increase the controllability, prevent from overloading and cascaded line tripping and would solve the reactive power and voltage problem in the South. Considerations similar to case B have to be done.

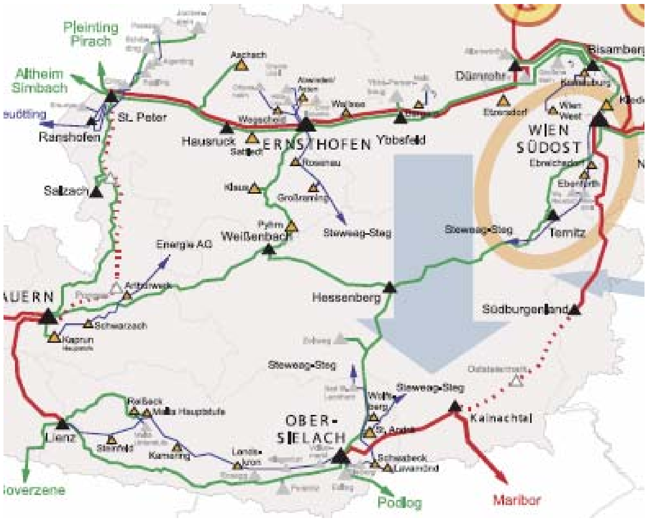


Fig. 14. Network situation in Austria

V. CONCLUSIONS

The application of FACTS devices in practice is in many cases just at the beginning. Planning scenarios are required to give guidance for the applications of these new technologies and show the benefit in comparison to conventional solutions. The paper introduces some new types of FACTS devices for power flow control (DPFC and VSC-HVDC), short circuit current limitation (SCFCL and VSC-HVDC) and voltage control (STATCOM and VSC-HVDC).

It can be proven that power flow controllability can increase the transmission capacity and reduce the system losses while increasing the flexibility in emergency situations. The additional functionality of VSC-HVDC can be used to reduce the short circuit power and control the voltage level. In conclusion a high flexibility for operation can be provided under the condition that appropriate control schemes are applied.

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