

HIGH VOLTAGE SERIES REACTORS FOR LOAD FLOW CONTROL

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1 INTRODUCTION

Liberalisation efforts are continuing in electricity markets all over the world. The change from monopolistic to free market structures leads to a significant increase in the trading of electrical energy. Since current power plant operation is driven by price aspects, the load flows in the networks are mainly determined by the economic situation and are no longer driven by the technical design of the networks. However, as the networks were built according to the former monopolistic market conditions and requirements, the desired load flows resulting from energy trading in the free market might cause problems when forced into the physical limitations of the actual networks, such as overloading of individual system components or stability/security limit violations. Also, the increasing transmission of large amounts of electrical energy over long distances and between different control areas requires more effort to co-ordinate and supervise inter-area energy exchange. It also creates further problems, such as loop flows.

This conflict of operating the transmission networks beyond the originally foreseen limits became clearly visible in the Italy blackout on September 28th, 2003 [1, 2]. Italy imported almost 7 GW from abroad, which was equivalent to 24 % of the total demand in Italy and above schedule. The resulting load flows pushed the interconnecting lines between Italy and its neighbours to an operating state close to the limits. Consequently, the failure of one interconnecting transmission line, which is tolerable in the normal operation state, together with the fact that counter-measures were not taken in the required time and sufficient extent, an additional 2nd line fault, led to the isolation of the Italian control area – which was not able to keep up island operation and caused a nation-wide blackout.

As there are very limited means for system operators to influence the contracted power exchanges and resulting load flows in Europe, it can be expected that operation conditions with high risks will become more and more common in the UCTE system.

Also within the Austrian transmission grid, the effects of liberalisation have led to a number of bottlenecks caused by changes in the load flow due to the new power plant regime. To ensure a safe grid operation VERBUND-Austrian Power Grid (APG), the Austrian transmission system operator (TSO), must apply cost-intensive measures for congestion management (CM), such as re-dispatch of power plant operation. APG plans to build new 380 kV overhead lines to overcome the bottleneck situations, but as the erection of new lines is delayed by extensive authorisation procedures and strong

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opposition by the public, APG faces an increasing need for CM measures in the near future until the new lines will be in operation.

In general, there are a number of approaches to overcome or mitigate load flow problems, including the installation of high voltage (HV) dry-type series reactors. The paper will describe in some detail the design and construction of HV series reactors. It will focus on dry-type air core reactors which have become the technology of choice for many applications because of their design features and their cost effectiveness. Finally, the relevance for load flow control in the Austrian transmission grid of APG is discussed.

2 LOAD FLOW CONTROL IN TRANSMISSION NETWORKS

2.1 Motivation

The basic problem motivating the necessity of load flow control in electric power networks is the fact that in today's deregulated energy markets, the contracted energy flows, which are oriented to the economic situation, result in ever more bottlenecks in the physical transmission network. As a result, special CM procedures generating significant cost have to be introduced in order to allow normal network operation without constantly violating security rules. Further problems are caused by:

- Deviations of the actual power flow on interconnecting lines from the schedules, which may occur for many reasons. If the systems are operating close to their limits, even minor deviations might already lead to difficult operating conditions.
- Power transfers causing loop flows in underlying or connected boundary networks, which are sometimes very difficult to predict in operational planning and might also lead to difficult operating conditions.
- Uneven loading of interconnection lines of dissimilar impedance between different control areas can occur with the result that the total transfer capacity is limited by the first component reaching its thermal loading limit and is not based on all components reaching their limits simultaneously.

As it is the political goal of the EU to strengthen the internal market for electricity [3], these problems have to be solved – especially, the available transfer capacity has to be increased. At the same time, building new lines becomes ever more difficult because of administrative, ecological and also economical reasons. So, techniques for load flow control gain importance, as they allow safe operation of the existing networks in conjunction with increasing international energy transports.

2.2 Theory and technical solutions for load flow control

There are three basic techniques for active power flow control: phase shifting transformers (PST), FACTS (flexible AC transmission systems), and series impedance elements such as reactors or capacitors. While PST are commonly used in electrical networks all over the world, impedance elements and especially FACTS (for load flow control) are used mainly in largely extended transmission systems, as for example in the USA [4].

Some basic principles are considered using a simple model network (Figure 1a). Two control areas are connected via two lines with impedances X_1 and X_2 . With resistances and shunt elements neglected, and assuming that voltages \underline{V}_A and \underline{V}_B are fixed by the connected networks, then the active power transferred from A to B is:

$$P_{AB} = \operatorname{Re}\{S_{AB}\} = P_1 + P_2 \quad \text{with} \quad P_i = \frac{V_A V_B}{X_i} \sin \delta, \quad \delta = \varphi_A - \varphi_B \quad (1)$$

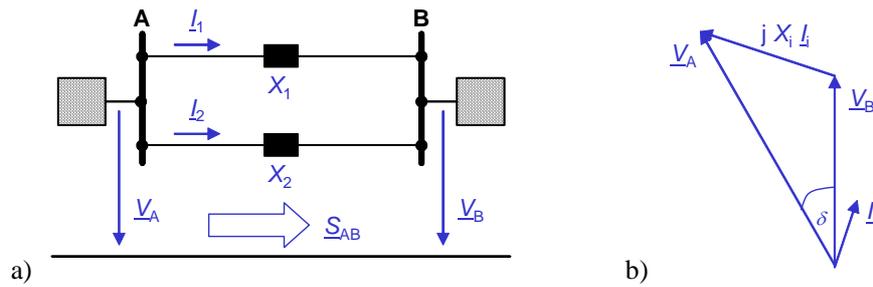


Figure 1 a) Model network and b) phasor diagram

PST influence the active power flow by changing the transmission angle δ (assuming that the transformer itself was already installed). Specific wiring of the transformer coils allows phase shifts of 30° , 60° or 90° , where the 60° phase shift is most commonly used. In addition, the voltage magnitude is also influenced with tap changers. Without phase shift, transformers only affect the voltage magnitude, and in consequence only the reactive power flow.

FACTS – especially the most general type, the Universal Power Flow Controller (UPFC) – allow the widest range of control of active and reactive power flows. UPFCs can influence the voltage magnitude, the transmission angle and the line impedance. Moreover, by using power electronics, FACTS can react very quickly and also allow the control of dynamic aspects.

Series impedance elements, such as reactors and capacitors, also allow active power flow control in a simple way by changing the impedance of the connection lines. By using equation (1) it can be easily seen, that symmetric line reactances $X_1 = X_2$ result in a symmetric power transmission ($I_1 = I_2$ and $P_1 = P_2 = P_{AB}/2$). The installation of a series reactor in line 1 increases X_1 . Using the condition for the line phasors $j X_1 I_1 = j X_2 I_2$, it is obvious that the current I_1 is also decreased by the ratio of the reactances – the “load flow control” shifts more power to the (e.g. stronger) line 2.

3 CHARACTERISTICS OF HIGH VOLTAGE SERIES REACTORS

3.1 General aspects

A series reactor can be an effective device for a more effective utilisation of the power system’s transmission capability. The required impedance of the reactor is easily determined by system studies. Series Reactors may be inserted either permanently to improve the load sharing between lines of dissimilar impedance, or temporarily to relieve loading of critical lines under specific operational conditions. The relatively low cost coupled with short lead times, as well as ease of transportation and implementation make series reactors particularly attractive when the load flow problem is a short or medium term situation which is expected to be resolved by e.g. the future construction of a new line. A time period less than 6 to 8 months from project approval to energization is feasible.

Reactors may be either dry-type or oil-immersed. Because of their design features and their cost effectiveness, air core reactors employing modern dry-type technology have become the technology of choice for many applications. Dry-type reactor technology has been applied for a number of load flow control reactor projects in transmission and sub-transmission systems around the world. The main features of air core dry-type reactors versus oil-immersed iron-cored reactors are:

- **Linear inductance-current characteristic**
As there is no iron core and thus no magnetic saturation effect, the impedance of a dry-type air core reactor is constant from minimum current levels to fault current. This linear L - I characteristic makes it an ideal candidate to be used as a series reactor for load flow control.
- **Absence of insulating oil**

Since dry-type reactors do not have an oil insulation system, there are no fire hazard and environmental concerns. Furthermore, no oil collecting system must be provided since there is no oil that can leak into the ground and no auxiliary equipment for oil supervision is needed.

- **Insulation to earth**

The major insulation to earth is simply provided by support insulators.

- **External magnetic field**

Due to the absence of a magnetic core or magnetic shield a dry-type air core reactor produces an external magnetic field. However, the field strength drops off very quickly with increasing distance from the reactor, since a solenoid has a magnetic dipole characteristic and the field decays with the third power of the distance.

3.2 Design and installation of a dry-type air core reactor

The following list gives the major construction features of a HV dry-type air core reactors (see figure 2a):

- The winding of the reactor consists of a number of concentric winding layers, all electrically connected in parallel by welding their ends to metallic beam structures (spiders).
- Each winding layer consists of film insulated, epoxy impregnated and fibreglass encapsulated aluminium cable.
- The number of layers and their respective turns are selected based on current and inductance requirements.
- The length of the winding is designed so that the axial voltage stress results in surface stress values that are far less than the typical creepage voltage stress on insulators.
- The turn-to-turn steady state operating voltages are well below the level at which partial discharge can occur.
- The winding layers are radially spaced by several fibreglass reinforced “duct sticks” which form vertical ducts for natural air cooling of the winding.
- Both the top and bottom spider are clamped together by several fibreglass ties located along the winding.
- The reactors are mounted on a number of support insulators and may include steel beams to provide additional clearance under the reactor.
- Corona bells or rings may be provided for screening of the metallic spiders.

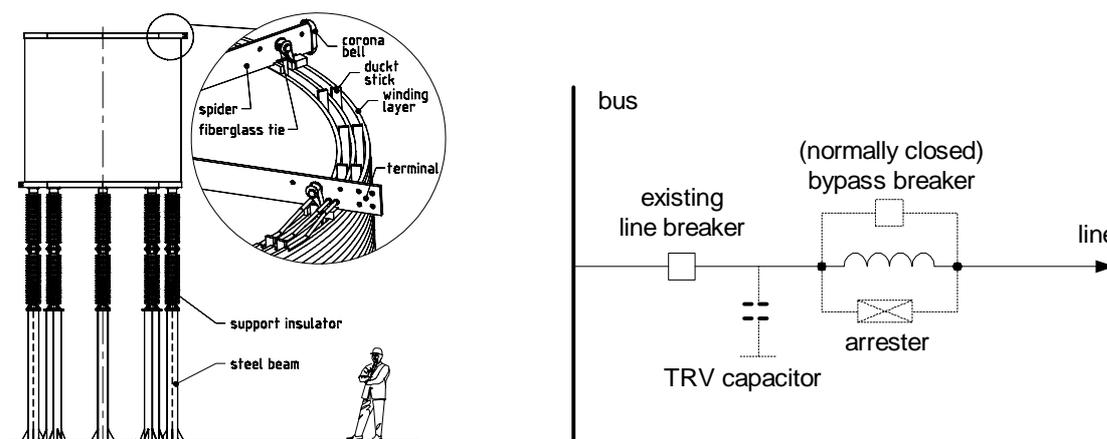


Figure 2 a) HV dry-type air-core reactor b) Auxiliary components of a series reactor

Large Mvar air core reactors are single-phase units mounted side by-side forming a three-phase reactor bank. Auxiliary components such as bypass circuit breakers, TRV (transient recovery voltage) control capacitors and surge arresters, are determined by the actual application. The one line diagram in Figure 2b illustrates the arrangement of a series reactor and its possible auxiliary components in a substation.

The installation of a series reactor will have an impact on the existing circuit breaker. Generally, the reactor tends to increase the rate-of-rise of the TRV appearing at the line side of the circuit breaker for faults on the line side of the reactor. This may require the addition of a capacitor to reduce the rate-of-rise of the TRV. Usually the capacitor is connected line-to-earth at the line side of the circuit breaker, but it may also be connected in shunt to the reactor.

If reactors are intended for operation under specific load conditions only, then they will be equipped with a normally closed bypass circuit breaker which shorts out the reactor under normal line loading. Under critical line conditions the bypass breaker will be opened and the reactor is thereby inserted. Since the bypass breaker is not expected to clear faults, a load break switch may also be used instead of a circuit breaker.

Although the series reactor is adequately protected by the line arrester, in most cases the reactors are additionally protected by surge arresters connected across the winding. The rated voltage of the arrester is selected to be in accordance with the short circuit voltage drop across the reactor.

In some projects a tapped reactor is preferred to provide some flexibility to adjust for future changing conditions on the system. Tapping of large Mvar HV air core reactors is usually achieved by providing individual coils which are connected in series in one single stack per phase. The range of reactance and the number of taps depends on the actual project requirement.

3.3 HV series reactors for the APG case study

The reactors are required to provide an impedance of 50 Ω. They will be installed in series to 220 kV transmission line systems. The basic data is given in figure 3a. A dry-type reactor design based on these data will primarily be governed by the voltage stress (steady state and transient) and by the continuous current coupled with the temperature rise limit of the winding insulation. Due to the low short circuit to continuous current ratio of 3.3 the short circuit current does not influence the winding design. Other factors however, such as physical constraints imposed by production and transportation must also be considered. Based on the specified data the reactor designed for class F temperature rise limits resulted in a coil size of 2.7 m in height and of 3 m in outer diameter. The mass of the reactor depends on the winding loss figure which is based on the selected current density. Assuming typical per phase losses (referenced to 75 °C average temperature) in the order of 90 kW, the mass of a single phase unit, including support insulators will be around 8.4 tons.

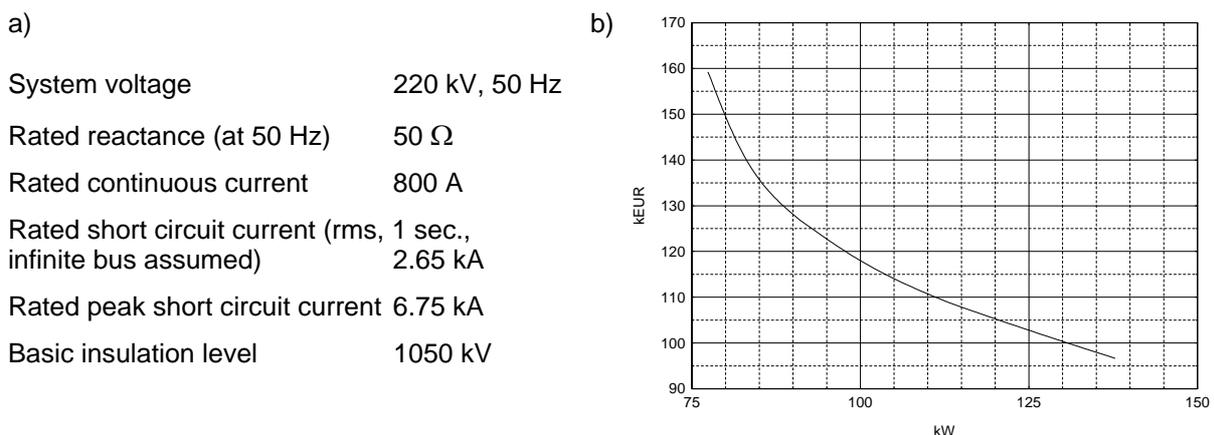


Figure 3 a) HV Series Reactors for the APG-Case Study – Technical data
b) Trend curve of equipment cost vs. loss (single phase reactor, incl. support insulators)
For a given coil shape and a temperature class limit the winding may be designed for different losses by varying the winding cross section of the individual layers and/or the number of the layers. Figure 3b shows the variation of the equipment cost vs. the losses. Assuming a capitalised loss factor

(in EUR/kW) specific for the application, the cost trend curve allows an optimum selection of the reactor losses to achieve minimum life cycle cost.

4 RELEVANCE OF LOAD FLOW CONTROL FOR THE AUSTRIAN TRANSMISSION NETWORK

4.1 Bottlenecks in the transmission network of VERBUND-APG

Due to the new regime of power plant operation, APG faces severe bottlenecks within the transmission grid, especially between the northern and the southern region (see figure 4). The connection between the two regions is provided by three nearly 50 years old and, referring to their transport capacity, rather weak 220 kV double circuit lines. Strong differences in the national power balance with a surplus of up to 1900 MW in the northern region and a deficit of about 1400 MW in the southern region, combined with international power flows (including unintended loop flows) lead to an overloading of the lines far beyond the (n-1)-security criterion. Without CM measures, the (n-1)-security criterion on the 220 kV lines from north to south is exceeded for long periods with the tendency to reach the thermal operation limit¹ of the lines. Operational restraints, the closing down of inefficient thermal power plants in the southern region and the ongoing construction of wind power plants (up to 1000 MW) in the northern region will increase the bottlenecks in the near future.

Besides CM measures, the limitation of power flows by increasing the impedance of the 220 kV north to south lines with series reactors could be an effective method to mitigate the bottlenecks. With regard to the technical characteristics of series reactors as mentioned before, the possible effects on the APG grid have been analysed by load flow studies.

High voltage transmission grid of VERBUND-APG

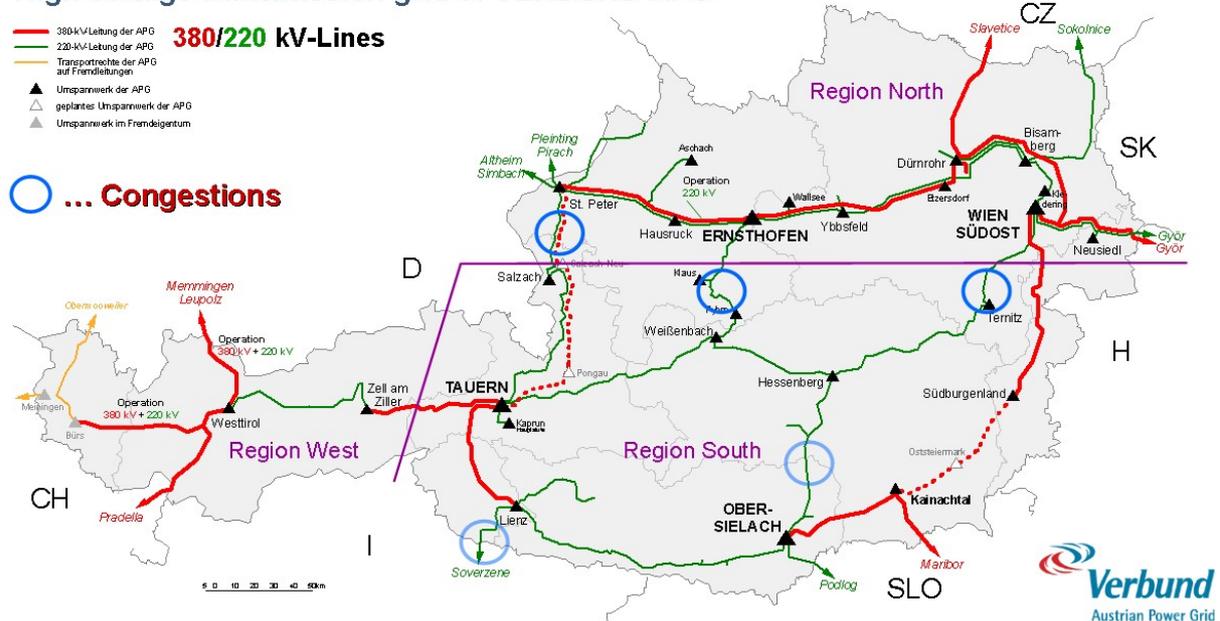


Figure 4 380/220 kV Transmission Grid of VERBUND-APG; the 220 kV north to south lines are subjected to congestion issues; 380 kV-projects are marked with dotted lines

4.2 Potential application of (switchable) series reactors for load flow control

¹ This high loading of the lines is only tolerable in connection with the automatic disconnecting device, which was installed in agreement with the Central-TSOs – if the load flow at specific lines reaches 115 % of the thermal limit, the interconnection lines to Czechia and Hungary are automatically disconnected in a predefined sequence.

The installation of series reactors leads to an increase of the line impedances which is technically comparable with an elongation of existing transmissions lines. This variation in the grid results in limited flows on the concerned lines, with the aim to reach acceptable levels of the load flows. As there are no changes in load and generation patterns the load flow is shifted to parallel branches.

To investigate the impact of series reactors in a real network, series reactors were installed for calculation purposes in a load flow snapshot (base case) of the APG grid. In a first step one series reactor with an impedance of 50Ω was installed in both circuits of the 220 kV double circuit line Ernsthofen – Weißenbach. Based on a typical high load situation (base case), a calculation was made to analyze the effects and deviation from the base case. According to the comments in chapter 2.2, a relief of the line Ernsthofen – Weißenbach was reached by shifting the flow mainly to the adjacent 220 kV lines St. Peter – Salzburg and Wien Südost – Ternitz with a further slight reduction of the total north to south flow within Austria (Figure 5).

Due to the existence of three parallel weak double circuit 220 kV north to south lines within Austria, the installation of series reactors in only one line is not sufficient to mitigate the congestion. In a second step, the installation of series reactors for each circuit of all three 220 kV lines St. Peter – Salzburg, Ernsthofen – Weißenbach and Wien Südost – Ternitz was simulated. In a third step, the serial connection of two reactors (each 50Ω) per circuit and line was calculated. Figure 5 gives the results of all calculations (step one through three) describing the achievable load reduction on each line and the resulting north to south flow depending on the installation of series reactors. The results of the load flow calculations based on the installation of series reactors are in the same order as the achievable load flow reductions on the lines with presently applied re-dispatch measures. Considering the enormous costs of re-dispatch measures, this alternative CM measure provides an additional beneficial aspect.

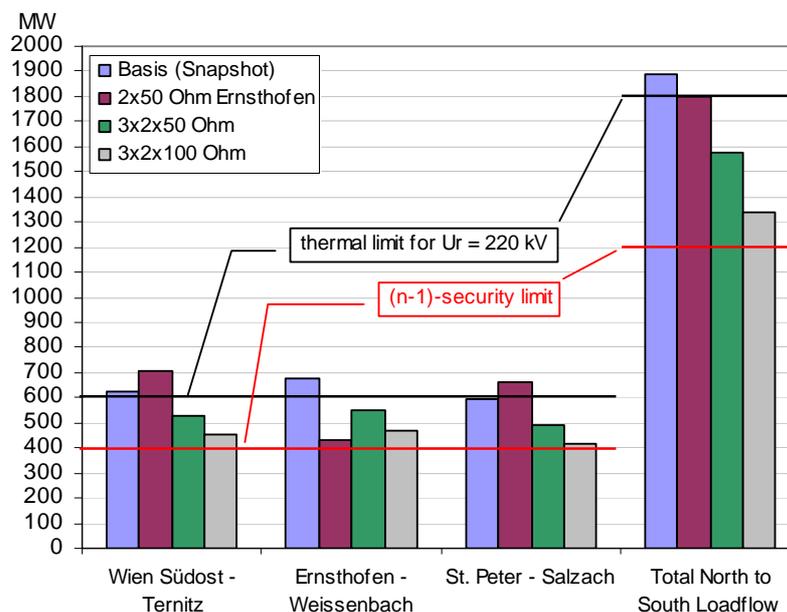


Figure 5 Load flow on the three 220 kV double circuit north to south lines and the total north to south flow with HV series reactors installed

Apart from the high voltage drop across the reactors, step three of the simulation with a serial connection of two reactors ($2 \times 50 \Omega$) for each circuit also leads to voltage angles which exceed 35° . This effect has to be considered and indicates possible limits for the grid operation.

The net result of the study is that the north to south load flow within Austria can be reduced and successfully limited with the installation of HV series reactors. Due to the increase of line impedances within the Austrian grid the load flow is mainly shifted to adjacent lines in the neighbouring countries, whereby the southern part of Austria is increasingly supplied by energy flows from the Western part

of Austria and from Slovenia. These effects will have to be discussed with the neighbouring TSOs and need to be further considered in the calculation and allocation of net transfer capacity values between neighbouring countries (otherwise loop flows could occur). Nevertheless, CM by implementation of series reactors constitutes a new interesting and effective possibility to relieve the bottlenecks in the transmission grid of APG – but it requires parallel powerful transmission lines with free capacity. Especially in combination with other measures, such as the usage of phase shifting transformers and special switching conditions within the grid, the installation of (switchable) series reactors becomes an attractive option for power flow control. The comparison of costs for power plant re-dispatch versus the investment cost for series reactors provides a good reason to consider the installation of series reactors if the intended extension of the 380 kV grid cannot be realised in the short term. A further additional benefit is a significant reduction of transmission losses by avoiding high loading of the existing 220 kV lines.

5 CONCLUSION

The present article briefly described the motivation and the technical options for load flow control and explained in detail the employment of HV series reactors. The advantages of the dry-type air core reactors are their simple implementation, the possibility of a short term installation and the significant cost advantages. Design and installation aspects of dry-type air core reactors for HV use were described to some detail.

The 220 kV north to south connection lines of the transmission system operator VERBUND-Austrian Power Grid are extremely (over)loaded. To reduce the power flows APG has to apply massive and highly cost-intensive congestion management measures until the future commissioning of planned new 380 kV lines. This is the reason why APG has made first studies considering the use of HV series reactors within its grid as an alternative solution.

Compared to other technologies such as PST and FACTS load flow control with series reactors offers many advantages. As the investment costs are rather low and there is a short payback time, series reactors would be an interesting alternative for congestion management in case of bottlenecks which will finally be removed by erecting new transmission lines.

Controlling load flows must be predominantly used to reduce loop flows and congestion. However, it must be pointed out that increasing the local impedances of lines in a meshed grid by using series reactors might impose further restrictions – also on parallel lines. It is therefore very important to evaluate the effects of any load flow control techniques together with all relevant partners.

6 REFERENCES

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