Influence of phase shifting transformers and HVDC on power system losses

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Abstract— **Power flow controlling devices such as phase shifting transformers are increasingly important in the power system. They can increase reliability and can serve as an alternative to new investments in overhead lines, which are difficult due to a lack of public support. Furthermore, they are an important means of control for a transmission system operator in the liberalized market. HVDC links recently also got renewed attention as they do not only provide the possibility to control the power flow, but can also be economically competitive to underground ac cables [1]. Especially with the emergence of VSC HVDC applications for bulk power transport, HVDC is a real alternative in the meshed power system.**

The usage of power flow controlling devices in a meshed grid causes the power to flow along alternative paths. However, these devices, and especially HVDC and VSC HVDC, incorporate significant losses. Furthermore, the shifting of power to other lines can cause losses in other parts of the grid.

In this paper, the losses caused by the different power flow controlling elements are discussed, and afterwards their influence on the power system losses of a meshed grid are investigated. An important issue that is addressed in this paper is the use of multiple power flow controlling devices in one grid, consisting of multiple control areas.

Index Terms— **Power flow control, phase shifting transformers, LCC HVDC, VSC HVDC, system losses.**

I. INTRODUCTION

A. Changing transmission grid

Originally, electric power flows were the result of the interaction between power generation, consumption and available transmission paths. As such, the system operator had little influence on the flow paths. He could connect or disconnect lines, change the tap settings of transformers, connect capacitors for reactive power injection, and give active or reactive control signals to power plants. At that time, the European grid was subdivided in several smaller, mostly national grids called control areas, each served by only one local, vertically integrated company. The power flow through the grid was rather well known, and could be controlled by redispatching power plants which were owned and operated by the same company. Interconnections between zones were intended only for emergency backup and maintaining synchronism with other systems, increasing the security of supply. Between these zones there were, and still are, few interconnections. Some lines were built for supporting long time contracts, as e.g. between Italy and France, France and Belgium, Belgium and The Netherlands and The Netherlands and Belgium. These long term contracts have been abandoned after the full opening of the electric energy market in Europe.

Two recent developments have changed the European electricity world significantly: the liberalization of the European electricity market, and the ever increasing penetration of intermittent distributed generation such as wind energy and other renewables, the latter being driven by the concern of greenhouse gases.

Due to the liberalization of the European electricity market, power exchanges tend to follow the price differences. However, electric power flows according to Kirchhoff's laws. As a result of liberalization of electricity markets, leading to an unbundling of generation and transmission, energy transactions in the meshed European grid are not centrally controlled or coordinated, but rather vividly take place until the very moment of the physical delivery, if allowed by so-called intraday trading. Therefore, power flows in real time differ at the moment of gate closure.

The increased penetration levels of undispatchable generation resources (e.g. wind power and heat driven CHP) give rise to a high amount of uncertainties in the international grid. Unexpected power flows, called loop flows, can be seen in the European grid, making it necessary for the Transmission System Operator (TSO) to operate with a larger safety margin and to improve cooperation by exchanging data cross border. The market operation, with its often hourly based scheduling, together with the recent rising penetration levels of non dispatchable generation, therefore add to the amount of uncertainty in the international grid and congestion problems at borders occur.

The most straightforward solution to solve this issue would be the construction of new power lines, and especially new interconnections between control areas. However, investments in grid reinforcements (new transmission lines) are limited throughout Europe, foremost caused by political unwillingness due to socio-ecological concerns about new overhead lines. Also regulatory pressure towards short term price reductions instead of strengthening the grid in the long term does not

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lead to many new investments [2], [3].

B. Controlling power flows

In the past, the main control means of the TSO were redispatching power plants, switching reactive power (capacitors), changing transformer taps and line switching operations. Due to unbundling, the TSOs no longer control the generators. This reduction of control means makes secure grid operation more difficult.

As a reaction to these reduced control means, power flow controllers (PFC) are installed in the power system. Furthermore, power flow controlling devices enhance power transmission capability without the need of erecting new overhead transmission lines. Phase Shifting Transformers (PST), Flexible AC Transmission Systems (FACTS) and High Voltage DC (HVDC) installations are recently installed [4], [5], or planned for the near future, in order to meet the new challenges in the grid. These devices and systems enable the grid operator to control the loop flows, thus allowing to use the existing system more efficiently, with a higher economic benefit. Doing so, installing control devices has the aim to improve the reliability of the system, thus contributing to avoid blackouts [6].

Power flow controlling devices are also often associated with Wide-Area Measurement Systems (WAMS) as the combination offers great prospects for the secure control of the power system of the future. Although both power flow controlling devices and WAMS are currently available, the combination still is in its infancy.

II. POWER FLOW CONTROL

This section covers the theory behind power flow control through a line, and the devices which enable flow control through a transmission line: phase shifting transformer and an HVDC system. A more comprehensive overview of the available power flow controlling devices can be found in literature [7]–[9].

A. Controlling the flow through a line

A simplified relation between active power transported over a transmission line between nodes s and r and the complex voltages at both nodes is:

$$P_{Line} = \frac{|V_s| \cdot |V_r|}{X_{Line}} \cdot \sin(\delta) \tag{1}$$

with V_s and V_r the voltages at the nodes, δ the phase angle between these voltages and X_{Line} the line impedance. The power flow through the line can be controlled by altering the voltage at a node, the impedance between nodes and the angle between terminal voltages. Since the voltage in a power system has to remain within strict limits, voltage regulation is not well suited. The line flow can also be altered by changing the line impedance. This can be done by inserting a variable series impedance. An example of such a device is a TCSC (thyristor controlled series capacitor). This device allows a fast varying active power flow control. Although series impedances can be used to alter the flow, they are mostly used for dynamic power system control such as power oscillation damping.

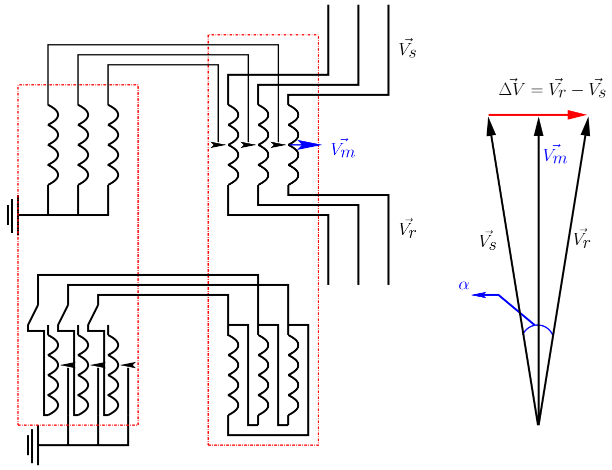

Fig. 1. Symmetric indirect phase shifting transformer.

B. Phase shifting transformers

Changing the phase angle between two nodes can be done by injecting a series voltage in quadrature to the phase voltage. In practice this can be done by using phase shifting transformers sometimes also referred to as quadrature boosters. The PST is a mechanically switched device which inserts a transformed, variable (using a tap changer) line voltage in series with the phase voltage. Fig. 1 depicts this for a symmetric indirect phase shifting transformer.

$$P_{Line\ with\ PST} = \frac{|V_s| \cdot |V_r|}{X_{Line} + X_{PST}} \cdot \sin(\delta + \alpha_{PST}) \tag{2}$$

Although phase shifting transformers enable the control of power flowing through a line, the flow itself is still a function of the grid situation, and the power flow can only be “shifted”.

C. HVDC

A special case of power flow control is using high voltage direct current (HVDC), separating both terminals by a dc link, allowing full control of the active power between the sending and receiving ends. Generally, there are two types of HVDC: the thyristor based LCC (line commutated converter) HVDC and the IGBT based VSC (voltage source converter) HVDC. Using VSC HVDC, or Static Var Compensators (SVC), reactive power at both terminals of the dc system, and therefore the voltage at both sides, can be controlled. VSC HVDC offers also several other advantages over thyristor based HVDC such as black-start capability and power oscillation damping. The disadvantages of VSC HVDC are the limited operational experience, the higher power losses, limited maximum capacity for a single system (1100 MW) and the higher costs [10]–[12]. Only cable based VSC HVDC systems exist, while LCC HVDC can also be combined with dc overhead lines.

Contrary to phase shifters, the flow through the HVDC line is fully controllable, and not influenced by the power system.

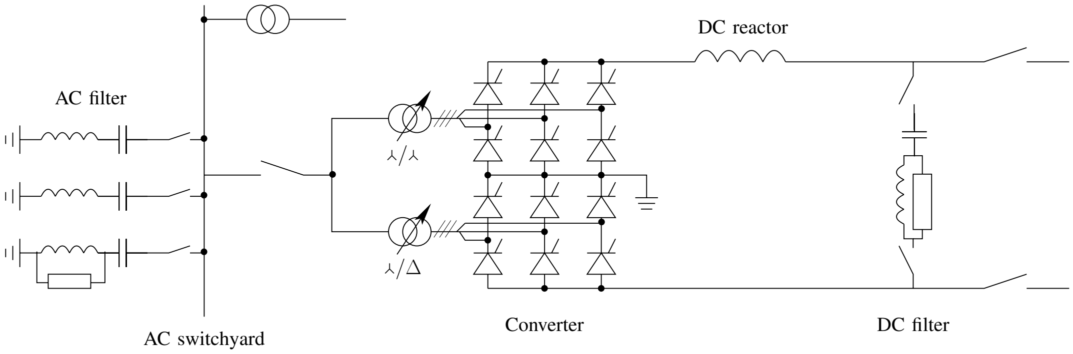

Fig. 2. Schematic view of a LCC HVDC installation

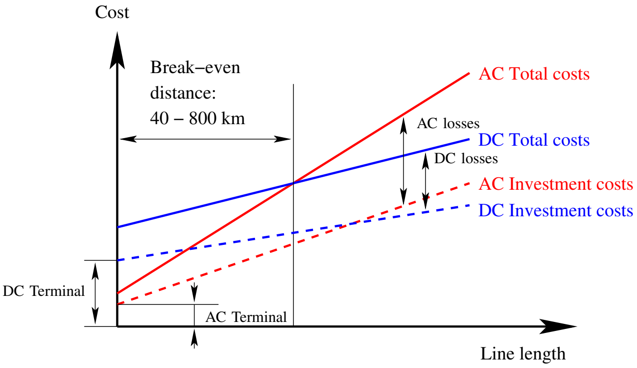

Fig. 3. Comparison of ac and dc system costs (after [13])

D. *Comparison ac and dc costs*

An ac installation (line + substation) has a relative low installation cost, and high line losses. A comparable dc installation has a significantly higher investment cost. The costs for a dc cable are lower per kilometer, so that there is a break-even distance where ac costs and dc costs are equal. Fig. 3 compares the costs of a HVDC connection and an ac connection. The break-even distance depends on a lot of factors, but is generally about $40 - 80$ km when the ac system uses cables (such as with undersea connections) and up to 800 km when overhead ac lines are used.

III. LOSSES OF POWER FLOW CONTROLLING DEVICES

A. *Phase shifting transformers*

Phase shifting transformers are special forms of tap-changing transformers, and have similar efficiency ratings. When discussing their losses, both iron and copper losses should be considered. The iron losses are constant for the transformer when energized, the copper losses are function of the current passing the transformer and the tap position α. The latter is neglected throughout the remainder of this paper.

$$P_{loss\ pst} = P_{Fe} + P_{Cu} = P_{Fe} + R_{series}(\alpha) \cdot I^2 \qquad (3)$$

For a large PST, the iron losses amount to approximately 0.025 $\%$ of rated power, while the per unit value of load losses can be in the order of magnitude of 0.18 $\%$ at rated current. These characteristics show a very high total efficiency of $\eta_{PST} \approx 99.8$ $\%$ at full load and maximum phase angle.

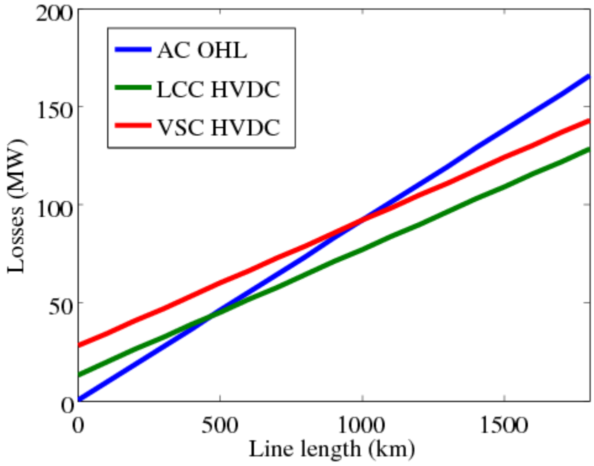

Fig. 4. Line losses as a function of the length for 800 MW power flow in a 1000 MW ac, LCC HVDC and VSC HVDC system.

The reactance of a PST is much higher, normally between 6 and 12 per unit, and also dependent on the tap setting.

B. *HVDC losses*

The HVDC system exhibits significant converter losses: the no load losses are approximately 0.1 $\%$ loss/station for LCC HVDC and 0.18 $\%$ loss/station for VSC HVDC. The load losses are about 0.7 $\%$ load/converter for classical thyristor based HVDC, and 1.52 $\%$ load/converter for VSC HVDC lines. The power losses in dc cables are however lower than losses in ac lines of equal length and power rating [11], [14]. Fig. 4 shows the losses as a function of the line length for a 1000 MW line with 800 MW power flow for a normal ac overhead line (without flow control), a LCC HVDC link and a VSC HVDC link. Fig. 5 shows the losses of a 60 km line as a function of line flow for the same three types of connection.

IV. SYSTEM LOSSES

When controlling the power flow, not only the flow through the line with the PFC is changed, but power flows throughout

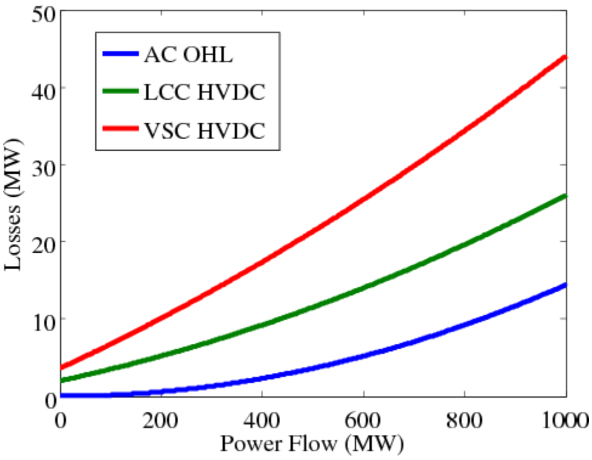

Fig. 5. Line losses as a function of the power transfer through the line for a 60 km connection in ac, LCC HVDC and VSC HVDC.

the system are altered. This will cause different, not necessarily higher, power losses. Although the solution without power flow controlling will lead to flows that follow the path of the minimum impedance, this does not necessarily lead to minimum power losses. This can be easily shown when considering two parallel paths between a source and a load, one purely resistive, and one purely inductive. Forcing more power to flow through the inductive path will lower the overall losses. A second consideration to take into account is the nonlinearity of the power losses: $P_{loss} = R \cdot I^2$. This simple equation has great repercussions on the losses: when some lines in the system are near to full load, they contribute more to system losses. Using power flow controlling devices, power can be shifted from congested lines to lines with more free capacity, lowering total system losses [15].

A. *Power system losses with a PST*

Simulations are performed on the IEEE New England 39-bus system, shown in Fig. 6. Subsequently, for each line located in some kind of loop (35 of the 46 branches in total), a phase shifter is placed in that line, and a varying phase shift of -25 to $25°$ is applied. For each such system, the system losses are calculated and compared to the system losses without phase shifter. Load flow calculations are done using MATPOWER [16]. The results are shown in Fig. 7 (red, full lines). Depending on the case, the system losses with phase shifter can be lower than those without flow control at some given angles. This is not generally the case as the phase shifter itself exhibits a loss, and the power system is in an equilibrium of minimum impedance (Kirchhoff) flows without the PSTs.

This equilibrium is distorted when large power flow shifts are induced in the grid. It can be seen that losses increase almost quadratically with phase angle. The maximum additional losses are ± 50 MW, which is significantly more than the losses without phase shifter. This is caused by the large circulating currents induced by the phase shifter. It is possible to reverse the power flow in some lines.

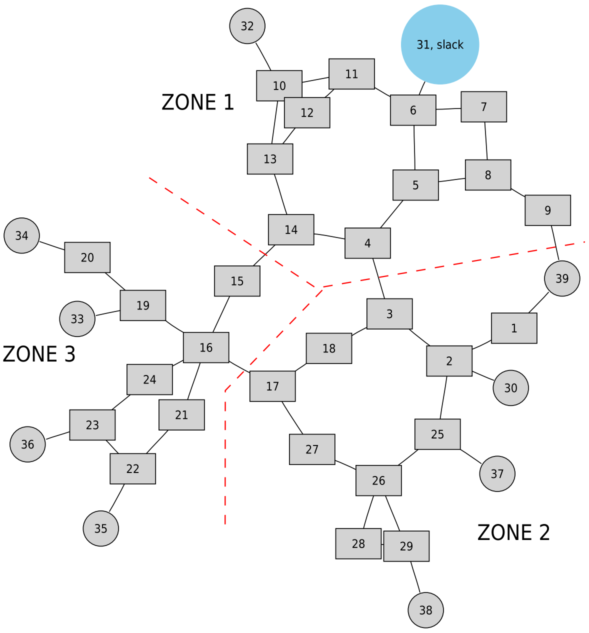

Fig. 6. The New England 39-bus system. Generator nodes are pictured as a circle, PQ nodes are pictured as boxes.

B. *Power system losses with HVDC*

When an HVDC system is included to control the power flow, dc cable losses and converter losses have to be considered. Although the cable losses of comparable systems are generally lower for dc systems, the converter losses are considerable, especially when short connections are considered (see Fig. 4 and 5).

The same tests as for the PST are performed for LCC HVDC systems: for each line in a loop, a 60 km, 1000 MW LCC HVDC system is inserted.

For inclusion of the HVDC line in the power system model, the LCC HVDC line is modeled as two PQ-nodes at the line terminals with opposite power generation. In order to be able to compare the losses of the LCC HVDC link with those of phase shifting transformers, the same line flows are used as with the phase shifter at different angles ($P_{HVDC\ line}(\alpha) = P_{PST}(\alpha)$). The HVDC line losses are not directly incorporated in the system, but afterwards added. Fig. 7 shows the losses for the LCC HVDC link (blue, dashed). It is clear that, as with the phase shifter, the losses increase with rising power shift. In Fig. 8, the difference between the LCC HVDC and the the phase shifter losses are shown. On average, the system losses using LCC HVDC are 1.166 MW higher compared to those with a PST, but in some cases the LCC link has significantly lower losses, especially at high phase shift angles.

C. *Effect of voltage control at the end terminals*

Using HVDC with controlled voltage can partly compensate for losses in the system. Furthermore, when large power flows are considered, power generators are less likely to reach their reactive limits as the reactive power balance of the system is

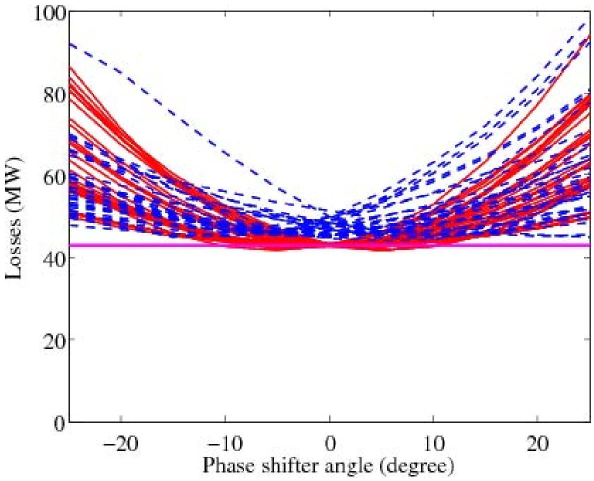

Fig. 7. Losses caused by power flow controlling devices in the New England system. Subsequently, a power flow controlling device is inserted in the system, and the power shift is altered. The results for PSTs are in red full lines, for LCC HVDC in blue dashed lines. The power system losses without power flow controller are shown in magenta and are about 42.7 MW.

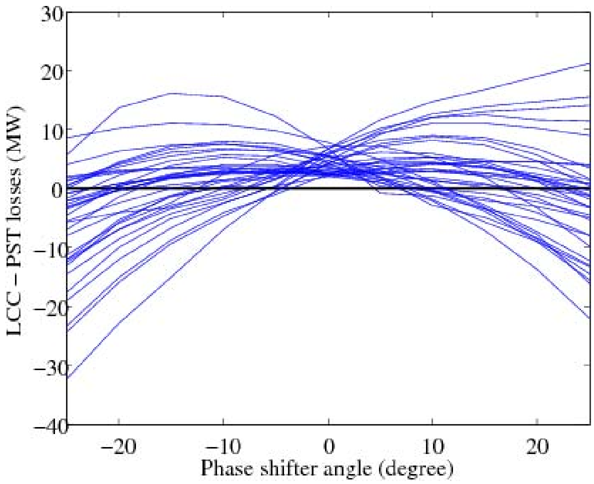

Fig. 8. Difference between the losses when using a LCC HVDC link and when using a PST.

improved. The HVDC lines with voltage control are modeled as two PV-nodes at the line terminals, with opposite power generation. The voltage at these nodes is set to the value between 0.925 and 1.075 per unit which leads to the lowest system losses. HVDC system losses are added afterwards.

Voltage control at the end terminals is performed using VSC HVDC, or using SVCs. Generators at the end nodes of the line can also assure a constant voltage.

In Fig. 9 the effect of voltage control on the power losses is shown for one specific case: a 1100 MW VSC HVDC link is inserted in the New England test system between nodes 17 and 18, both with and without voltage support. The effect of the voltage control can clearly be seen in the negative part of the characteristic, where the system losses without control of the voltage are more than 100 MW higher than those with control. The effect of voltage control can also be seen when increasing both the system load and generation with an equal factor. The system becomes more loaded, and in case of the VSC connection this gives less problems of generators reaching their reactive limits, while in case of LCC HVDC and especially PSTs, the system voltage can not maintain within the specified limits at all nodes. Of course, in real systems, this problem can also solved by installing additional switchable reactive compensation or SVC in the system.

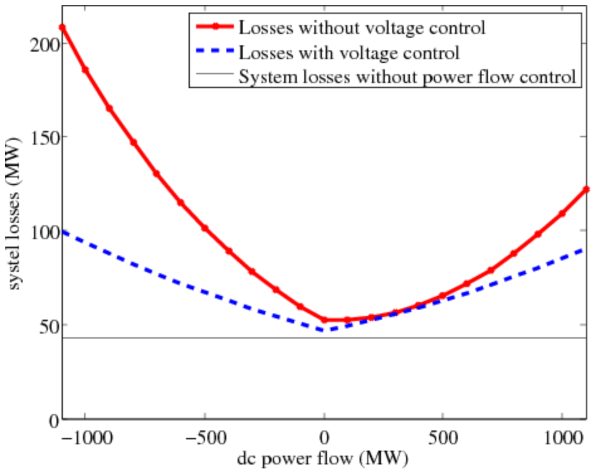

Fig. 9. Power system losses in the New England 39-bus system with a HVDC link between nodes 17 and 18. The effect of voltage control on both terminals is shown.

When the same simulations as in section IV-B are performed, but using a VSC HVDC link as PFC, it appears that the loss reduction by voltage support does not weigh up to the increased converter losses. On average, the system losses with VSC HVDC were 7.9 MW higher than those with a PST.

V. SYSTEM LOSSES WITH MULTIPLE PFC

When multiple PFC devices are incorporated in a power system, the power system losses are not the algebraic sum of the losses in the independent line losses by the individual PSTs as calculated in the previous section. The devices can cooperate and in fact reduce the losses in the system, or they can worsen the situation and cause high losses. The system is not linear. In Fig. 10, the system losses of PST, LCC HVDC and VSC HVDC are compared, when two power flow controllers are placed in the system. PFC 1 is placed in the line between nodes 14 and 15, and PFC 2 between 17 and 18. Again, in order to be able to compare PSTs with HVDC links, the power flow through the PST at a certain angle is again used as flow through the HVDC line. For all three solutions there is a part of the control area where that application is the solution with the lowers losses. On average, the PST solution has the lowest losses. As can be seen from Fig. 10, the losses can add up to nearly 250 MW in the case of LCC HVDC, which is nearly five times the losses of the system without control. This is partly caused by the modeling of the reactive power demand of the LCC HVDC link.

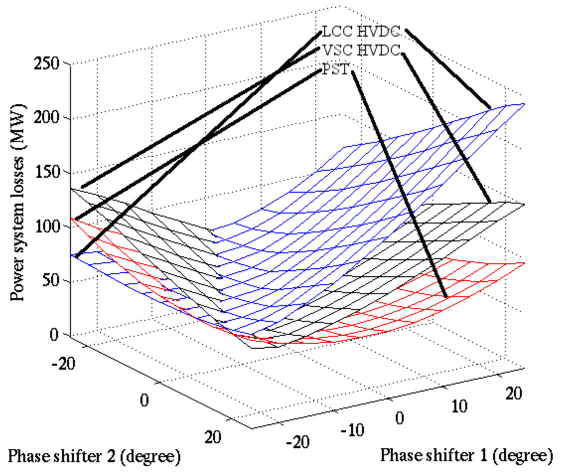

Fig. 10. System losses with two PFC devices installed. PFC 1 is placed in the line between nodes 14 and 15, and PFC 2 between 17 and 18.

VI. MULTI-ZONE SYSTEMS WITH PFC

A. Need for global and coordinated control

When multiple power flow controlling devices are installed in the transmission grid, local control can cause suboptimal or inefficient use of the available power system. Some possible problems that can arise when dealing with power flow controlling devices are shown in Fig. 11.

Case A depicts the base case, where a simple four zone example is given, with a net generation in zone C and a net withdrawal in zone A. Both flow paths cross zones B and D respectively, both with an equal share of the load.

Case B gives the situation after implementing a power flow controlling device in zone B. 30 % of the flow is shifted from the path through B to the path through D. This case is beneficial for zone B, as lower losses occur in that zone and the lines in system B are generally less loaded. In zone D, however, the flow rises, and congestion can occur. Furthermore, the system operator in zone D is normally not informed about the status of the grid in zone B, and is not always able to cope with it.

Case C depicts the situation where zone B sets its power flow device in such a way that there is a flow from zone A to zone C. The flow through D has to compensate this and there is a resulting 10 % circulating current.

In case D, there is an additional power flow controlling device installed in A, which counteracts the device in B. Note that this can be intentional (counteracting the system operator in B for a better utilization of the grid in A) or unintentional (since both system operators have different, local, objectives for the control of their local equipment).

These simple examples state the need for coordination, not only between different devices in the grid, but also cross-border.

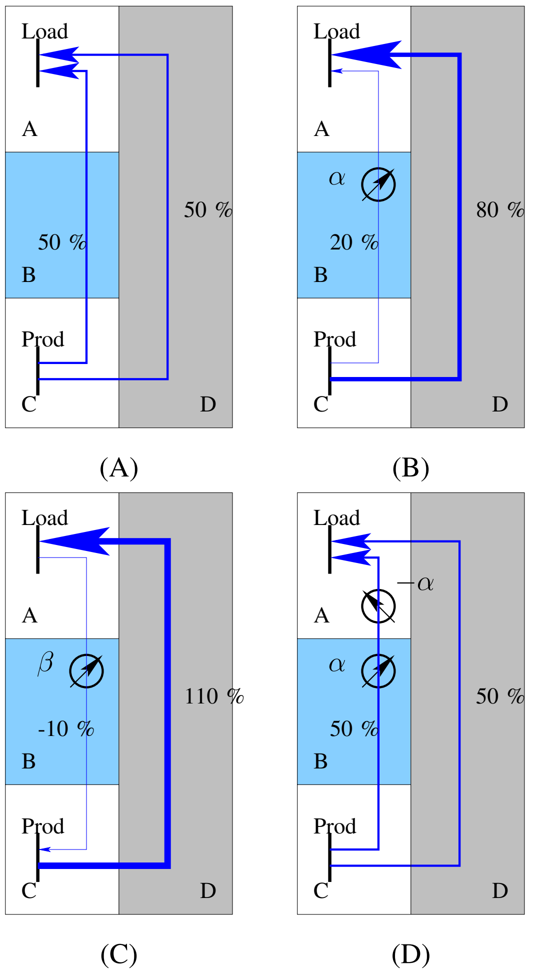

Fig. 11. Example of possible problems with power flow control

B. Sub-optimal loss optimization

Although total system losses mitigation is a noble cause, often this is not the aim of a TSO. Their main objectives are to maintain and develop the grid infrastructure, to operate it and to improve the operation of the electricity market. Concerning losses, the overall system losses are less an issue than those in the local zone. As an example, the New England system (Fig. 6) is subdivided in three parts, and two power flow controlling devices (in this case phase shifting transformers) are inserted. Phase shifting transformer 1 is placed in the line between nodes 14 and 15 (between zone 2 and 3), and phase shifter 2 between 17 and 18 (within zone 1). In Fig. 12, a contour plot of the losses in each separate zone is shown as a function of the phase shifting angles of both PSTs.

The results in Fig. 12 have important repercussions for the control of the power flow controlling devices. Depending on which TSO is the owner of the phase shifters, the desired set-point will differ. For zone 1 (red, full lines on Fig. 12), the optimal phase shifting angles will be $-13°$ for PST1, and $0°$ for PST2. However, this is not the optimal setting for either of the two other regions. Table I gives an overview of the different

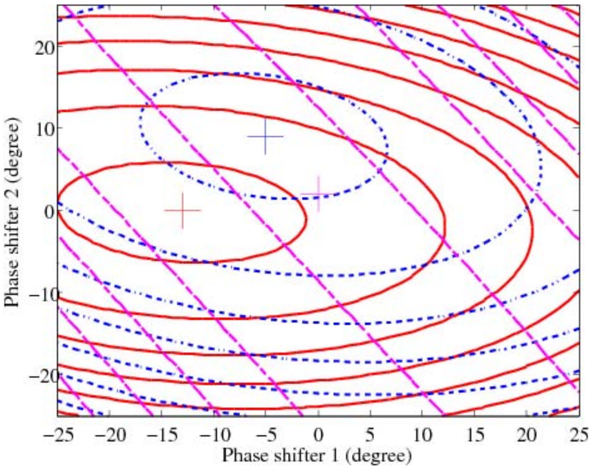

Fig. 12. Contour plots of the losses in the 3 zones, dependent on the settings of the two installed power flow controlling devices. Zone 1 is indicated in red with full lines, zone 2 in blue with a dash-dotted line and zone 3 in purple with a dashed line.

TABLE I

LOSSES PER ZONE WITH POWER FLOW CONTROL AND THE DIFFERENT OPTIMAL VALUES (IN MW). THE MINIMUM IS TYPESET IN BOLD.

	Angle (PST1, PST2)			
Losses	$(-13°, 0°)$	$(-5°, 9°)$	$(0°, 2°)$	$(-5°, 6°)$
Zone 1	**11.4**	13.2	12.3	12.4
Zone 2	11.6	**8.72**	9.8	8.91
Zone 3	12.0	9.18	**9.17**	9.23
Total	35.0	31.1	31.3	**30.6**

zones and their losses at the different “optimal” angles. As phase shifter 2 is located between two nodes of zone 1, it is most probable that the TSO of zone 1 will operate this phase shifter. The phase shifter between nodes 14 and 15 lies on an interconnection, and can be operated by either TSO 2 or TSO 3, dependent on the actual location of the device.

The control of multiple PFC can lead to different grid usage, dependent on the different TSOs and their interactions:

- each TSO operates its phase shifter as they seem fit, without coordination. In the end, a sub-optimal “Nash” equilibrium will be reached.
- there is a price on phase shifter setting, sold in a market based system, resulting in a compensation for the TSO that has to operate its PFC in a less favorable setting [17].
- the different TSOs coordinate the phase shifter usage across borders

Due to the fact that power flow control actions usually have a further reach than local generation dispatch, more coordination and transparency between grid operators is needed. Of course the minimization of the system losses is not the only optimization objective (e.g. increasing transfer capacity), but the same conclusion is valid: coordination improves overall efficiency.

VII. CONCLUSIONS

Power flow controlling devices are increasingly present in the power system, also in meshed systems. The increased occurrence of uncontrolled flows through international systems, and the reduced control capabilities for TSOs in the unbundled power system are the causes of this phenomenon.

Reducing power system losses is one of the main tasks of a TSO, as it forms a high portion of the operational cost. This paper compares the losses in the overall meshed grid when phase shifting transformers, LCC HVDC and VSC HVDC links are introduced. It is shown that the losses in a power system are strongly linked to the degree of flow control, and a significant rise in system power loss can be expected, although it is possible to reduce the power system losses using control. Special attention is given to the loss reducing effects of voltage control with VSC HVDC.

It is shown that in the case of multiple power flow controlling devices installed in a single system, and especially in systems with multiple control areas, the coordination between power flow controlling devices is key for the economic use of the power system.

APPENDIX
SIMULATION DATA USED

Next to the New England 39-bus system which was provided in the MATPOWER program, the data presented in table II was used.

TABLE II

LOAD FLOW DATA USED

	PST	LCC HVDC	VSC HVDC
Standby losses		0.1 %	0.18 %
load losses		0.7 %	0.152 %
X_{PST}	8 %		
R_{PST}	0.2 %		
$R_{dc\ cable}$		0.018 Ω/km	0.018 Ω/km
Line length	60 km	60 km	60 km
Power rating	1400 MVA	1000 MW	1000 MW

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