

Phase shifting transformers installed in the Netherlands in order to increase available international transmission capacity

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The Netherlands

1 Introduction

Because of the liberalisation of the market, electricity import to the Netherlands increased substantially in recent years [1]. TenneT, the Dutch Transmission System Operator (TSO), is faced therefore with the desire of the market to increase the available cross-border capacity. From studies within TenneT, it was concluded that an increase in import capacity could be reached within reasonable time by installing phase shifters. Installing these devices at the Dutch 380-kV substation Meeden in series with the two interconnections to the grid of E.ON Netz, was found to contribute most to this desire.

To reach an agreement on installing the phase shifters and to determine the major ratings of the phase shifters, a joint study was carried out by all international parties directly involved.

In the paper some technical aspects of the design of the phase shifters will be treated. The specification turned out to impose severe constraints on many design options. The first device came in test operation mid 2002 and the second one early 2003. A picture of a single-phase transformer unit during transport and equipped with test bushings, is given in figure 1. Operational aspects will be described and some recent experience with the phase shifters will be commented upon in this paper.



Figure 1 Single-phase transformer unit

2 Initial planning studies

The Netherlands (figure 2) has five interconnectors, comprising 10 circuits, with two neighbouring countries. Because of the geographical and electrotechnical location of the country, main interconnection flows are directed from Germany to the Netherlands. The loading of the circuits from Rommerskirchen and Siersdorf to Maasbracht in the South, is often causing a transfer limitation. To maintain an n-1 security on the interconnectors the total import capacity in 1999 was limited to 3600 MW. At that time, a feasibility study within TenneT was carried out to determine the optimal solution for increasing the import capacity on the shortest term possible. The idea of constructing new circuits was abandoned immediately because of the long period of time needed to reach agreements

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with neighbouring TSOs and most of all because of time consuming efforts to design a suitable corridor and to obtain all necessary permits.

In the first study it was found that installing phase shifters in the 380-kV substation Meeden at the German border in the North would be most beneficial regarding import capacity. This solution had two major advantages: it created the largest increase in import capacity and it could be realised in a relatively short time of two years. When placing the phase shifters in the Maasbracht interconnector with Germany, which is situated in the South, the shift of flow would be from the German border to the Belgian border and would not much influence the interconnector in the North, which had the lowest loading.

In the above-mentioned study it was already found that the Dutch 380-kV grid has sufficient transmission capacity to accommodate 5000 MW import under n-1 conditions, assuming that the consequences for reactive power can be solved adequately [2].

A second study was necessary to determine the rating of the phase shifters and to analyse the physical availability of the German 380-kV grid to handle such large flows. This study was also a good opportunity to involve E.ON Netz and RWE Transportnetz into the plans of TenneT and to reach agreement on a technical level. Elia (the Belgium TSO) was informed later about the results of the studies.

Scenarios and modelling

The joint system study accomplished in 2000 was intended to investigate the feasibility of the import target and to determine the necessary rating and phase shift angle of the devices. The basic layout, given in figure 3, shows two identical phase shifters, located at the 380-kV substation Meeden, each in series with one of the interconnecting circuits to Diele and Conneforde (E.ON) respectively. In 2003, not foreseen during the study, the circuit to Conneforde has been looped in and connected to the substation Diele, which gives nowadays two identical parallel circuits.

The UCTE load flow of January 2000 formed the basis for all power flow calculations; in that model, import to the Netherlands amounted to approximately 3000 MW. An improvement of the model was made by RWE to include changes in the near future, regarding topology and production in the neighbourhood of Rommerskirchen.

To increase import to 5000 MW, production in the Netherlands has been reduced and production either in the east part of France or in Switzerland or in Poland have been increased. It was found that different production scenarios within the Netherlands, while maintaining the same amount of imported power, gave nearly similar results. Therefore only one Dutch production scenario was taken into account. A total of nine cases were studied deduced from combinations of the following production scenarios while maintaining a constant load condition:

1. The original case with the following changes in production:
 - a) A base case with only changes in Dutch production to increase the import to 5000 MW;
 - b) A case with additionally a 2500 MW production shift from the RWE area (decrease) to the E.ON area (increase) compared to the base case;
 - c) A case with additionally a 2500 MW production shift from the E.ON area (decrease) to the RWE area (increase) compared to the base case.

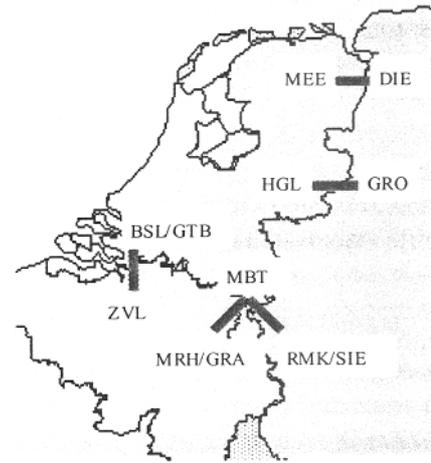


Figure 2 Interconnectors

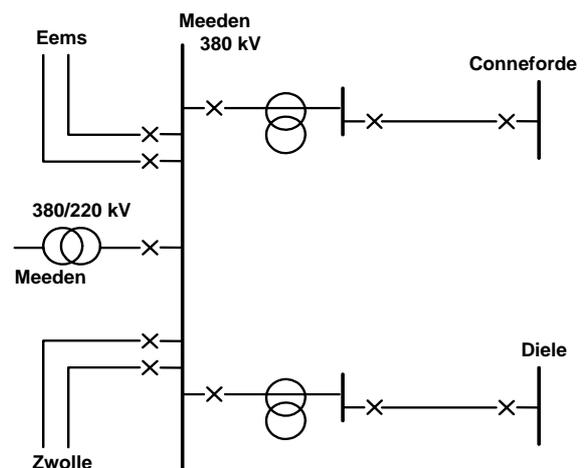


Figure 3 Integration of the two phase shifters in the Dutch 380-kV network

2. Three foreign export scenarios, which consists of three alternative mutually excluding locations for increased export to the Netherlands. The 2000 MW production increases has been obtained by a proportional increase of the generation in different areas:
 - a) In the east part of France;
 - b) In the Swiss area;
 - c) In the Polish area.

Furthermore it is important to know that in all cases the import through the proposed phase shifters at Meeden was set to 2×700 MW. The import through the interconnector Hengelo-Gronau was kept constant.

Simulations and results

Load flow calculations consisted mainly of setting up the nine cases, running n-1 contingency analyses and the interpretation of results. The effectiveness of the control of power to Germany could be well observed: only the non-controlled "gates" showed differences in loading for the nine cases. Especially in the E.ON area large load flow changes could be observed in the different cases. The flow, for instance, in the circuit Diele-Meppen changed from 800 MW in the south direction (case 1b2c) to 1400 MW in the north direction (case 1c2a).

Overloading of one of the phase shifters at the substation Meeden may be caused by an outage of the second one or the overhead line connected in series. In that case loading amounts to approximately 1200 MW. Because of some remaining capacity on other interconnectors, the overloading can be reduced to a value within its allowable operating range by activating the tap changer in the appropriate direction. Therefore, the phase shifters should be designed to sustain such an overload during the time needed to reduce the flow.

E.ON reported overloading in some circuits and transformers in their 380-kV grid during n-1 contingencies; especially the 380/220-kV transformer 421 in Conneforde was sometimes heavily overloaded, up to 190% in case 1b2c and the circuit Diele-Meppen up to 123% in case 1c2a and 1c2c. If such cases, with threatening overloads during n-1 contingencies, would become reality, the imports to the Netherlands must be redispatched. This can be done by limiting the flow through the phase shifters in Meeden and Gronau. When this is not sufficient, imports must be reduced.

Large differences between required phase shift angles were found in the nine cases in order to reach the desired flows through the interconnectors (figure 4). The phase shift angle is defined as the angle between the source and the load terminals of the phase shifter under load conditions. It is obvious that a shift in production within Germany influences the required angles most, as these changes are close to the interconnectors with Germany. Also power produced more to the south of Europe demands for larger phase shift angles. From the diagram it was concluded that a net maximum absolute value of 30° will be sufficient. With such a large angle and therefore a large quadrature voltage a symmetrical design is the only possibility to maintain the input and output voltage of the phase shifters within the required operational voltage range.

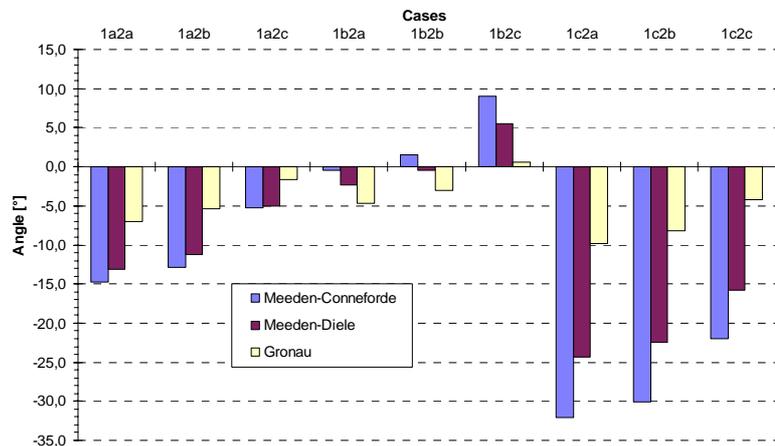


Figure 4 Phase shift angle between input and output of phase shifters in nine cases

The study delivered vital information that was used in making specifications. The power rating of the phase shifters was set to 1000 MVA with a minimum overload requirement of up to 1200 MVA during one hour. There was no distinct preference for the maximum short circuit impedance but there was a general feeling to keep it as low as possible because the phase shifters will be operated mainly

in the advanced mode. The necessary net phase shift angle range in the study was established to be $\pm 30^\circ$; this angle was specified as the maximum angle between input and output voltage under full load condition.

3 Design aspects of phase shifters

A phase shifter of the indirect type [3] consists of two transformers, a series transformer and a regulating transformer with (one or more) on-load tap-changers (OLTC). The MVA rating of each of these transformers is approximately equal to the through rating multiplied by the sine of the no-load phase angle. In the case this rating and the system voltage are small both transformers can be put in one tank. If the rating increases, especially at a system voltage of 400 kV, it is almost impossible, due to transportation limits, to arrange both transformers in the same tank. The result is that each transformer needs its own tank and there is a three phase connection between both tanks at 400 kV level and a three phase connection at a lower voltage level for connection of the regulating winding. If the rating increases more, it requires putting the tap-changers also in a separate tank. Alternatively, two separate phase shifters each having half the phase angle can be connected in series, resulting in four separate tanks. These solutions are quite complex having a lot of connections and reliability becomes an issue.

Due to the high rating of this phase shifter a different approach was taken, and it was decided to design the phase shifter as a bank of three single-phase units. The advantages of this design are: three identical units (which are easy to transport), no tank-to-tank interconnections at 400 kV level and the possibility for testing of each phase separately [4].

Each single-phase unit (see figure 5) consists of:

- A single-phase series transformer of 213 MVA, which is a two-legged core design. Each leg has a series winding of 70 kV (both legs connected in series) and an excitation winding with a rated voltage of 133 kV (both legs in parallel);
- A single phase regulating transformer of 202 MVA, which is also a two-legged core design and each leg has a source winding with a rated voltage of 208 kV (both legs connected in parallel) and a regulating winding with a rated voltage of 38,4 kV (connected in series);
- Two tap-changers RI 3600 (Reinhausen), and two current control transformers for a proper current distribution between the contacts of the tap-changers, to satisfy switching and overloading requirements of the tap changer.

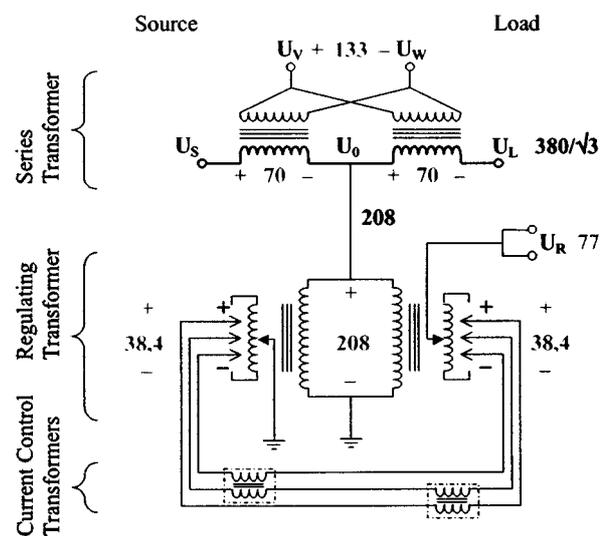


Figure 5 Connection diagram of a single-phase unit, with rated voltages given in kV

From a design and construction point of view, the series transformer and regulating transformer can both be considered as normal single-phase transformers. A phase shifter's role in the system is to control the flow of active power. Because of the angle between the system voltage and the quadrature voltage, the power factor in the series and regulating transformers may well be almost equal to zero, which is an "unusual" loading for a transformer. A 90-degree phase shift between the voltage across the winding and the current through it will result in a voltage decrease or increase depending on the load flow direction. This change in voltage across the series winding translates to a decrease or increase of the phase angle. This is an important issue for the system engineer: it necessitates specification of a phase angle both at no-load (37.2 degrees) and at rated load (30 degrees).

At the same time one wants to limit the short circuit reactance, in order to limit the change in phase angle (impedance < 12 %). This is also important for system protection, because a load flow direction leading to voltage increase will result in over-excitation of the core. In operation, the phase angle under load should be limited so that a certain over-excitation percentage is not exceeded (117 %).

The tap changer specification dictates the maximum short circuit current through it. Indirectly, this specifies the minimum value of the reactance in series with the tap-changer, which is related to the short circuit power of the system (50 kA) and the short circuit reactance in the zero degree tap position (> 7 %).

Each single-phase unit of the phase shifter consists of 4 windings and many interconnections. External surge arrestors only protect the load and source terminals. At the other points, resonances can occur due to switching operations in the system, which could lead to excessive voltages. Therefore the neutrals of the source and regulating windings are directly earthed, and it is only allowed to energise the phase shifter in the zero degree position.

Energising a transformer results in an inrush current. A phase shifter of this size and such a low reactance results in an inrush current of about double the magnitude as of the standard transformers in the system.

The phase shifting transformers are installed next to the 380-kV substation Meeden. This GIS-substation was built in the middle of the nineties when the Dutch 380-kV grid was extended to the north. During the site assessment in the pre-engineering phase different layouts for connecting the phase shifters to the existing lines of the interconnection to Germany were investigated. The preferred alternative was to build the transformers as close as possible to the substation Meeden under the existing line circuits to Diele and Conneforde. The construction of the phase shifters substation started in July 2001 lasted 12 months. The first phase shifter arrived at the substation Meeden in April 2002 and was commissioned in July 2002. The second one was commissioned in January 2003.

4 Protection and control concept

The basic requirements for the protection concept are well known: it should be highly dependable and highly secure. In other words the protection system has to trip when there is a fault within the protected zone and remain stable under all other circumstances.

The basis for the protection concept was derived from a report submitted to the Substation Subcommittee of the IEEE Power System Relaying Committee [5]. The protection scheme was developed during the initial design stage of the phase shifting transformers. This has led to the possibility to install current transformers at the optimal locations in relation to selectivity within the phase shifting transformer and within the connected switchgear.

The primary windings of the transformer are protected by two redundant biased differential protections. The protected area for the primary windings is purely electrical. There are no magnetic circuits involved so saturation and inrush phenomena do not play a role. Consequently there is no need for harmonic restraint in the primary differential protection.

The secondary windings of the regulating and series transformers are protected by a single differential protection. The position of the current transformers differs from the preferred locations as mentioned in the IEEE report. The current transformers are located directly in the connections between the secondary windings instead of being installed in the primary source and load connection of the phase shifter. By doing so the protected zone is again limited to electrical components only without any magnetic circuits.

The regulating transformer is equipped with backup over current protections at the neutral side of both the primary and secondary windings. These protections operate with the phase currents and the neutral current. The protections are stabilised for inrush and saturation currents by means of a harmonic restraint function.

The functional requirements for the control system of the phase shifters are the following:

- Independent and autonomous system and bay control [6];
- Standard control functionality of all switchgear;
- Fully redundant communication from the bay directly to two different control centres;
- Implementation of specific automation functions such as: energising the phase shifter, overload supervision, over-excitation protection and tap changer supervision.

The layout of the control system for each phase shifter is shown in figure 6. All operational bay control is performed from remote control centres. For emergency and maintenance purposes an interface is present for local control. Communication to control centres is realised by two redundant communication channels. These channels use the standard IEC 60870-5-101.

To energise the phase shifter the circuit breaker on the busbar side in Meeden and the circuit breaker in Diele are closed first. Closing of the circuit breaker in Meeden is only possible with the tap changer of the phase shifter in neutral position, in order to limit the inrush phenomena on the phase shifter. Secondly, the circuit breaker on the line side to Diele is closed. To close the circuit breaker, it is checked whether the voltage difference, the frequency difference and the difference in phase angle across the circuit breaker are within limits.

A phase shifting transformer has to be protected against high internal voltages that lead to saturation of the core and to fast and extreme overheating. The over-excitation protection function is integrated in the control system, but acts completely independent from any other function in the control system. The same for the overload indication: these functions are always active. Excitation calculation uses current and voltage measurements on both sides of the phase shifter. In case of over-excitation the phase shifter steps two taps in the direction of the neutral tap position. If the voltage after these two steps is still above the limit, the phase shifter will continue stepping towards the neutral position. A protection function trips the transformer if over-excitation remains too long.

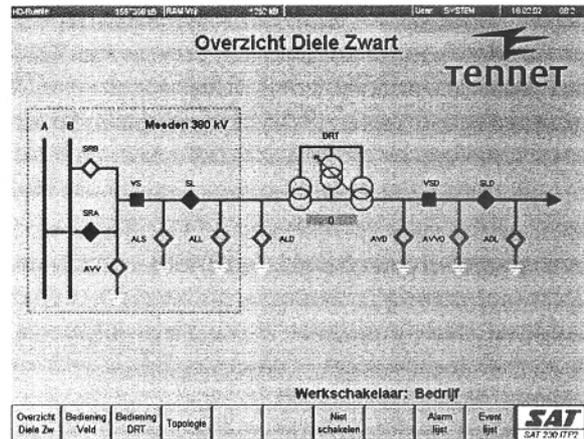


Figure 6 Schematic overview bay layout

5 Test programme with phase shifters

After some provisional tests in December 2002, the TSOs involved agreed upon a formal test programme, which was executed in February and March 2003.

The first goal was to investigate the impact of changes of the transformer's tap setting on the power flow through the interconnectors. Therefore the flows in the lines between Germany and The Netherlands, The Netherlands and Belgium, and between Belgium and France have been recorded during the tests.

Figure 7 gives, as example, the results for a certain moment (10h12) compared to another moment (10h33) of the test on March 27th, where the power flow through the interconnection Meeden-Diele was changed approximately 1100 MW by changing the tap position from 4 to 15. This was done

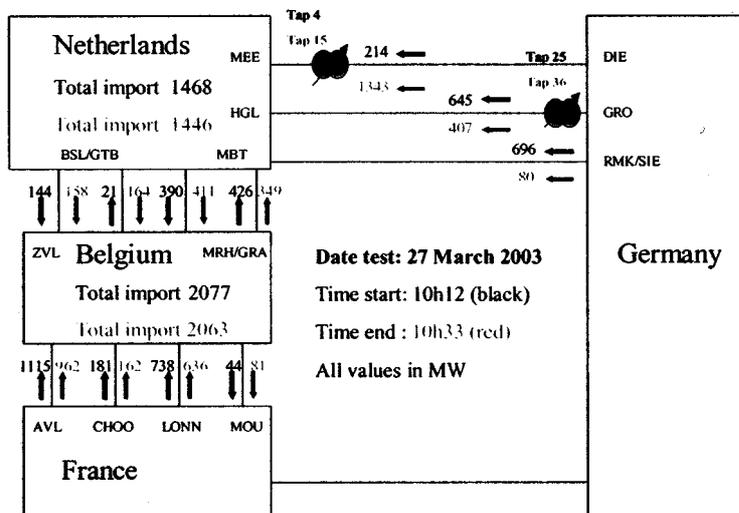


Figure 7 Example of power flow during test programme

within 10 minutes; during this period the tap position of the phase shifter in Gronau was changed also, from position 25 to 28, but this was not enough to keep the power flow in the interconnection Hengelo-Gronau constant. During the next 10 minutes the position of the phase shifter in Gronau was changed further until the maximum tap was reached. But the initial power flow of 660 MW could not be brought back, as can be seen in the figure. It is obvious that the change in tap position of the phase shifter in Gronau influences the power flow on the interconnection Meeden-Diele also.

In table 1 the changes in flows derived from the tests of March 27th, are given. While comparing the flows one should be aware of the fact that each moment the total situation changes, especially the import/export values change. Therefore in the table the exchanges are adjusted in a certain way, in order to get values as if the imports would have stayed constant.

The change in power flow through the interconnection Meeden-Diele, results in a change in power flow on the interconnectors Belgium-Netherlands and Belgium-France of 15% of this power flow change when the phase shifter in Gronau is kept in the same position. When the tap position of this phase shifter is moved also, 25% of the change through the interconnection Meeden-Diele is found back in the change on the interconnectors B-N and B-F. In cases where the tap position in Gronau does not reach its maximum a percentage of 30% is attainable.

This leads to the conclusion that normally a change of the power flow on the interconnector Meeden-Diele by changing the tap position of the phase shifters in Meeden, has an effect of a change in the power flows on the interconnectors between the Netherlands and Belgium, and the same between Belgium and France, of 15% up to 30% of this change in power flow on the interconnector Meeden-Diele.

The second goal of the test programme was to create situations with maximum physical flows in order to find out whether higher available cross-border capacities could become possible. Tests were made with extra available capacities of 250 MW and 500 MW for imports and exports. These tests were successful but do not give yet full confidence that also more extreme situations can be handled adequately by controlling the flows on the interconnectors where the phase shifters are located.

Higher losses in the network are often seen as an important disadvantage of phase shifters. In load flow calculations this can be easily proven, but in reality, it is more difficult to find a clear indication of increased losses. During the test period, the losses in the Dutch 380-kV network were continuously monitored. It could be observed that for higher tap positions there is an increase in losses, up to 20% extra losses in the 380-kV network, in situations with maximum tap positions.

6 Operational aspects and recent experience

Each day TenneT, together with the TSOs in neighbouring countries that are involved in the joint auction of cross-border transmission capacity, determines the level of transmission capacity for imports and exports to be made available to market players [7]. The joint auction covers only a small part of the Western European high voltage network. All networks of the synchronous UCTE area are interconnected, which implies that there is an influence between all so-called control zones. This has led to the awareness that at least RTE of France should also be involved in the operational process in order to improve the cross-border capacity assessment.

To secure firmness of the auctioned cross-border capacity, TSOs have agreed upon Congestion and Security Management (CSM) measures to be carried out in case of congestions. These measures consist of topology changes, like line switching, busbar opening and tap changing of phase shifters. TSOs have defined which network elements are part of the monitoring area to be considered as a trigger in case of a (near) congestion situation. If such a trigger gets activated each TSO can request for support of the other TSOs to relieve this (near) congestion situation.

The phase shifters are there to enhance the control of the power flows from Germany and enable better distribution between the various cross-border connections between Germany and the Netherlands, with the ultimate aim of stepping up usage of the transmission capacity on these interconnections. During the period of a year of experience, TSOs found out that only to a certain extent, power flows can be controlled with the phase shifters. The control range is mainly influenced and limited by the volume of power injected by generating units in the immediate vicinity of the phase shifters. The choice of a large phase angle for the phase shifters in Meeden has proven to be useful and necessary.

Table 1 Example 27th March 2003

Exchange in MW between TSOs (Adjusted for import/export changes)			
	10h12	10h23	10h33
E.ON-TenneT	214	1528	1357
RWE-TenneT	1341	218	492
Elia-TenneT	-87	-278	-381
RTE-Elia	1990	1799	1696
Tap Meeden	4	15	15
Tap Gronau	25	28	36

Although the phase shifters are situated on the border in the North between Germany and the Netherlands, even the flows between Belgium and the Netherlands can be influenced to a certain level. The record shows that frequent requests of the neighbouring TSOs have been granted to change the tap settings of the phase shifters in both Meeden and Gronau to increase or restore the security margin on the interconnections between both Germany and the Netherlands, as well as between Belgium and the Netherlands and Belgium and France.

It can be said that the phase shifters at Meeden are effectively being used to prevent or overcome congestions. This is needed more and more. Since the start of the operational use of the phase shifters some unpredictable factors have changed the circumstances in the West European network:

- Strong fluctuations in the quantity of wind power being injected into the high voltage grid, especially in northern Germany; due to this, conventional power generation pattern has changed as well;
- Strong fluctuations in the deployment by market players of generating assets in several constituent areas in the neighbouring countries;
- Strong fluctuations in transmission across the HVDC-interconnection between France and the United Kingdom, which has a large impact on the interconnections between France and Belgium.

Nevertheless, experience has shown that it is possible in certain scenarios to:

- Increase the cross-border transmission capacity that is available to market players, depending on the grid situation, which can vary from one day to the next, without jeopardising the security of the high voltage grids in Belgium, Germany and the Netherlands;
- Realise physical power flows on the German-Dutch border that approximately match the cross-border programmes that have been nominated for this particular border;
- Exert some influence on the power flows on the German-Dutch border while somewhat reducing the power flows across the Belgian-Dutch and French-Belgian borders at the same time.

7 Conclusion

The first experiences with the new phase shifting transformers in Meeden show that the power flow from Germany to the Netherlands can be controlled effectively thus allowing in principle for an increased capacity. In practice, it turned out that it is very difficult to make more firm cross-border capacity available for the market, yet. Additional investments in the Belgian and German high voltage grids have to be made and this will take some time. But also the power flow in the European networks must become more predictable and controllable. Phase shifters can be very helpful in this respect.

Throughout the UCTE area TSOs have ideas to install new phase shifters. This is also the case for the border between Belgium and the Netherlands, where Elia plans to install two phase shifters. In future, this will make an adjustment of the current operational agreement among TSOs involved in the joint auction, necessary. In UCTE, an ad hoc working group is starting up to investigate which general guidelines for coordination between TSOs on the use of phase shifters are needed.

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