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Application of phase shifting transformers in the tie-lines of interconnected power systems

***Abstract**. Unscheduled power flows (also known as loop flows) are an increasing problem in the Central and Eastern European (CEE) region. These flows can negatively affect the secure operation of interconnected power systems and limit their cross-border trade capacity. Transmission system operators can prevent unscheduled flows entering their systems by installing phase shifting transformers (PSTs) in their tie-lines. This paper presents selected results of a study on the possibilities for cross-border active power flow control using PSTs installed in the tie-lines on Polish–German and Czech–German interfaces. The interactions between these devices are also demonstrated. One of the most frequently used designs of PST is shown as well. The problem is discussed of unscheduled flows in the CEE region as well as the active power flow control method using PSTs.*

***Streszczenie.** Nieplanowe przepływy mocy (określane również jako przepływy kołowe lub karuzelowe) są coraz większym problemem w rejonie Europy Środkowo-Wschodniej (CEE). Przepływy te mogą negatywnie wpływać na bezpieczeństwo pracy połączonych systemów elektroenergetycznych oraz ograniczać ich zdolności wymiany transgranicznej. Operatorzy systemów przesyłowych mogą zapobiegać przepływom nieplanowym poprzez instalację przesuwników fazowych (PF) w liniach wymiany transgranicznej. W artykule przedstawiono wybrane wyniki badań dotyczących możliwości sterowania międzysystemowymi przepływami mocy za pomocą PF instalowanych w liniach wymiany na przekrojach Polska–Niemcy i Czechy–Niemcy. Pokazano również interakcje tych urządzeń. Przedstawiono jedno z najczęściej stosowanych rozwiązań PF. Omówiono kwestię przepływów nieplanowych w rejonie CEE oraz metodę sterowania przepływami mocy czynnej z wykorzystaniem PF. (**Zastosowanie przesuwników fazowych w liniach wymiany transgranicznej połączonych systemów elektroenergetycznych**).*

Keywords: power flow control, phase shifting transformers, unscheduled flows, cross-border power flows.
Słowa kluczowe: sterowanie przepływami mocy, przesuwniki fazowe, przepływy nieplanowe, transgraniczne przepływy mocy.

Introduction

In recent years in Central and Eastern Europe (CEE), a strong increase in unscheduled compensatory power flows between transmission systems of the respective countries, known as loop flows, has been observed. Cross-border energy trading within the CEE region and the ever-increasing number of variable energy sources (mostly wind) in Germany combined with insufficient intra-Germany transmission capacity are the main factors that contribute to the escalation of this phenomenon. These unscheduled flows can block a significant part of the physical transmission capacities on the interconnectors in the CEE region, in particular related to the tie-lines of the Polish and Czech power systems, thereby limiting the amount of transmission capacity available to market participants interested in cross-border energy trading. However, a much more serious consequence of this situation is the fact that, due to their nature, unscheduled flows can lead to acutely critical operational situations and a threat to the secure operation of CEE transmission systems [1, 2, 3, 4].

One of the possible solutions to reduce significantly (or even eliminate) these undesirable flows is the use of phase shifting transformers (PSTs), i.e. special transformers that are used to control power flows in transmission networks [5]. These transformers are also known as phase angle regulators (PARs) or quadrature boosters (QBs).

At the common border with Germany, the Polish transmission system operator (TSO) is planning to install four sets of PSTs, one in each circuit line, with two of these sets in the Mikulowa (PL) – Hagenverder (DE) double-circuit line and the other two sets, after switching to a voltage of 400 kV, in the Krajnik (PL) – Vierraden (DE) double-circuit line. Furthermore, the Czech TSO is planning to install PSTs in tie-lines on the Czech–German border [6].

The main objective of this paper is to present how the application of PSTs in the tie-lines on the Polish–German and Czech–German interfaces affects cross-border power flows in the CEE region.

Power flow control

The active power flow through a transmission line is given by the following equation [7]:

(1) $$P = \frac{V_s \cdot V_r}{X_L} \cdot \sin\delta$$

where: V_s and V_r are the voltage modules at the sending- and receiving-end of the transmission line, respectively, δ is the power angle (the phase angle difference between $\underline{V}_s$ and $\underline{V}_r$), and X_L is the transmission line reactance.

Equation (1) shows that the active power flow through the transmission line can be controlled by changing voltage levels V_s and V_r, the reactance X_L and the power angle δ. The ability to control the active power flow by changing voltage values V_s and V_r is relatively small because the voltages in the network must be close to nominal voltages and cannot be changed within wide limits. Larger adjustable flow gives a line reactance change, the so-called series compensation, which involves the artificial reduction of inductive reactance X_L using a series-connected capacitor bank with a properly selected reactance. However, the full extent of active power flow in the transmission line can be changed by adjusting angle δ (by controlling angle δ, not only the value of power flow but also the direction of flow can be changed) [8]. In practice this can be done by installing a PST in the transmission line, as shown in Figure 1b. This transformer creates a phase shift between the source and load (S and L) terminals that can increase or decrease the existing angle δ. This is achieved by inserting a voltage $\Delta\underline{V}$ in quadrature (perpendicular) to the phase voltage of the transmission line [9]. The quadrature voltage can be varied in definite steps, or even reversed, by means of an on-load tap changer [10].

The active power flow through the transmission line with a PST is given as follows [7]:

(2) $$P = \frac{V_s \cdot V_r}{X_L + X_{PST}} \cdot \sin(\delta + \alpha)$$

where: X_{PST} is the PST reactance, α is the PST angle (the phase angle difference between the PST terminal voltages).

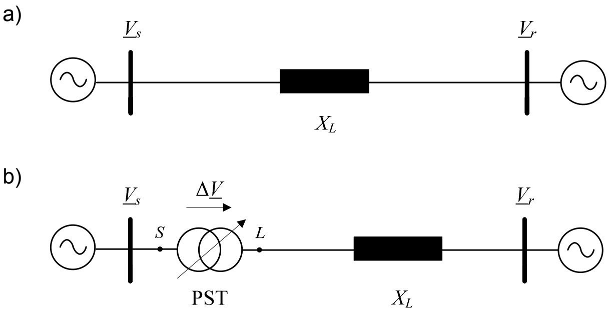

Fig.1. Schematic diagram of a transmission line without (a) and with (b) a PST

PSTs are usually used to control the cross-border power flow in interconnected power systems or to control the power flow in parallel transmission corridors in meshed networks [11]. These devices have either been implemented or at least seriously considered by several countries [12-20].

Typical design for PST

There are several different types of PSTs [21, 22, 23]. The most often used design for large ratings of PST and a larger range of phase angle shift is the two-core, symmetrical PST (Fig.2). This type of PST essentially consists of a series unit and a main (or exciting) unit, each housed in separate tanks. When the design is used for smaller ratings and lower voltages, these two transformer units may be housed in the same tank. The primary windings of the series unit, between the source and load terminals, are split into two halves, and the primary windings of the main unit are connected to the connection point of these two split windings [24]. The secondary windings of the series unit are connected in delta (to obtain the quadrature voltage) and are connected to the secondary windings of the main unit containing the taps [12]. The term "symmetrical" means that under the no-load condition the voltage magnitudes at the source and load terminals are always equal, independent of the phase shift between them [10, 23]. Figure 3 shows an advanced phase shift obtained for the load terminal voltage with respect to the source terminal voltage. The main design parameters of a two-core symmetrical PST are reviewed elsewhere [8].

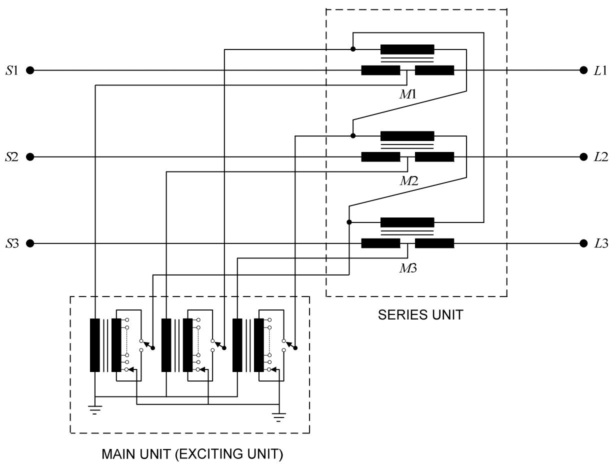

Fig.2. Connection diagram of a two-core, symmetrical PST (own elaboration based on [22])

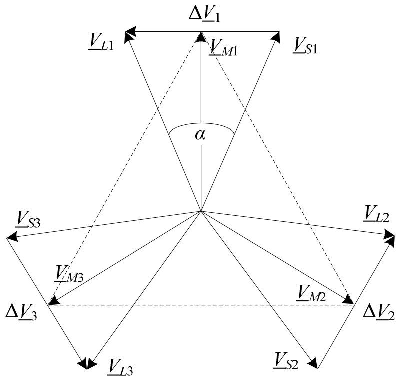
Fig.3. Phasor diagram of a two-core, symmetrical PST (with an advanced phase shift) (own elaboration based on [22])

Unscheduled power flows in the CEE region

Unscheduled flows (or loop flows), which are the differences between actual and scheduled (commercial) flows on a given border [1, 25], cause an additional load on the cross-border and inner transmission lines, as well as becoming a serious problem for interconnected power systems. A small volume of unscheduled flows can be tolerated as a natural effect of the synchronous operation of interconnected transmission systems and a strongly meshed network configuration in Europe, resulting from the laws of physics. Currently, however, at many borders of the CEE region, the actual power flows are considerably higher in comparison to the commercial flows resulting from scheduled cross-border transactions. In many cases, it can be observed that the actual flow is in the opposite direction to the commercial one. A root cause for this state involves the trade transactions concluded by the German and Austrian market participants, which do not take into account the physical aspects of the interconnected transmission systems [1].

Most German wind power plants are located in the northern part of Germany, which is characterised by low electric power demand (lower industrial concentration and lower population density) in comparison to the southern part of Germany [26]. Due to a lack of sufficient transmission capacity in Germany in the north-south direction, the excess amount of power in the north of Germany is transferred to the south of Germany and Austria through the transmission networks of the neighbouring countries [27] since electrical power takes the path of least impedance. Consequently, the transmission networks in the CEE region, particularly in Poland and the Czech Republic, are frequently excessively loaded by unscheduled power flows which can exceed the values at which the transmission system is able to operate safely [1, 2, 4]. An outage of a single element or component in the system, such as a transmission line, generator, or transformer, while the transmission system is overloaded could lead to a large-area power supply failure.

Two main routes of unscheduled flows can be seen in the CEE region (Fig.4). Route 1 involves power from the north of Germany flowing through Poland and the Czech Republic and then into Austria and the southern part of Germany, with some of these flows also relating to the Slovakian and Hungarian transmission systems. Route 2 involves unscheduled flows through the Czech transmission system, where power from the German transmission system flows into the Czech Republic via the Hradec (CZ) – Rohrsdorf (DE) tie-line and then flows out through the Hradec (CZ) – Etzenricht (DE) and Prestice (CZ) – Etzenricht (DE) tie-lines (Fig.5).

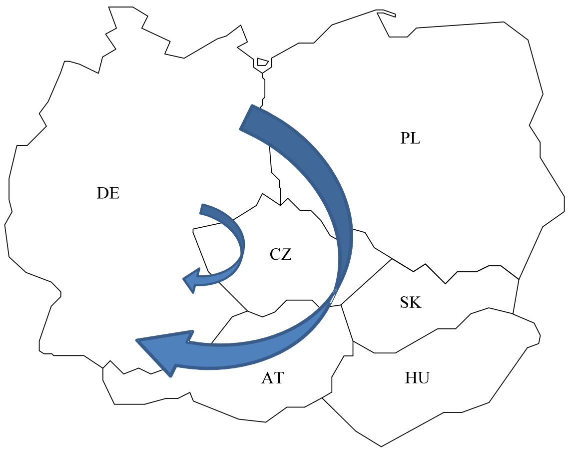

Fig.4 Main routes of unscheduled power flows in the CEE region (own elaboration based on [1])

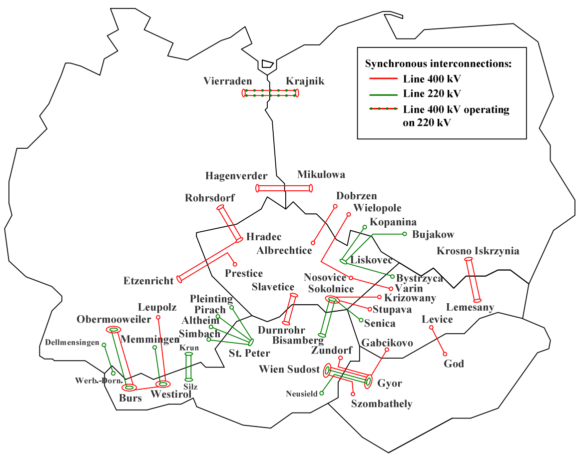

Fig.5. Main tie-lines in the CEE region – current state

Power flow analysis and results

The analysis included power flow calculations based on models of the interconnected power system in CEE, elaborated for the years 2014 and 2020 (summer and winter peak demand), involving the Polish 400/220/110 kV networks and the transmission networks of the neighbouring countries. Following the power flow analysis, an installation of PSTs was considered in all circuits of the 400 kV tie-lines on the Czech–German interface: Hradec–Rohrsdorf (HRD–ROE), Hradec–Etzenricht (HRD–ETZ) and Prestice–Etzenricht (PRE–ETZ) as well as on the Polish–German interface: Mikulowa–Hagenverder (MIK–HAG) and Krajnik–Vierraden (KRA–VIE). At present, the Krajnik–Vierraden tie-line operates at 220 kV; however, it will be modified to utilise 400 kV parameters (the analysis assumed that the line operated at 400 kV). PST control was performed within a phase shift range of ±45 degrees, in 5 degree steps. The results for an analysis of winter peak demand in 2014 are shown in Figs. 6, 7 and 9-12 (positive values correspond to input power and negative to output power from the Polish and Czech systems, respectively). A summary of the selected results for the analysed operational conditions of the interconnected power system is presented in Table 1.

PSTs on the Polish–German interface

The analysis indicates that the management of the active power flows on the interface between Poland and Germany, using PSTs installed in each tie-line circuit at Mikulowa–Hagenverder and Krajnik–Vierraden by performing parallel control (i.e. the phase angle on all PSTs is changed simultaneously by the same value and in the same direction) enables a considerable reduction in the active power that flows into Poland from the German power transmission system (Fig.6). Therefore, this leads to a significant reduction of unscheduled flows in the CEE region. However, obtaining such effects requires the use of PSTs with a wide phase angle regulation range (±40 degrees). Furthermore, the study shows that management using PSTs installed at the Polish–German border has an impact on the power flow changes on interconnectors of the neighbouring transmission systems, which is illustrated in Figure 7. Because PSTs influence the active power flows throughout the transmission system, they also influence the active power losses in the transmission system (Fig.8). It can be seen that the active power losses change non-linearly with PST angle. Depending on the settings of the PSTs, the joint operation of the PSTs can either reduce the active power losses in the transmission system or can worsen the situation and cause higher losses.

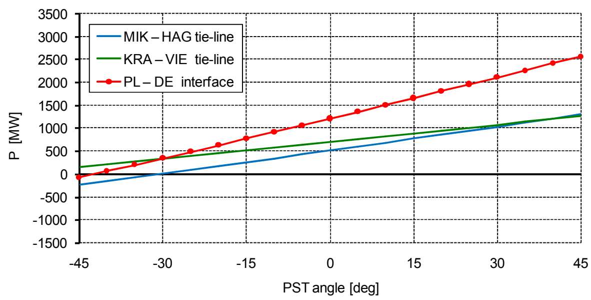

Fig.6. Influence of parallel control using PSTs installed in the Mikulowa–Hagenverder and Krajnik–Vierraden tie-lines on active power flows on the Polish–German interface

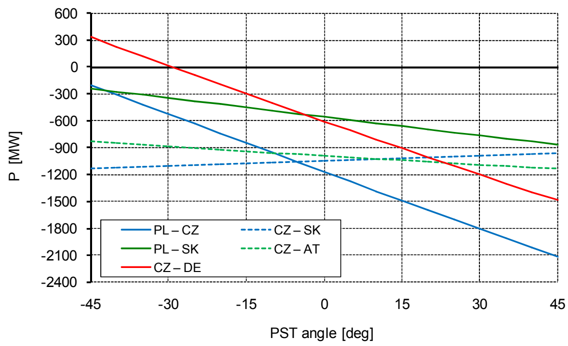

Fig.7. Influence of parallel control using PSTs installed in the Mikulowa–Hagenverder and Krajnik–Vierraden tie-lines on active power flows in the particular interfaces on the CEE region

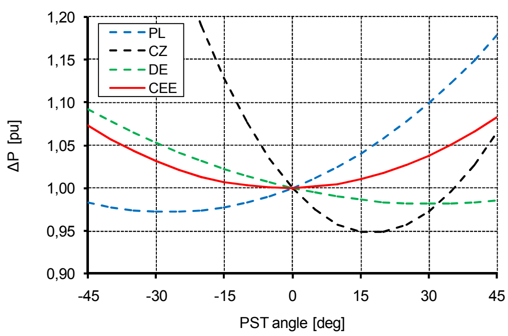

Fig.8. Influence of parallel control using PSTs installed in the Mikulowa–Hagenverder and Krajnik–Vierraden tie-lines on active power losses (normalised to zero PST angle) in transmission systems

PSTs on the Czech–German interface

The achieved results show that parallel control using the PSTs installed on the Czech–German interface (Figs. 9 and 10) causes the opposite effects for changes in active power flows in comparison to parallel control using the PSTs on the Polish–German interface (Figs. 6 and 7).

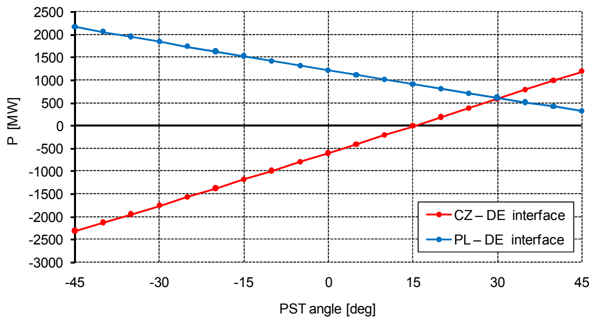

Fig.9. Influence of parallel control using PSTs installed in the Czech–German tie-lines (all tie-lines) on active power flows on the Polish–German and Czech–German interfaces

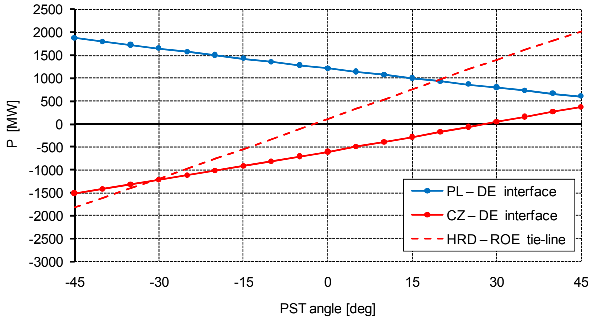

Fig.10. Influence of parallel control using PSTs installed in the Hradec (CZ) – Rohrsdorf (DE) tie-line on active power flows on the Polish–German and Czech–German interfaces

PSTs on the Polish–German and Czech–German interfaces

The influence of control by the PSTs installed at the Polish–German and Czech–German borders is shown in Figs. 11 and 12. The analysis results show that parallel-type control by PSTs on both interfaces leads to a reduced range of changes in active power flows. However, if undertaken in the opposite way (i.e. the phase angle on the PSTs at the Polish–German and Czech–German borders are changed simultaneously by the same value but in opposite directions), then it instead leads to an increased range of changes in active power flows.

Conclusion

The combination of wind energy penetration and cross-border trade gives rise to the problem of unscheduled flows, causing congestion problems on the interconnectors and a serious threat to the operational security of interconnected power systems. Power flow control using PSTs can offer a possibility of dealing with these congestions and enhancing network security.

The power flow analysis shows that active power flows can be controlled in a quasi-linear way with PSTs. Moreover, the method of operation of the PSTs influences the active power losses in the transmission system.

The study concerning PSTs installed on the Polish–German and Czech–German interfaces have proved that it is possible, with PST control of the Czech–German interconnectors, to significantly neutralise the effects achieved by PST control on the Polish–German interconnectors. On the other hand, a suitably coordinated control method will result in improving the desired effects. This means that coordination between these devices is crucial and a challenge for future work is to develop a method of achieving coordinated PST control in the CEE region. This will ensure an increase in the operational security of the interconnected power systems, an improvement in their economic operation and an increase in the possibility of energy trade exchange between particular areas.

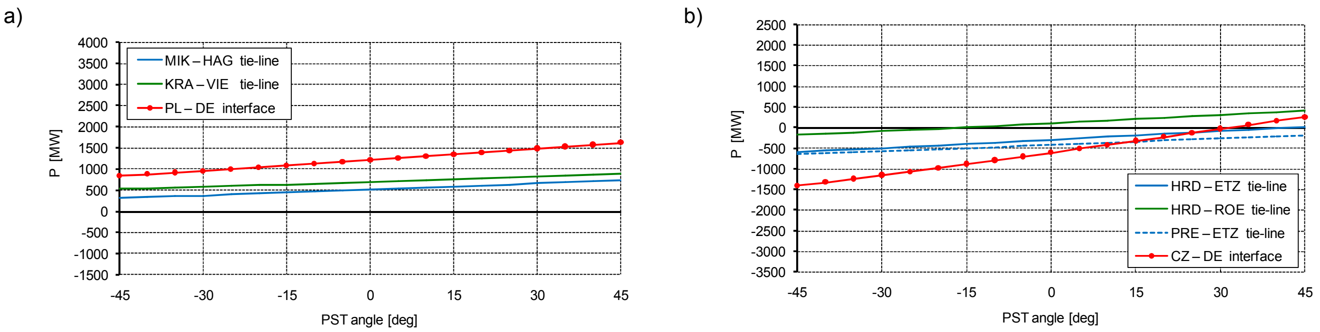

Fig.11. Influence of parallel control using PSTs installed in the Polish–German and Czech–German tie-lines (all tie-lines) on active power flows on the interconnections: a) Poland–Germany, b) the Czech Republic–Germany

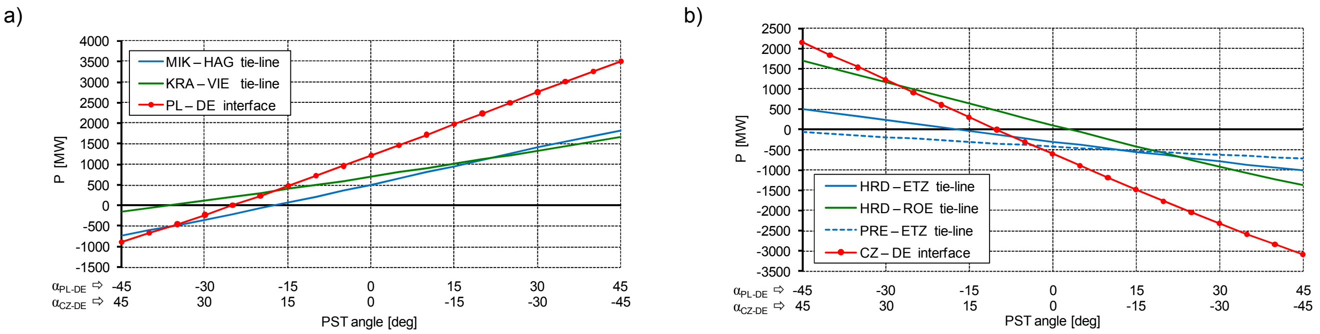

Fig.12. Influence of opposite control using PSTs installed in the Polish–German and Czech–German tie-lines (all tie-lines) on active power flows on the interconnections: a) Poland–Germany, b) the Czech Republic–Germany

Table 1. Possibilities of controlling active power flows on the Polish–German and Czech–German interfaces using PSTs

Model	Interface	Control range of active power flows [MW]			
		Variant			
		Parallel control on the PL – DE interface (all tie-lines)	Parallel control on the CZ – DE interface (all tie-lines)	Parallel control on both interfaces	Opposite control on both interfaces
summer peak demand 2014	PL – DE	-274 ÷ 2199	107 ÷ 1812	567 ÷ 1327	-1017 ÷ 3068
	CZ – DE	-1621 ÷ 100	-2447 ÷ 945	-1595 ÷ 63	-3170 ÷ 1849
winter peak demand 2014	PL – DE	-74 ÷ 2566	322 ÷ 2170	839 ÷ 1576	-886 ÷ 3499
	CZ – DE	-1484 ÷ 335	-2314 ÷ 1186	-1409 ÷ 255	-3080 ÷ 2146
summer peak demand 2020	PL – DE	-647 ÷ 2146	-214 ÷ 1711	306 ÷ 1162	-1484 ÷ 3167
	CZ – DE	-1568 ÷ 335	-1168 ÷ 2363	-1408 ÷ 191	-3223 ÷ 2158
winter peak demand 2020	PL – DE	-235 ÷ 2629	211 ÷ 2183	743 ÷ 1626	-1101 ÷ 3661
	CZ – DE	-1400 ÷ 533	-2182 ÷ 1335	-352 ÷ 1217	-3045 ÷ 2332

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