ANALYSIS OF THE USE OF PTDF IN THE UCTE TRANSMISSION GRID

Christof Duthaler
ETH
Zürich, Switzerland
christof.duthaler@epfl.ch

Marc Emery
swissgrid ag
Laufenburg, Switzerland
marc.emery@swissgrid.ch

Göran Andersson
ETH
Zürich, Switzerland
andersson@eeh.ee.ethz.ch

Martin Kurzidem
ETH
Zürich, Switzerland
kurzidem@eeh.ee.ethz.ch

Abstract –In this article, Power Transfer Distribution Factors (PTDF) and the underlying flow-based model proposed for capacity determination and allocation in electricity grids are studied. Several factors with influence on PTDF coefficients, such as topological and seasonal changes as well as zone-building, are empirically analyzed using an AC power flow simulation of the UCTE transmission network. Furthermore, the determination of border capacities is examined.

According to the findings of this work, introducing the PTDF system in the highly meshed UCTE transmission system seems only feasible with a nodal network model, as the scattering of the coefficients due to the aforementioned factors precludes an efficient use in a zonal model. Moreover, it is shown that border capacities are over-determined in a zonal model and hence cannot be computed univocally.

Keywords: Power Transfer Distribution Factors (PTDF), flow-based model, border capacity, AC load flow

1 INTRODUCTION

In the mid-1990s, the European Union started liberalizing the electricity markets of its member states, envisaging a unified and competitive Internal Electricity Market (IEM) according to the concepts outlined in EU regulation 1228/2003. As national markets get coupled and electricity exchange between them continually increases, advanced concepts for transmission capacity determination and allocation become more and more important. Traditionally, capacities have been computed bilaterally or multilaterally according to ETSO's Net Transfer Capacity (NTC) scheme [1], controlling physical flows by limiting commercial transaction volumes. Lately, in order to control physical flows more directly, a flow-based approach based on distribution factors and so called flowgates (see 2.1) has been proposed [2]. However, the feasibility of this approach in the highly meshed network of Central Europe hasn't been demonstrated so far. More specifically, it is not yet clear to what extent PTDF coefficients are influenced by zone-building according to political borders [3, 4], seasonal and topological changes [5, 6] or different locations of generation [7, 8]. Additionally, a well defined mechanism for determining border capacities other than on a bilateral basis is still missing [9, 10].

This paper is organized as follows: Chapter 2 outlines some conceptual prerequisites as well as the methods applied. Chapter 3 and 4 present the findings in the field of PTDF coefficients and border capacities. Chapter 5 draws the conclusions.

2 METHODOLOGY

2.1 The PTDF System

The PTDF system ensures that the commercial transactions between *zones* (e.g. countries but also individual nodes) do not jeopardize network operation by observing *flowgates* (e.g. borders but also individual branches).

Starting from a to-be-defined base case characterized by the initial physical vector on flowgates PhT_0 [MW] and the initial commercial vector between pairs of zones CoT_0 [MW], the *PTDF matrix (PTDF)* is calculated, theoretically by performing transactions (e.g. 100 MW) between each pair of zones and observing the variation occurring on each flowgate.

When transactions take place, the commercial variation vector ΔCoT, multiplied by the *PTDF matrix (PTDF)*, yields the physical variation vector ΔPhT:

$$\Delta PhT = (PTDF)\,\Delta CoT \quad (1)$$

Finally, the physical vector on flowgates is given by

$$PhT = PhT_0 + \Delta PhT = PhT_0 + (PTDF)\Delta CoT \quad (2)$$

The physical viability of the commercial variation (ΔCoT) is checked by comparing the physical vector to both vectors of flowgates' *border capacities* PhT_{max} *and* PhT_{min}:

$$PhT_{max} \geq PhT \geq PhT_{min} \quad (3)$$

2.2 Transmission system data

Transmission system data used for all the simulations hereafter consist of the full European grid model as provided by the UCTE[1]. It is either a 'reference case' (denoted 'R' plus date-stamp, done twice a year with all elements in operation (summer peak, winter peak)) or a 'snapshot case' (denoted 'S' plus date-stamp, done four times a year (summer peak, summer night, winter peak, winter night)).

Flowgates are given by the two-letter ISO codes of the respective countries (e.g. 'SI->IT' for the Slovenian-

[1] Union for the co-ordination of transmission of electricity

Italian flowgate), whereas transactions are denoted by their respective one-letter UCTE code (e.g. “L->I” for a transaction from Slovenia to Italy). An overview of country names is given in the appendix.

While all simulations were run on the full UCTE network model, for the purpose of clarity results shown in this paper focus on ERGEG’s[2] Central South region, comprising the countries of Austria, France, Germany, Italy, Slovenia and Switzerland. However, the findings are applicable equally well to other regions of Central Europe, e.g. Central West (Belgium, Switzerland, Germany, France, Netherlands) or Central East (Austria, Switzerland, Czech Republic, Germany, Hungary, Poland, Slovenia, Slovakia).

2.3 *AC PTDF vs. DC PTDF*

In many publications, the calculation of the PTDF matrix with DC load flow is recommended because of the supposedly prohibitive duration of AC load flow calculations [11]. Compared to AC load flow, DC load flow makes the following assumptions to linearize load flow equations:

- Flat voltage profile (disregarding reactive power)
- Small differences in voltage angles
- Lossless transmission

However, the authors were able to perform their calculations with a very powerful and quick AC load flow software package available on the market [12].

For example, for the 6’000 node, 9’000 branch UCTE network, the AC load flow iterative process for the base case takes about 70 milliseconds on a notebook with 2 GHz Pentium processor running on Windows XP. The total computing time for a list of ca 2000 outages in the same network is ca. 35 seconds. The contingency analysis of all the ca 300 Swiss branches, calculated with the entire UCTE network, is performed in 3.5 seconds.

Thus, computational speed was not a limiting factor for using an accurate AC power flow. This is why an AC calculation of the full UCTE grid model underlies all the simulations described hereafter. Nevertheless, it was shown that the linear assumptions underlying DC calculations are valid in quite a wide operational range of the European 380kV and 220kV transmission system. Figure 1 compares the elements of the PTDF matrix calculated by AC load flow to those yielded by DC load flow using a UCTE reference case. As it can be seen, the elements match quite well, and therefore the aforementioned linear assumptions are fulfilled [13].

[2] European Regulators’ Group for Electricity and Gas.

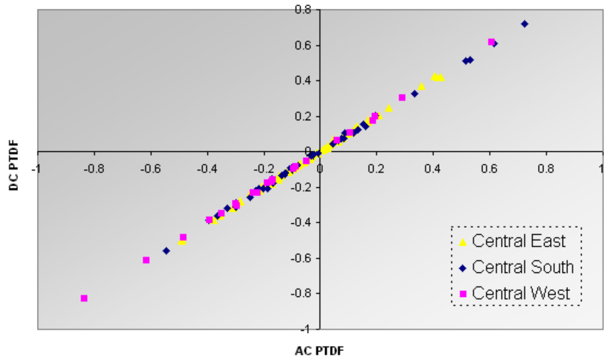

Figure 1: Comparison of AC and DC PTDF.

2.4 *Generation shift methods*

While performing the variations necessary for filling in the PTDF matrix, there are three main generation shift methods within a zone:

- all generations are shifted proportionally to their output in the base case (method 1)
- all generations are shifted proportionally to the remaining power plant capacity (method 2)
- all generations are shifted according to a cost-based merit order (method 3).

Method 3 considers actual price signals and therefore is the most realistic shift method. For method 2, production limits of all power plants need to be known. As neither of this information was available, method 1 was chosen for the scope of this study.

However, it has to be borne in mind that PTDF coefficients depend to some degree on the choice of the generation shift method, as simulations show.

2.5 *Statistical significance of results*

Before examining the impact of different factors on the scattering of PTDF coefficients, three levels of statistical significance have been specified in accordance to TSO standards and benchmarks of other scientific authors [12, 14]. Thus, relative deviations of coefficients (based on absolute PTDF value) below 5% are considered insignificant, and the corresponding entries of the PTDF matrix are coloured green. Deviations between 5 and 10% are deemed significant and coloured orange, while deviations above 10% are highly significant and coloured red.

3 SENSITIVITY OF THE PTDF MATRIX

3.1 *Influence of Topology*

The influence of topology is assessed by calculating on the one hand the PTDF matrix of a summer reference case (with all elements in operation) and on the other hand the seven PTDF matrixes of the same reference case modified taking into account the planned outages during seven consecutive dates of August 2007. Table 1 shows the maximal relative deviation for some elements of the PTDF matrix of Region Central South yielded by the following formula:

$$rel\_dev = \frac{\max(PTDF_{outage} - PTDF_{base\_case})}{PTDF_{base\_case}} [\%] \quad (4)$$

Flowgates	Transactions O->I	S->I	D->I	F->I	L->I
CH->IT	4.46%	3.88%	4.85%	8.81%	4.94%
CH->DE	6.24%	28.08%	6.48%	11.95%	6.30%
CH->FR	37.29%	12.40%	15.26%	3.04%	36.00%
CH->AT	27.03%	593.18%	37.79%	54.26%	25.54%
DE->FR	12.64%	70.77%	10.33%	6.20%	10.07%
DE->AT	5.29%	29.94%	10.25%	13.61%	8.93%
IT->FR	13.01%	13.64%	13.11%	13.70%	12.92%
IT->SI	-0.84%	-2.30%	-1.77%	-3.65%	-0.37%
AT->SI	10.14%	41.73%	31.40%	37.83%	7.11%

Case: R060719, Central South

Table 1: Influence of topology on PTDF matrix.

3.2 Influence of the operating point

In this section, the influence of the operating point (on which the zonal generation profile, load pattern and the topology depend) is analyzed.

3.2.1 Seasonal influence

The elements of the PTDF matrix calculated with the snapshot from 19th July 2006 10h30 are compared to the elements of the PTDF matrix calculated with the snapshot from 17th January 2007 10h30. The deviations shown in Table 2 are yielded by the following formula:

$$rel\_dev = \frac{\max(PTDF_{Summer} - PTDF_{Winter})}{avg(PTDF_{Summer}, PTDF_{Winter})} [\%] \quad (5)$$

Flowgates	Transactions O->I	S->I	D->I	F->I	L->I
CH->IT	-18.17%	-13.63%	-17.04%	-14.77%	-32.54%
CH->DE	-12.57%	32.69%	-25.29%	-50.29%	-28.57%
CH->FR	-4.67%	5.51%	31.92%	17.78%	-22.35%
CH->AT	-20.67%	-8.89%	-24.26%	-27.24%	-32.60%
DE->FR	-2.73%	-648.98%	-29.16%	27.62%	-18.90%
DE->AT	-6.24%	61.98%	17.49%	26.54%	0.21%
IT->FR	3.79%	17.97%	16.87%	8.14%	-9.63%
IT->SI	-29.87%	-39.41%	-44.92%	-47.23%	-20.21%
AT->SI	-12.35%	20.04%	2.52%	12.42%	1.86%

Cases: S060719 and S070117, Central South

Table 2: Seasonal Influence on PTDF matrix.

Table 2 shows that the PTDF matrix coefficients are very sensitive to seasonal changes, mainly as the zonal generation profile, load pattern and grid topology differ substantially between seasons.

3.2.2 Day/night influence

The elements of the PTDF matrix calculated with the snapshot from 19th January 2005 03h30 are compared to the elements of the PTDF matrix calculated for the same day, 10h30. The deviations shown in Table 3 are yielded by the following formula:

$$rel\_dev = \frac{\max(PTDF_{day} - PTDF_{night})}{avg(PTDF_{day}, PTDF_{night})} [\%] \quad (6)$$

Flowgates	Transactions O->I	S->I	D->I	F->I	L->I
CH->IT	-11.05%	-6.35%	-7.76%	-6.86%	-11.60%
CH->DE	-6.23%	51.38%	-5.14%	-7.65%	-8.70%
CH->FR	17.14%	-15.50%	-10.58%	-3.46%	-36.67%
CH->AT	-18.89%	55.61%	-6.71%	-7.58%	-9.80%
DE->FR	-5.14%	42.07%	-4.75%	0.19%	-11.51%
DE->AT	-26.22%	48.44%	6.69%	8.75%	-14.95%
IT->FR	-9.37%	-8.48%	-9.71%	-8.21%	-13.31%
IT->SI	0.37%	-3.05%	-2.65%	-0.46%	-3.47%
AT->SI	-29.60%	-15.69%	-24.73%	-19.84%	5.96%

Case: S050119, Central South

Table 3: Day/night influence on PTDF matrix.

Some matrix coefficients differ greatly between day and night; the reason is that the zonal generation profile can be dramatically different, especially in the case of countries with hydro or wind power plants.

3.3 Influence of zone-building

As mentioned before, in most cases, zones correspond to countries. However, in the following example, France, Germany, Switzerland and Austria are divided into smaller zones shown in Figure 2.

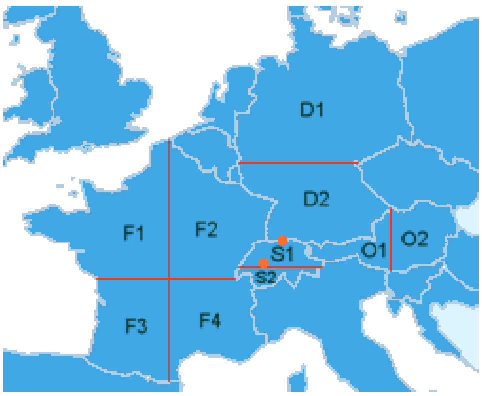

Figure 2: Subzones in Central Europe.

In Table 4, the variability of coefficients of the PTDF matrix due to zone-building is shown based on the following formula:

$$rel\_dev = \frac{\max(PTDF_{subzone\_i} - PTDF_{zone})}{PTDF_{zone}} [\%] \quad (7)$$

The transactions are always from

- the whole country (zone = country) or
- the various sub-zones of the respective country

to Italy.

E.g. for France, the PTDF coefficients are calculated for five different transactions: F=>I, F1=>I, F2=>I, F3=>I and F4=>I.

	Zones/Subzones				
Flowgates	FR	DE	CH	CH (n)	AT
CH->IT	11.13%	3.99%	2.00%	3.94%	18.20%
CH->DE	42.20%	14.73%	98.76%	47.71%	15.23%
CH->FR	6.18%	37.42%	49.74%	104.53%	59.83%
CH->AT	18.11%	14.04%	312.93%	14.64%	44.58%
DE->FR	29.13%	33.11%	343.08%	250.00%	6.81%
DE->AT	13.13%	26.78%	104.69%	9.27%	64.31%
IT->FR	17.36%	8.68%	9.56%	17.63%	12.21%
IT->SI	9.52%	3.83%	5.99%	4.80%	14.05%
AT->SI	8.80%	7.64%	4.63%	5.70%	39.90%

Case: R070117, Central South

Table 4: Influence of zone-building.

Table 4 shows that the PTDF coefficients vary considerably depending on zone-building, i.e. on the boundaries of the zones. The figures would even become worse if Italy (as recipient of transactions) had also been divided into smaller zones.

In a second step, sub-zones were further divided into smaller geographical parts until reaching the nodal network level. At the example of Switzerland, the column denoted ‘CH (n)’ in Table 4 illustrates how PTDF coefficients belonging to two power plants (shown by dots in Figure 2) lying less than 100km apart[3] still differ significantly from each other. In the highly meshed network of Central Europe, introducing a PTDF system efficiently therefore requires the use of a nodal network model.

Generally speaking, the variations due to zone-building are mainly caused by the fact that, ideally, the impedance of flowgates should be very high, and the impedance inside zones very low (notion of ‘copper plate’). In the highly meshed UCTE network, this is not the case as cross-border lines have constantly been enhanced and bottlenecks are often located within the countries. A more realistic zone-building would have to take the impedances into account, and the found zones will probably not coincide with political borders. In contrast, European market and control areas are politically predefined.

3.4 Safe PTDF

The preceding chapters made clear that several factors have a significant impact on the variation of PTDF coefficients. On one hand, applying PTDF coefficients lower than those actually measured for a certain situation clearly compromises network security, as actual power flows would be underestimated. On the other hand, anticipating coefficients higher than those observed comes at the expense of an efficient network usage, as physical flows will be overestimated and grid capacity cannot be fully utilized.

Hence, the question arises whether there exist PTDF values guaranteeing network security for a certain set of operating scenarios (‘safe PTDF’) and if so, how much physical flows will be overestimated by these factors on average. To answer these questions, AC load flows were run for six different snapshot cases between 2004 and 2007 and the corresponding PTDF matrices were derived. Next, the maximum value observed per coefficient was divided by the average value of the same coefficient. The fraction thus yielded shows how strong a safe PTDF value would overestimate average flows. Table 5 provides these findings as percentage values.

	Transactions				
Flowgates	O->I	S->I	D->I	F->I	L->I
CH->IT	111%	112%	111%	111%	118%
CH->DE	112%	136%	113%	119%	119%
CH->FR	193%	118%	168%	118%	216%
CH->AT	128%	223%	128%	130%	124%
DE->FR	128%	175%	138%	126%	126%
DE->AT	112%	143%	125%	130%	119%
IT->FR	121%	122%	117%	108%	115%
IT->SI	111%	136%	121%	133%	110%
AT->SI	119%	145%	143%	145%	106%

Central South

Table 5: Overestimation by ’safe’ PTDF coefficients.

As can be seen, the values range from 108% to 223% of average flows. The more zones are considered for the computation, the worse the performance becomes: For instance, in Central South (6 zones) about 70% of the safe coefficients overestimate average flows by 30% or less (see Table 5), while in Central East (8 zones), only about 43% of safe coefficients overestimate by 30% or less. This is because the more zones are included, the higher the variation due to the aforementioned factors becomes.

In conclusion, using safe PTDF coefficients would considerably compromise an efficient use of the network. On top of that, the coefficients shown in Table 5 are still not safe: While the numbers were computed for zone-to-zone average transactions, the variability of coefficients would even increase if sub-zones had been considered as well (see 3.3) [15]

4 CALCULATION OF BORDER CAPACITIES

4.1 Three types of border capacities with increasing levels of security

The available literature does not provide much insight into how border capacities have to be calculated. Therefore, in this work, three types of border capacities with an increasing level of security are defined:

[3] Plants located in Leibstadt and Mühleberg.

- **flowgate-secure:** no thermal overload appears on the flowgate elements
- **n secure**: no thermal overload appears in the normal load flow case either on the flowgates or within the zones
- **n-1 secure:** no thermal overload appears in the n-1 contingency analysis either on the flowgates or within the zones

In Table 6, the border capacity is estimated for each transaction, based on an extrapolation of the loadings of each of the lines constituting the flowgate. This leads to flowgate-secure border capacities. The column labelled 'NTF' shows the notified transmission flows included in the reference case, a negative number indicating a flow in the reverse direction of the flowgate.

	Transactions					
Flowgates	O->I	S->I	D->I	F->I	L->I	NTF
CH->IT	3801	7062	5759	5526	3394	2870
CH->DE	-2486	-1378	-3757	-2763	-2238	-1893
CH->FR	-1546	-343	-1977	-2979	-1526	-1487
CH->AT	-790	-629	-1123	-888	-637	-480
DE->FR	-834	-1089	-278	-1989	-911	-1046
DE->AT	-709	280	721	498	-370	-172
IT->FR	-2710	-3489	-3478	-4221	-2600	-2401
IT->SI	-1481	-1616	-1819	-1642	-1887	-1032
AT->SI	306	294	333	286	-288	30

Case: R070117, Central South

Table 6: Flowgate-secure border capacities [MW].

It is striking to see how strongly the border capacities depend on the transactions. Therefore, contrary to common perception, border capacities are not vectors, but matrixes, the columns being the transactions. Note that Table 6 only shows transactions to a single recipient (Italy).

If the extrapolation is done not only on the lines constituting the flowgates, but also on the zone-internal lines, n secure border capacities are obtained. Table 7 shows the border capacities guaranteeing the n security of the 380 kV lines.

	Transactions				
Flowgates	O->I	S->I	D->I	F->I	L->I
CH->IT	4421	5585	5174	3865	3476
CH->DE	-2880	-1559	-3380	-2219	-2292
CH->FR	-1586	-746	-1878	-2046	-1532
CH->AT	-996	-577	-993	-633	-662
DE->FR	-692	-1073	-433	-1399	-890
DE->AT	-1068	121	540	79	-401
IT->FR	-2916	-3106	-3260	-3084	-2631
IT->SI	-1781	-1410	-1660	-1260	-2021
AT->SI	490	201	271	126	-338

Case: R070117, Central South

Table 7: N secure border capacities [MW].

Zone-internally, only the 380 kV lines are monitored, because:

- it makes little sense to include 220 kV lines into the security assessment as they are strongly influenced by local load flows and less by synchronous grid-wide transits.
- the overload of 380/220 kV transformers can often be removed by the TSO (e.g. tap change, topology change).

Once again in a similar way, the n-1 relative loadings of the internal lines in a country are extrapolated, which leads to the n-1 secure border capacities shown in Table 8 for the 380 kV lines:

	Transactions				
Flowgates	O->I	S->I	D->I	F->I	L->I
CH->IT	3645	3775	3638	3202	3149
CH->DE	-2387	-1782	-2389	-2002	-2076
CH->FR	-1536	-1240	-1617	-1673	-1508
CH->AT	-738	-512	-651	-531	-564
DE->FR	-869	-1055	-842	-1164	-974
DE->AT	-620	-74	65	-88	-277
IT->FR	-2659	-2636	-2688	-2629	-2507
IT->SI	-1406	-1158	-1241	-1108	-1487
AT->SI	260	87	110	62	-139

Case: R070117, Central South

Table 8: N-1 secure border capacities [MW].

By comparing the values contained in tables 6, 7 and 8 and taking into account the direction of flowgates and transactions, one can see that the higher the security level (flowgate-secure => n-secure => n-1 secure) the lower the flowgate capacities.[4]

4.2 Critical network elements

The results of the preceding chapter illustrate that in Central Europe, network constraints usually aren't located on tie-lines between national grids, but inside these grids. Moreover, the n-1 security criterion is almost always the limiting factor, as opposed to thermal or stability constraints.

Because the border capacities of flowgates consisting of several tie-lines cannot be computed univocally, it is sometimes suggested to consider the capacities of single lines within or between zones instead ('critical network elements' or 'single-line concept') [16]. Although the capacities of these elements are well defined, the scattering of PTDF coefficients due to the aforementioned factors becomes stronger. This is because a multi-tie-line flowgate acts as a low pass filter and compensates

[4] In some cases, n secure border capacities are higher than flowgate-secure capacities. This is because some flowgates consist of 380kV and 220kV lines, whereas the n security analysis considered only 380kV lines.

deviations on its individual tie-lines. For example, Table 9 shows the impact of a topological change (see 3.1) on flowgates and their individual tie-lines. Clearly, a single line is far more exposed to such a change. Additionally, recent experiences made in highly meshed US electricity markets suggest that often a multitude of lines have to be considered simultaneously to guarantee network security, rendering computational processes tedious [8].

Flowgates	Scattering of PTDF on flowgate	individual tie-lines
CH->IT	4.40%	25.61% to 43.02%
FR->IT	5.74%	40.94% to 78.26%
CH->DE	6.80%	0.00% to 132.31%

Table 9: Scattering of PTDF on flowgates and tie-lines.

5 CONCLUSION

In theory, applying the flow-based PTDF system would guarantee an efficient transmission capacity allocation while respecting physical capacity limits of the electricity grid. However, the findings of this paper lead to the following conclusion: if applied in the context of a zone model (e.g., based on political boundaries), PTDF coefficients are strongly influenced by factors such as seasonal and topological changes or location of generation. Moreover, it was shown that border capacities of flowgates are technically overdetermined in a zone model and hence cannot be computed univocally.

The main problem is that by replacing a full network model by a reduced model, the model is immensely distorted: it is like looking at a landscape with a distorting lens. While at first glance a reduced grid model seems easier to use and understand than a complete model, if decisions are made based on the reduced model, they might often lead to erroneous actions. To cope with arising operational uncertainties, available network capacities may even get decreased.

These findings are confirmed by recent observations in some US electricity markets. For example, both CAISO (California) and ERCOT (Texas) are currently transforming their zonal electricity market design to a nodal one, as the zonal model increasingly compromised the efficient functioning of their markets [17, 18].

APPENDIX

Country	ISO code	UCTE code
Austria	AT	O
France	FR	F
Germany	DE	D
Italy	IT	I
Slovenia	SI	L
Switzerland	CH	S

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