Critical evaluation of the currently discussed approach and the PFD method

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1 Requirements on an ITC mechanism

Article 3 of EU Regulation 1228/2003 specifies the requirements on an Inter-TSO Compensation (ITC) Mechanism with regard to grid costs accruing from cross-border power flows. In detail, according to EU Regulation 1228/2003, this mechanism must be compliant with the following requirements:

- The utilisation of every single network element in the interconnected transmission system caused by cross-border power flows has to be identified.
- The mechanism shall take into account benefits that a network incurs as a consequence of hosting cross-border power flows, with the result that compensations received may be reduced accordingly.
- Cross-border power flows have to be determined based on physical flows of electricity actually measured in a given period of time.

To meet these provisions, a model has to be based on technically correct engineering principles (power flow equations) for the computation of cross-border power flows.
Such a technically correct approach taking into consideration the responsibilities for all power flows in the interconnected network is necessary to meet all the other requirements on a longer term ITC mechanism:

- A technically sound method fulfils the criterion of *cost reflectiveness* because only if the utilisation of a network is determined in a technically correct manner associated costs are reflected correctly by the respective model.
- Every TSO is charged or compensated on the basis of the actual utilisation of network equipment due to cross-border flows. A method based on technically correct engineering principles of network calculation is valid for every power system and therefore *suitable for the European network*.
- Approved engineering principles are compliant with the criteria of *implementation* and *transparency* as they can be understood and interpreted on the basis of common technical knowledge and physical principles.

2 Technical evaluation of the currently discussed approach

The currently discussed approach, described in the *"ERGEG Draft Proposal on Guidelines on Inter TSO Compensations"*, as well as all formerly proposed methods[1] suffer from their technical incorrectness and thus are not compliant with the provisions of Regulation (EC) No 1228/2003, Article 3. The main drawbacks of the approach within the ERGEG Draft Proposal are:

- The physics of electrical power flows are ignored by disregarding that every generator

1 Average Participations Method, With and Without Method, With and Without Method applied to Transits, Marginal Participations Method

in a network participates in the supply of every load.

- The calculation of transit power flows in an interconnected network with the applied method of minimizing the total use of transited networks is neither based on the approved engineering principles (power flow equations) nor technically justified. Furthermore, the approach could lead to a discrimination of transited TSOs.
- The definition of transit power flows as the minimum of import- and export power flows in the context of the calculation of losses is arbitrary.

The general tenor that it is only possible to identify transit power flows with simplifications and arbitrary assumptions is wrong. Based on the power flow equations and the principle of superposition it is possible to decompose power flows in the interconnected transmission system into import, export, transit, loop and internal power flows. These power flows can be assigned to agents located at the different nodes of the network. A technically correct method for the computation of transit power flows as well as import, export, loop and internal power flows, which complies with Article 3 of Regulation (EC) No 1228/2003, is introduced in the next section.

3 PFD (Power Flow Decomposition) method

There are widely accepted and approved engineering principles for the computation of power flows in electrical power systems, namely the power flow equations based on Kirchhoff's laws /1,2/. Additionally, in the context of an ITC mechanism the principle of superposition has to be applied for the decomposition of a total power flow into individual responsibilities of agents in a network.

This section introduces the PFD method, which is based on technically correct engineering principles. It allows for the decomposition of power flows in interconnected transmission systems into import, export, transit, loop and internal power flows. Based on the power flow equations these power flows are assigned to agents located at the different nodes of the network. It is possible to determine the benefits that a network incurs as a result of hosting cross-border power flows. Additionally, the PFD method is independent of political borders and consequently complies with the single system paradigm. The PFD method is solely based on the well established algorithms of power flow computation and the principle of superposition and does not rely on any arbitrary assumptions. Hence, the method is straightforward and cost effective to implement. Furthermore it follows, that it can be easily understood and verified. It can be applied to an entire interconnected transmission system or a single transmission system.[2]

For the implementation of the PFD method the same power system data as for the usual power flow computation is needed:

- network topology,

[2] In the latter case, it is generally impossible to determine the responsibilities of external agents for cross-border power flows.

- impedances of the network elements (transformers and lines),
- nodal powers (generation and demand).

4 Derivation of the PFD method

Linear power flow equations are applied within the PFD method /1,2/. In transmission networks the active resistances of lines and transformers can be neglected. Lines and transformers are modelled as quadrupoles. Figure 1 shows a quadrupole with the terminal voltages $\underline{U}_{\mathrm{L}l}$ and $\underline{U}_{\mathrm{L}m}$ and the terminal currents $\underline{I}_{\mathrm{L}l}$ and $\underline{I}_{\mathrm{L}m}$. The terminals of the quadrupoles are connected with the network nodes.

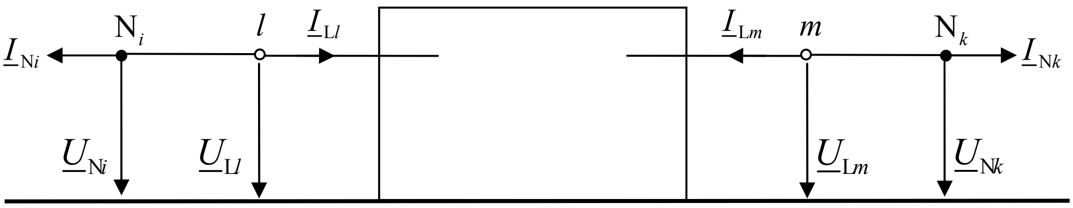

Figure 1 equivalent-circuit diagram of a quadrupole

The correlation between the terminal values of all quadrupoles of a network in terms of a matrix equation can be formulated with the admittance matrix $\underline{\boldsymbol{Y}}_{\mathrm{L}}$ as follows:

$$\underline{\boldsymbol{Y}}_{\mathrm{L}}\underline{\boldsymbol{u}}_{\mathrm{L}} = \underline{\boldsymbol{i}}_{\mathrm{L}} \tag{1}$$

The incidence matrix $\boldsymbol{K}^{\mathrm{T}}$ describes the correlation between the terminal voltages and the nodal voltages as follows:

$$\boldsymbol{K}^{\mathrm{T}}\underline{\boldsymbol{u}}_{\mathrm{N}} = \underline{\boldsymbol{u}}_{\mathrm{L}} \tag{2}$$

The nodal voltage equations can be formulated with the nodal admittance matrix $\underline{\boldsymbol{Y}}_{\mathrm{NN}}$ as follows:

$$\underline{\boldsymbol{Y}}_{\mathrm{NN}}\underline{\boldsymbol{u}}_{\mathrm{N}} = \underline{\boldsymbol{i}}_{\mathrm{N}} \tag{3}$$

Equations (1), (2) and (3) lead to a linear correlation between the terminal currents and the nodal currents:

$$\underline{\boldsymbol{Y}}_{\mathrm{L}}\boldsymbol{K}^{\mathrm{T}}\underline{\boldsymbol{Y}}_{\mathrm{NN}}^{-1}\underline{\boldsymbol{i}}_{\mathrm{N}} = \underline{\boldsymbol{i}}_{\mathrm{L}} \tag{4}$$

Equation (4) is extended:

$$\underline{\boldsymbol{s}}_{\mathrm{L}} = \underline{\boldsymbol{U}}_{\mathrm{L}}\underline{\boldsymbol{Y}}_{\mathrm{L}}^{*}\boldsymbol{K}^{\mathrm{T}}\underline{\boldsymbol{Y}}_{\mathrm{NN}}^{-1*}\underline{\boldsymbol{U}}_{\mathrm{N}}^{-1}\underline{\boldsymbol{s}}_{\mathrm{N}}$$

with:

$$\underline{\boldsymbol{U}}_{\mathrm{N}} = \mathrm{diag}(\underline{\boldsymbol{u}}_{\mathrm{N}}),\ \underline{\boldsymbol{s}}_{\mathrm{N}} = 3\underline{\boldsymbol{U}}_{\mathrm{N}}\underline{\boldsymbol{i}}_{\mathrm{N}}^{*}$$

$$\underline{\boldsymbol{U}}_{\mathrm{L}} = \mathrm{diag}(\underline{\boldsymbol{u}}_{\mathrm{L}}),\ \underline{\boldsymbol{s}}_{\mathrm{L}} = 3\underline{\boldsymbol{U}}_{\mathrm{L}}\underline{\boldsymbol{i}}_{\mathrm{L}}^{*} \tag{5}$$

The dependency of the active power flows and the nodal active power can be written as follows:

$$\boldsymbol{p}_{\mathrm{L}} = \boldsymbol{D}\,\boldsymbol{p}_{\mathrm{N}} \tag{6}$$

with:

$$\boldsymbol{D} = \mathrm{Re}\{\underline{\boldsymbol{U}}_{\mathrm{L}}\underline{\boldsymbol{Y}}_{\mathrm{L}}^{*}\boldsymbol{K}^{\mathrm{T}}\underline{\boldsymbol{Y}}_{\mathrm{NN}}^{-1*}\underline{\boldsymbol{U}}_{\mathrm{N}}^{-1}\} \tag{7}$$

It is assumed that the integrated network consists of n transmission systems. In equation (8) the nodal and terminal powers are arrayed as follows:

$$\begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}} \\ \boldsymbol{p}_{\mathrm{L2}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{D}_{11} & \boldsymbol{D}_{12} & \cdots & \boldsymbol{D}_{1\mathrm{n}} \\ \boldsymbol{D}_{21} & \boldsymbol{D}_{22} & \cdots & \boldsymbol{D}_{2\mathrm{n}} \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{D}_{\mathrm{n}1} & \boldsymbol{D}_{\mathrm{n}2} & \cdots & \boldsymbol{D}_{\mathrm{nn}} \end{bmatrix} \begin{bmatrix} \boldsymbol{p}_{\mathrm{N1}} \\ \boldsymbol{p}_{\mathrm{N2}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Nn}} \end{bmatrix} \tag{8}$$

Equation (8) shows the impact of the nodal powers of every single transmission system on the power flows in the network elements in all n transmission systems. By means of equation (8) and the principle of superposition, the power flows on every network element can be decomposed into import, export, transit loop and internal power flows. Furthermore, every power flow (import, export, transit loop and internal power flows) can be traced through the network, and responsible injections and withdrawals for these power flows can be identified. The decomposition of the power flows by means of the principle of superposition leads to:

$$\begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}} \end{bmatrix} = \left\{ \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{11} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{11} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{11} \end{bmatrix} + \cdots + \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{1\mathrm{n}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{1\mathrm{n}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{1\mathrm{n}} \end{bmatrix} \right\} + \cdots + \left\{ \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{i1} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{i1} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{i1} \end{bmatrix} + \cdots + \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{ij} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{ij} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{ij} \end{bmatrix} + \cdots + \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{i\mathrm{n}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{i\mathrm{n}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{i\mathrm{n}} \end{bmatrix} \right\} + \cdots + \left\{ \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{\mathrm{n}1} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{\mathrm{n}1} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{\mathrm{n}1} \end{bmatrix} + \cdots + \begin{bmatrix} \boldsymbol{p}_{\mathrm{L1}}^{\mathrm{nn}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{L}k}^{\mathrm{nn}} \\ \vdots \\ \boldsymbol{p}_{\mathrm{Ln}}^{\mathrm{nn}} \end{bmatrix} \right\} \tag{9}$$

The superscripts in the power flow vectors in equation (9) represent the responsible transmission systems for this particular power flow vector. For instance the power flow vector $\boldsymbol{p}_{\mathrm{L}k}^{ij}$ represents the transit power flows through transmission system k originating in transmission system i and ending in transmission system j. In equation (9) all import, export, transit loop and internal power flows are included. Table 1 shows the notation for export, transit loop and internal power flows. Import power flows are not included because import power flows of a transmission system are equal to the negative export power flows of the transmission system where these power flows originate.

export power flow in k from k to i	$\boldsymbol{p}_{\mathrm{L}k}^{ki}$
transit power flow through k from i to j	$\boldsymbol{p}_{\mathrm{L}k}^{ij}$
loop power flow through k from i to i	$\boldsymbol{p}_{\mathrm{L}k}^{ii}$
internal power flow in k	$\boldsymbol{p}_{\mathrm{L}k}^{kk}$

Table 1 notation of power flows

5 Conclusions

The approach described in the *"ERGEG DRAFT Proposal on Guidelines on Inter TSO Compensations"* is not suitable to be implemented within a longer-term ITC mechanism as it does not meet the requirements of Article 3 of Regulation (EC) No 1228/2003 shown in Section 1. Due to its technical inadequacies the currently discussed approach would lead to an incorrect determination of transit power flows. As a consequence the resulting compensation payments are not cost reflective. Furthermore, the minimisation of the total utilisation of TSOs due to transit power flows leads to a discrimination of transited networks.

For the computation of cross-border power flows, as required in Article 3 of Regulation (EC) No 1228/2003, the PFD method should be applied within a longer-term ITC mechanism. The PFD method does solely rely on technically sound and established engineering principles without any arbitrary assumptions. Therefore, it is straightforward and cost effective to implement and can be easily understood and verified. The PFD method needs the same data set as a power flow calculation.

References

/1/ Stagg, G. W., El-Abiad, A. H.: Computer Methods in Power system Analysis. Mc Graw-Hill Book Company, New York, Sydney, 1968

/2/ Oeding, D., Oswald, B. R.: Elektrische Kraftwerke und Netze. 6. Auflage Springer-Verlag 2004