SOFTWARE TOOL FOR POWER TRANSFER DISTRIBUTION FACTORS (PTDF) COMPUTING WITHIN THE POWER SYSTEMS

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Abstract: **With the restructuring of the electric power system, the role of transmission companies is to provide reliable electric service to customers. The ability of a transmission system to serve loads is an important factor that weighs heavily on the reliability of the system. Uncertainties in the system are important in considering the system reliability. The uncertainty in the demand or load stems from the fact that the load is a constantly varying parameter that is largely uncertain. This paper is presenting a software tool developed in Matlab environment. The software is designed for power transfer distribution factors (PTDF) computing within a complex power system, when a specific transaction is taken into consideration. PTDFs are used to show how a particular transaction will affect the system. The algorithm of the software is based on the methodology developed by the authors for PTFDs computing. Using the PTDFs, the change in flow on each transmission line in the system may be calculated for the load change at certain buses. The power system based on the West and South-West side of the National Romanian Power System is used as a study case.**

***Index Terms*: power systems, PTDF factors, software tool, power flow equation, load variation.**

I. INTRODUCTION

With the restructuring of the electric power system, the role of transmission companies is to provide reliable electric service to customers [1].

The revenue generated from transmission tariffs for the system's ability to serve load can be used to determine the economic value of a transmission system. The economic value of the transmission system generated from tariffs is affected by the ability to serve load, which depends on certain characteristics of the system, such as thermal, voltage, and stability limits.

On the other side, these characteristics, limit the ability of the transmission system to transfer power among elements in the system and to deliver power from the generation units to the customers or customer demand sites. As a result, the criteria used for the planning and expansion of the system must ensure that the system is able to deliver and transfer power to meet the total customer demand in the event of disturbances or contingencies by operating reliably within the limits of the system [1].

Uncertainties in the system are important in considering the system reliability. The uncertainty in the demand or load stems from the fact that the load is a constantly varying parameter that is largely uncertain. The load forecast is based on historical data, such as: demographic and economic factors such as economic growth, environmental factors such as temperature and precipitation, electronically controlled loads and variations in load power factors.

Section II of the paper deals with the analysis of the PTDF problem. Section III illustrates the power system used as a study case. Within the IVth Section the application developed is presented. Section V provides the numerical results and their discussion. Section VI contains the concluding remarks.

II. ANALYZING THE PTDFs PROBLEM

The power transfer distribution factors (PTDFs) are computed based on direct current power flow equations. The PTDFs are defined as the relative change in the power flow on a particular branch from bus i to bus j due to a change in injection and corresponding withdrawal at the system swing or slack bus. Using the PTDFs, the change in flow on each transmission line in the system may be computed for the change in injection at one or more buses. This computed change in flow on the transmission line causes a change in the amount of revenue generated. The calculation of the change in revenue ultimately leads to the evaluation of the distribution of the revenue [10].

The PTDFs computing process is divided into two steps:

- susceptance matrix computing;
- distribution factors computing.

In the following these two steps will be presented.

The objective for the first step of the method developed is to compute the susceptance matrix, based on DC power flow.

Consider a transmission line in the network, between buses i and j, having the line impedance Z, voltages at its two ends and real power flow as shown in Fig. 1.

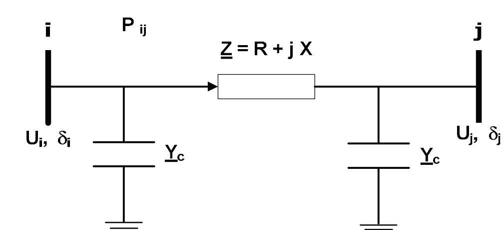

Fig. 1 – Representation of a symbolic transmission line model

The classic Newton power flow scheme is an iterative method that solves the system of equations in corrections, in case of each iterative step.

$$J \cdot \Delta x = -f \qquad (1)$$

where: Δx represents the array of the corrections; f represents the array of the functions (active and reactive powers); J represents the Jacobian matrix.

It is stated that in the following that all the quantities presented in the relations described, are expressed in p.u.

The unknowns array is partitioned in two sub-arrays: the array of voltage phases (δ) and the array of voltage modules (U). The array of the functions is also divided in two sub-arrays corresponding to active, respectively reactive powers.

$$\Delta \boldsymbol{x} = \begin{bmatrix} \Delta \boldsymbol{\delta} \\ \Delta \boldsymbol{U} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \Delta \delta_1 \\ \Delta \delta_2 \\ \vdots \\ \Delta \delta_n \end{bmatrix} \\ \begin{bmatrix} \Delta U_1 \\ \Delta U_2 \\ \vdots \\ \Delta U_n \end{bmatrix} \end{bmatrix}; \boldsymbol{f} = \begin{bmatrix} \boldsymbol{F}_P \\ \boldsymbol{F}_Q \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} f_{P_1} \\ f_{P_2} \\ \vdots \\ f_{P_n} \end{bmatrix} \\ \begin{bmatrix} f_{Q_1} \\ f_{Q_2} \\ \vdots \\ f_{Q_n} \end{bmatrix} \end{bmatrix};(2)$$

The structure of the Jacobian matrix appears as shown in equation (3):

- J_1 – corresponds to the relationship active power – voltage phase;
- J_2 – corresponds to the relationship active power – voltage angle;
- J_3 – corresponds to the relationship reactive power – voltage phase;
- J_4 – corresponds to the relationship reactive power – voltage angle.

$$J = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} = \begin{bmatrix} \dfrac{\partial F_P}{\partial \delta} & \dfrac{\partial F_P}{\partial U} \\ \dfrac{\partial F_Q}{\partial \delta} & \dfrac{\partial F_Q}{\partial U} \end{bmatrix} \tag{3}$$

The four relationships are leading to the following conclusions. The active power is more sensitive to perturbations in the voltage angle as opposed to perturbations in the voltage magnitude. Thus, the reactive power is more sensitive to changes in the voltage magnitude than changes in the voltage angle. From those two dominating relationships, the active power – voltage angle is selected $(\Delta P - \Delta\delta)$. Taking into consideration these assumptions and the simplifications specific to DC power flow, the matrix equations for an n-bus system may be determined using relation (4).

$$\begin{bmatrix} \Delta P_1 \\ \cdots \\ \cdots \\ \Delta P_n \end{bmatrix} = -\begin{bmatrix} B_{11} & \cdots & \cdots & B_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ B_{n1} & \cdots & \cdots & B_{nn} \end{bmatrix} \cdot \begin{bmatrix} \Delta\delta_1 \\ \cdots \\ \cdots \\ \Delta\delta_n \end{bmatrix} \tag{4}$$

The elements of the susceptance matrix (B) are computed based on the following relations:

- the off-diagonal elements:

$$B_{ik} = \frac{1}{x_{ik}} \tag{5}$$

- the diagonal elements:

$$B_{ii} = -\sum_{k=1}^{N} \frac{1}{x_{ik}} \tag{6}$$

The susceptance matrix remains constant and only need to be calculated once. Thus, the DC power flow equation is obtained:

$$\Delta P = -B\Delta\delta \tag{7}$$

Relation (7) is pointing out that only the active power flow on the system branches is computed. The relation involved does not offer any information regarding the reactive power flow. For the objective of the current investigation, is enough.

The distribution factors use the matrix calculated based on the DC power flow equations presented previously. Given the linearity of the DC power flow model, the changes due to any set of system conditions can be calculated. For the case of the current investigation, the load at several P-Q buses is changed. Thus, a relationship between the resulting changes in the bus voltage angles Δδ and the change in the bus power Δ P is desired.

Based on relation (7) it can be obtained:

$$\Delta\delta = -X \cdot \Delta P \tag{8}$$

where X represents the inverse of the susceptance matrix incremented with a row and column of zeros at the slack bus.

The B matrix is an n x n matrix, corresponding to an n-bus power system. It cannot be inversed. Thus, the line and column corresponding to the slack bus of the power system are eliminated from the matrix and the n-1 x n-1 inverse matrix is computed.

$$X = \begin{bmatrix} 0 & | & \cdots & \cdots & 0_n \\ - & | & - & - & - \\ \cdots & | & & & \\ \cdots & | & & B^{-1} & \\ 0_n & | & & & \end{bmatrix} \tag{9}$$

The X matrix in equation (9) includes an entry of zeros on the row and column corresponding to the system slack bus (considered to be bus number 1, as an example).

To accomplish the PTDFs computing process the equation of active power flow on the *ij* branch is requested.

$$P_{ij} = U_i^2 \cdot G_{l\,ij} - U_i U_j \cdot [G_{l\,ij} \cdot \cos(\delta_i - \delta_j) + \\ + B_{l\,ij} \cdot \sin(\delta_i - \delta_j)] \quad (10)$$

Taking into consideration the simplifications specific to the DC power flow, yields

$$P_{ij} = \frac{\delta_i - \delta_j}{x_{ij}} \quad (11)$$

where x_{ij} represents the reactance of the branch *ij*.

In the following, regarding our objective, it is studied the variation of active power flow on a certain branch, when the power consumed is increased.

$$\rho_{l,k} = \frac{d\,P_l}{d\,P_k} \quad (12)$$

where: $\rho_{l,k}$ represents the PTDF factors corresponding to branch *l*; P_l represents the active power flow on the *l* branch; P_k represents the active power consumed at the consumer from bus *k*.

Replacing the expression (11) into (12) we obtain:

$$\rho_{l,k} = \frac{d\,P_l}{d\,P_k} = \frac{d\,P_{ij}}{d\,P_k} = \frac{d}{d\,P_k}\left(\frac{\delta_i - \delta_j}{x_{ij}}\right) \quad (13)$$

In the following it yields:

$$\rho_{l,k} = \frac{d}{d\,P_k}\left[\frac{1}{x_{ij}}\left(\delta_i - \delta_j\right)\right] = \\ \frac{1}{x_{ij}}\left(\frac{d\,\delta_i}{d\,P_k} - \frac{d\,\delta_j}{d\,P_k}\right) = \frac{1}{x_{ij}}\left(\frac{1}{\frac{d\,P_k}{d\,\delta_i}} - \frac{1}{\frac{d\,P_k}{d\,\delta_j}}\right) \quad (14)$$

Then finally the relation for PTDFs computing is established

$$\rho_{l,k} = \frac{1}{x_{ij}}(X_{ik} - X_{jk}) \quad (15)$$

where: x_{ij} represents the reactance of the branch *i-j*; X_{ik}, X_{jk} represents the *ik*, respectively *jk* elements extracted from the *X* matrix; *l* represents the branch for which the PTDF factors are computed, taking into consideration the load from the P-Q bus *k*.

Applying relation (15) a matrix called the PTDF matrix is obtained. This matrix has a number of lines equal to the number of branches and a number of columns equal to the number of consumers within the power system analyzed. Each value from the matrix represents the percent of the power involved within a specific transaction, which is transported on the branches from the power system analyzed.

For the case of the current power system, having a number of 42 P-Q buses the resulting change in the flow of real power on line *l* connecting buses *i* and *j* is calculated as ΔP using the sensitivity factor from relation (15) as shown in (16).

$$\Delta f_l = \sum_{k=1}^{42} \rho_{l,k} \Delta P_k \quad (16)$$

where: Δf_l represents the change in the line flow in case of the line *l*; $\rho_{l,k}$ represents the PTDF corresponding to line *l*, computed for the case of P-Q bus number *k*; ΔP_k – the difference between the newly calculated load value and the base case value for the P-Q bus number *k*.

III. DESCRIPTION OF THE POWER SYSTEM ANALYZED

The power system used as a study case (Fig. 2) is developed based on the West and South-West side of the National Power System. It has 88 buses and 107 branches. The 35 P-U buses are divided in 17 real generating units and 18 equivalent P-U buses, obtained by extracting the analyzed part from the National Power System. The system has a number of 42 P-Q buses. Within the power system the buses at medium voltage, 220 kV, 400 kV are represented. At 110 kV voltage level, only the generated and consumed powers are represented.

It is designed in Powerworld version 8 software.

IV. DESCRIPTION OF THE APPLICATION DEVELOPED

The software tool is developed in Matlab environment. It has a user friendly interface, specific to Windows applications. The application created uses the power system designed in Powerworld software, together with the related data too.

The software created allows the computing of the power transfer distribution factors, as the main objective. In the following, once these factors are known, the new values for the power flows on the system branches are computed, without running the power flow algorithm. These values correspond to a load increase at a certain load. The third option of the software tool allows the computing of the revenue for each branch.

In Fig. 3 the flowchart of the software tool created is presented.

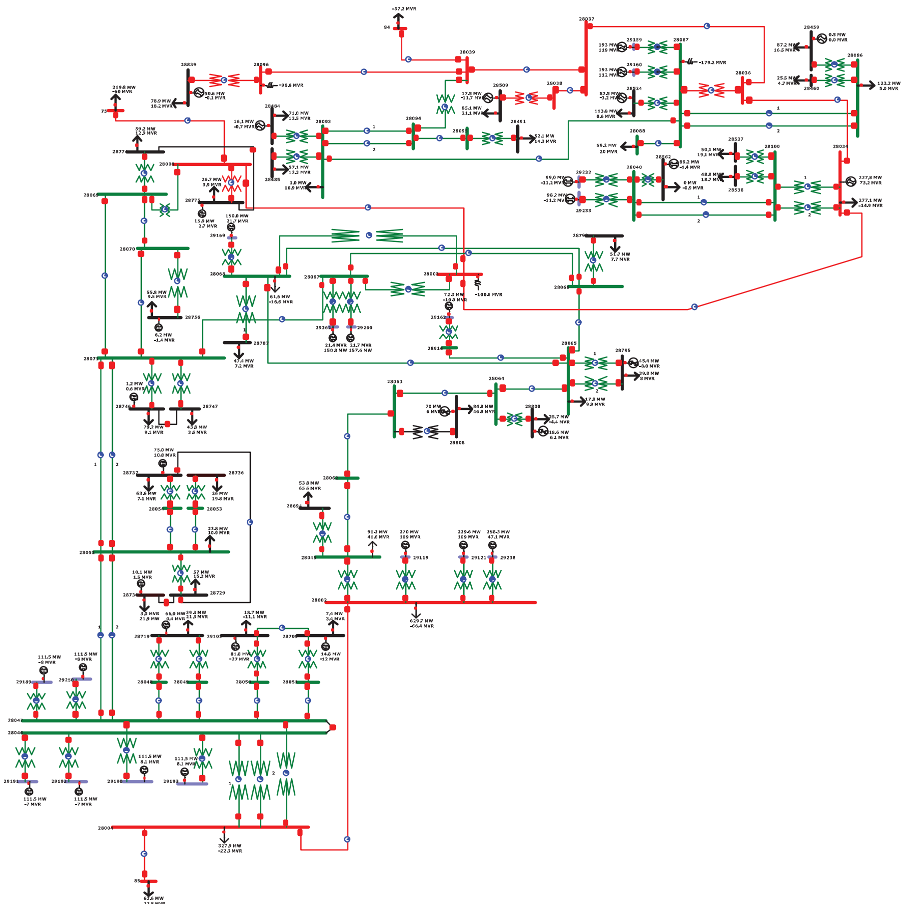

Fig. 2 – The scheme of the power system used as a study case

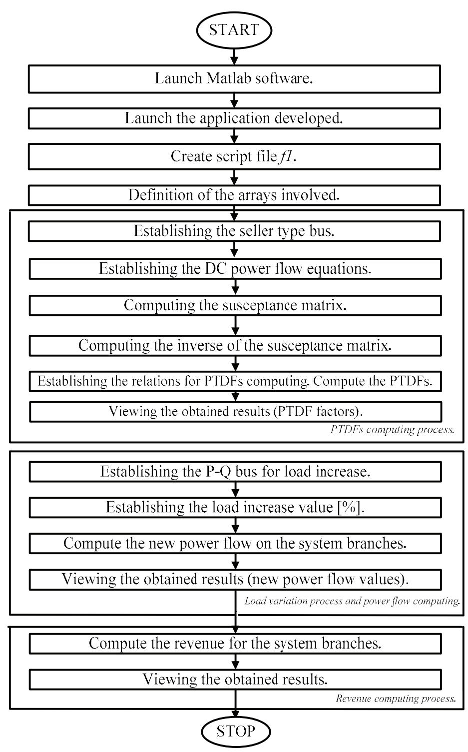

Fig. 3 – The flowchart of the software tool developed

The application created uses a script file. It is a special type of file that allows the user to automatically extract the necessary data from Powerworld software. These data are represented by the length of the branches, the reactance of the branches, the branches of the power system analyzed, the active power consumed, the P-U buses, the P-Q buses, respectively all the buses within the power system.

The main window of the application is presented in Fig. 4. For the beginning the user is requested to create the script file (previously discussed). Once this file is created, it has to be run in Powerworld software, Powerworld being operated in script mode. The necessary data are extracted from Powerworld in individual text files. Based on these files, the arrays necessary within the computing process, are defined (*File* menu, *Arrays definition* option).

Fig. 4 – The main window of the application

Once the arrays were defined the computing process of the PTDFs can be started selecting menu *Operations*, option *PTDFs computing* (Fig. 5). The window presented in Fig. 5 appears. The upper part of the window contains basic information extracted from the power system analyzed such as the total active power consumed, respectively the total number of buses within the power system. In the following the user is requested to type the value corresponding to the transport tariff.

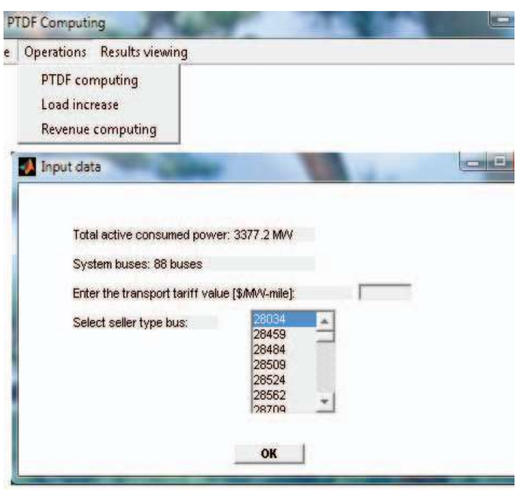

Fig. 5 – Input data window for PTDFs computing

To compute the PTDFs a transaction has to be specified. The transaction is established between a seller bus (from the P-U buses) and a buyer type bus (from the P-Q buses). Using the window presented in Fig. 5, the user is able to select the seller type bus. The software created does not request the user to establish the buyer type bus too, because all the P-Q buses will be taken into consideration. And several transactions will be considered, between the seller type bus (specified by the user) and each of the possible buyer type buses within the power system analyzed. Pressing the *OK* button (Fig. 5), the PTDFs are computed.

The distribution factors computed for each load bus of the power system and the seller type bus specified by the user are saved in text file. In this manner the user can easily analyze or extract the data results, concerning a certain transaction.

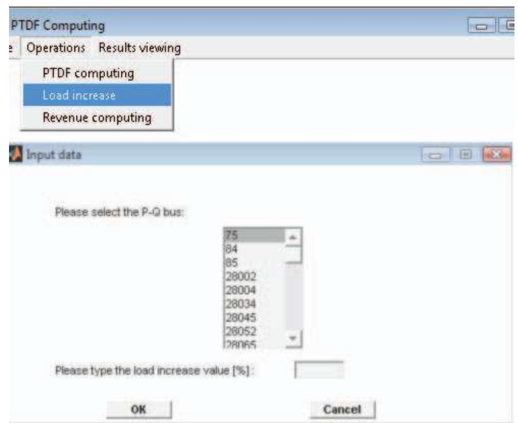

Fig. 6 – Input data window for load increase

Selecting *Operations* menu, option *Load increase*, the active consumed power at a specific bus can be increased. In Fig. 6 the user is requested to select the P-Q bus, from a list of all the P-Q buses within the power system, where the active consumed power will be increased. The value corresponding to the load increase has also to be entered using the same window.

Based on the PTDF factors previously computed, the new values corresponding to the active power flows on the system branches are computed, taking into consideration the load increase specified. These new values are obtained without running the power flow algorithm, thanks to the PTDFs.

For a certain transport tariff specified by the transport system operator (TSO) the revenue for each transmission line can be computed. This is useful information for the TSO to allocate the revenue among the transmission lines.

V. NUMERICAL RESULTS

The software application created is applied for the case of the power system based on the West and South-West side of the National Romanian Power System.

The slack bus of the power system analyzed is represented by bus 28034. To compute the PTDF factors a transaction must be established.

For the first case of the analysis, a transaction is established between buses 29119 (seller type bus) – 28729 (buyer type bus). The results are presented in Table 1.

Table 1 contains 33 branches from those 107 of the power system analyzed. Within the table presented, only the distribution factors greater than 2 % are selected.

Table 1. PTDFs for the case of 29119 – 28729 transaction

Nr.	Branch	PTDF [%]
1.	28002-28004	-75.14
2.	28045-28002	24.86
3.	28002-29119	100
4.	28003-28008	-14.01
5.	28067-2800	-3.29
6.	28068-28003	-10.72
7.	28046-28004	26
8.	28046-28004	26
9.	28047-28004	23.14
10.	28069-28008	11.61
11.	28008-28775	-2.41
12.	28045-28062	-24.86
13.	28046-28047	-52
14.	28047-28052	-37.57
15.	28047-28052	-37.57
16.	28052-28054	-23.79
17.	28052-28071	12.43
18.	28052-28071	12.43
19.	28052-28729	-76.21
20.	28054-28737	-23.79
21.	28062-28063	-24.86
22.	28063-28064	-24.86
23.	28064-28065	-24.86
24.	28065-28066	-14.95
25.	28065-28068	-9.91
26.	28066-28067	-14.14
27.	28067-28071	-10.85
28.	28069-28070	-5.64
29.	28069-28071	-8.37
30.	28069-28774	2.41
31.	28070-28071	-5.64
32.	28729-28737	23.79
33.	28774-28775	2.41

The distribution factors computed have positive and negative values too. These values are leading us to the following important conclusions:

- if the PTDF is positive, than the power flow on the corresponding branch is decreasing, in case of the transaction established;
- if the PTDF is negative, than the power flow on the corresponding branch is increasing, in case of the transaction established.

Analyzing the values presented in the previous table, the branch 28002-29119 is loaded at limit (100 %), in case of the transaction established.

Branch 28052-28729, for the current transaction is characterized by a negative value of the distribution factor (-76.21 %). This value of the PTDF predicts a possible congestion situation, in case of future transactions.

Within the base of the power system analyzed, the branch 28002-28004 has a loading level of 20 %. According to the distribution factors computed (Table 1), in case of the transaction established, the new reached value is 75.14 (absolute value). This fact proves that the current branch is suspicious to be congested.

In the following the load at bus number 28729 is increased by 20 % of the base case load value, with all the other loads remaining the same as the respective base case values.

The initial load value from the base case is $P_{28729\_initial} = 57\ MW$. The new value for the load taking into consideration the increase percent, yields $P_{28729\_increase} = 68.4\ MW$. In this case the difference between the two values is $\Delta P = 11.5\ MW$.

In Table 2 there are presented the changes in power flows of the system branches corresponding to a load increase at bus number 28729.

Table 2. Analysis of PTDFs with change in bus 28729

Nr.	Branch	Calculated Δf_l [MW]
1.	28002-28004	8.5662
2.	28045-28002	-2.8338
3.	28002-29119	-11.4000
4.	28003-28008	1.5974
5.	28067-28003	0.3751
6.	28068-28003	1.2223
7.	28046-28004	-2.9640
8.	28046-28004	-2.9640
9.	28047-28004	-2.6381
10.	28069-28008	-1.3232
11.	28008-28775	0.2742
12.	28045-28062	2.8338
13.	28046-28047	5.9280
14.	28047-28052	4.2831
15.	28047-28052	4.2831
16.	28052-28054	2.7115
17.	28052-28071	-1.4169
18.	28052-28071	-1.4169
19.	28052-28729	8.6885
20.	28054-28737	2.7115
21.	28062-28063	2.8338
22.	28062-28063	2.8338
23.	28064-28065	2.8338
24.	28065-28066	1.7044
25.	28065-28068	1.1294
26.	28066-28067	1.6115
27.	28067-28071	1.2364

Nr.	Branch	Calculated Δf_l [MW]
28.	28069-28070	0.6430
29.	28069-28071	0.9544
30.	28069-28774	-0.2742
31.	28070-28071	0.6430
32.	28729-28737	-2.7115

The values presented previously are obtained based on PTDFs computed, without running the power flow algorithm. Table 2 contains only the branches with a change in power flow different from zero. These branches are not affected by the load increase, at the bus specified.

For the second case of the analysis the transaction 29260 (seller type bus) – 28774 (buyer type bus) is established. The results are presented in Table 3.

Table 3. PTDFs for the case of 29260 – 28774 transaction

Nr.	Branch	PTDF [%]
1.	28002-28004	-8.98
2.	28045-28002	-8.98
3.	28003-2800	-65.94
4.	28067-28003	-45.7
5.	28068-28003	-20.24
6.	28046-28004	3.11
7.	28046-28004	3.11
8.	28047-28004	2.77
9.	28069-28008	18.5
10.	28008-28775	-47.44
11.	28045-28062	8.98
12.	28046-28047	-6.21
13.	28047-28052	-4.49
14.	28047-28052	-4.49
15.	28052-28071	-4.49
16.	28052-28071	-4.49
17.	28062-28063	8.98
18.	28063-28064	8.98
19.	28064-28065	8.98
20.	28065-2806	12.81
21.	28065-28068	-3.83
22.	28066-28067	29.22
23.	28066-28068	-16.41
24.	28067-28071	-25.08
25.	28067-29260	100
26.	28069-28070	13.71
27.	28069-28071	20.35
28.	28069-28774	-52.56
29.	28070-28071	13.71
30.	28774-28775	47.44

Like in the previous case too, Table 3 contains only the PTDF values greater that 2 %.

According to Table 3, branch 29260-28067 is loaded at limit, having a PTDF = 100 %. This fact means that there is no other path between bus 29260 (P-U bus) and the other part of the power system, where the P-Q bus 28067 (buyer type bus) is situated. So the entire power (100 % of it) is transported using this branch.

In the following, continuing with bus number 28067, the power path is 28067-28003 (-45.7 %), 28003-28008 (-65.94 %), 28008-28775 (-47.44 %), 28775-28774 (47.44 %). For all the branches, except the last one, the distribution factors have negative values, with different percents from the power involved in the transaction established. In this case, the amount of power added increases the previous power flow value on that branches.

For the last branch (28775-28774), a further analyze is required. The buyer type bus, for the transaction established, is bus number 28774. The power can be transported to this bus, using two paths: 28775-28774 and 28069-28774. In case of these two branches, the last one has a negative distribution factor (-52.56 %), leading to a higher loading percent for this branch, that the initial one known from the base case. If the absolute values of these two percents are analyzed, the maximum percent of the power involved in the transaction is transported on branch 28069-28774. The situation is found for the base case of the power system analyzed, too. Branch 28775-28774 (electrical overhead line) has a loading percent of 14 % and a greater value for the branch 28069-28774 (electrical transformer) of 25 % is found (for the base case of the power system analyzed).

Based on this analyze it can be concluded that the most susceptible branch to be congested is 28069-28774, taking into consideration the initial power flow and the additional power flow, involved by the transaction established.

VI. CONCLUSION

The transmission system operator (TSO) from our country is interested in developing a software toolbox necessary for power system analysis. The analysis is focusing on congestions management, uncertainties and risk management. The software application created is intended to be implemented within the TSO.

The PTDFs can be applied in two research directions. First of all, based on the PTDFs a congestion analysis can be effectuated. The branches of the power system susceptible to congestion situations are revealed. These factors describe the way the power system behaves in case of a certain transaction. The second research direction, the authors are working on, is represented by the computing of the available transfer capability (ATC), based on the previously computed distribution factors.

Regarding the congestion management approach, the software application presented in the paper represents only a “first and quick view”. The authors, in previous works [10-11], have elaborated a more complex application designed for congestion management. Thanks to its simple computing, based on DC power flow equations, the software tool presented in the current paper is very flexible to be applied. It offers an accurate "picture" of the branches that are loaded in repeated tines, during different transactions. And in this way, is pointing out the areas within the power system that need to be reinforced, or those that are characterized by a high degree of uncertainty.

Once the PTDFs have been computed, the change in line flows can be estimated, in case of load increase at a certain P-Q bus. This is also another advantage, creating a first view of the new situation that will be obtained, as a consequence of the load increase.

The PTDFs are a modern and quick tool largely applied for power system analysis. In the current paper the PTDFs have been computed for the case of a real power system, operated by a real TSO. As a future research direction, the ATC value computing based on the PTDFs is identified.

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