DISTRIBUTION FACTORS TRANSMISSION COST ALLOCATION IN CASE OF INDIRECT POWER TRANSFERS

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Abstract - Transmission corridors represent an important role and are considered by UCTE members to be an optimal integration solution into a common electricity market. Power exchanges between systems are achieved through another interconnected system and may cause congestion in transmission networks. This paper is focusing on transmission cost allocation to market participants using distribution factors method, in case of indirect power exchanges through an interconnected power system. Case study refers to a real system, represented by West, South-West and North-West parts of the Romanian Power System.

Keywords: interconnected power systems, congestion, power exchanges, cost allocation, distribution factors.

1. INTRODUCTION

In recent years, interest in congestion management problem for UCTE members has been increased due to electricity markets' development and their integration into one unique and competitive energy market. Increasing power exchanges volume may involve large MW amount transfer at European, regional or subregional levels could lead to severe blackouts, affecting a large number of users. At national and European level, transmission corridors can provide different advantages and benefits [1].

In some cases power exchanges may be achieved through indirect exchange using an interconnected region or power system [2], [3]. Interconnected power system is interposed between a source and a sink and in many cases position between source and sink can be inversed. Considering all these situations, the congestions' occurrence degree presents higher amplitude. Thus, the current and future interconnections' reinforcement at regional level is appropriate to be considered and the congestion analysis using complete power flow model should be used.

Another common electricity market integrating issue is represented by transmission cost sharing among market participants. In literature there are a variety of approaches, which attempt to clarify the problem of transmission cost allocation. Few of these methods have passed through several extensions and adaptations, especially due to the power sector evolution: Bialek method [4], MW-km method [5], distribution factors' method [6], [7] and methods based on impedance matrix [8] and equivalent bilateral exchanges (EBEs) [9].

This study is motivated by recent changes within the Romanian electricity market, renewable energy sources' development and increasing number of transactions. According to the Transmission Network Perspective Plan of the Romanian OTS [10], transmission system encompasses several tightly meshed electrical areas that are interconnected through transmission corridors which, if removed, would cause network islanding. Transmission corridors in the Romanian power system are particularly based on pattern of the MW transfers across the network. Six sections have been identified.

The authors are proposing a complex congestion management mathematical model corresponding to indirect transfer using an interconnected power system. The objective of the paper is focusing on determining the transmission corridors' use by the market participants. Also, an analysis of transmission cost values allocated to generating units and to consumers is performed. The allocation method used is distribution factors method. A software tool has been developed in Mathematica environment. It includes the new mathematical model and part of transmission cost allocation to generating units and consumers. The analysed system and used transmission tariffs are based on official data received from the Romanian Transmission System Operator (OTS).

2. MATHEMATICAL MODEL

The mathematical model key elements are represented by: variables, constrains and objective function.

- **variables**:

⇒ state variables:

$$\begin{gathered}\delta_i, i \in N \setminus e, \quad P_{ge}, \quad U_i, i \in C, \quad Q_{gi}, i \in G \\ P_{ij}, Q_{ij}, ij \in R, \quad S_{ij}, ij \in R \text{ or } I_{ij}, ij \in R\end{gathered} \tag{1}$$

where U_i, δ_i – voltage value and phase in bus i; P_{ge} – slack bus real generated power; Q_{gi} – reactive generated power at bus i; P_{ij}, Q_{ij}, S_{ij} – power flow through the ij network element; N – set of buses; C – subset of the PQ buses; G – subset of the PV buses; R – set of the network elements;

⇒ control variables:

$$\begin{gathered}U_i, i \in G, \quad P_{gi}, i \in G \setminus e, \quad K_{ij}, ij \in T \\ \Omega_{ij}, ij \in T \quad P_{ci}, i \in N\end{gathered} \tag{2}$$

where P_{gi} – real generated power at bus i; K_{ij}, Ω_{ij} – transformer ratios' absolute value and phase; T – subset of the transformers and autotransformers; e – slack bus; P_{ci} – consumed power at bus i.

- **constraints**:
  ⇒ equality constraints:

$$\begin{cases} P_i(U,\delta,K,\Omega) - P_{gi} - P_{ci} = 0, & i \in N \\ Q_i(U,\delta,K,\Omega) - Q_{gi} - Q_{ci} = 0, & i \in N \end{cases} \tag{3}$$

  ⇒ inequality constraints:

$$\begin{aligned} & P_{ge}^{min} \le P_{ge} \le P_{ge}^{max} \\ & P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}, \quad i \in G\backslash e \\ & Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}, \quad i \in G \\ & P_{ci}^{min} \le P_{ci} \le P_{ci}^{max}, \quad i \in N \\ & U_i^{min} \le U_i \le U_i^{max}, \quad i \in C \\ & U_i^{min} \le U_i \le U_i^{max}, \quad i \in G \\ & K_{ij}^{min} \le K_{ij} \le K_{ij}^{max}, \quad ij \in T \\ & \Omega_{ij}^{min} \le \Omega_{ij} \le \Omega_{ij}^{max}, \quad ij \in T \\ & P_{ij}^{min} \le P_{ij}(U,\delta,k,\Omega), \quad ij \in R \\ & S_{ij}^{min} \le S_{ij}(U,\delta,k,\Omega), \quad ij \in R \end{aligned} \tag{4}$$

  where: $\boldsymbol{U}$ and $\boldsymbol{\delta}$ – array of bus voltage values and phases; $\boldsymbol{K}$, $\boldsymbol{\Omega}$ – array of transformer ratio absolute values and phases; P_{ij}, S_{ij}, $ij \in R$ – real and apparent power flow through the ij network element, from the i bus to the j bus; P_{ij}^{min}, S_{ij}^{min} – inferior limit of the P_{ij} and S_{ij} power flow.
- **objective function** contains four terms: generated power cost characteristics, consumed power mitigation cost at specific buses of the power system, the congestion penalty cost and investment costs necessary to achieve additional power branches, requested by the opportunity to ensure the power transfer through interconnected power system without congestion.

$$\begin{aligned} min(OBF) = & \sum_{i \in G} C_i(P_{gi}) + \sum_{i \in N} C_i(P_{ci}) + \\ & + \sum_{ij \in R} TP_{ij} \cdot (S_{ij} - S_{ij}^{**}) + \sum_{w \in W} I_w \end{aligned} \tag{5}$$

The generation hourly cost has a quadratic form:

$$C_i(P_{gi}) = a_i \cdot P_{gi}^2 + b_i \cdot P_{gi} + c_i, \quad i \in G \tag{6}$$

where a_i, b_i, c_i – i generating unit cost coefficients.

TP_{ij} is the penalty tax of the apparent power upper limit overpass through the ij network element; S_{ij}^{**} is defined as:

$$S_{ij}^{**} = \begin{cases} S_{ij} & if \;\; S_{ij} \le S_{ij}^{max} \\ S_{ij}^{max} & if \;\; (S_{ij} > S_{ij}^{max}) \end{cases}, ij \in R \tag{7}$$

The consumed power mitigation cost characteristics has a non linear form, the simpler being a second order P_{ci} polynomial.

$$C_i(P_{ci}) = t_i \cdot \Delta P_{ci}^2 + v_i \cdot \Delta P_{ci}, \quad i \in N. \tag{8}$$

where t_i, v_i – consumer characteristic cost coefficients.

The term I_W represents the investment hourly costs involved in investment achieving w, $w \in W$.

A non linear optimization problem with constraints is obtained. It is solved using the penalty function method, associated with the generalized Lagrange multiplier method and the Fletcher-Reeves gradient method. The lagrangian function Φ is presented in relation (9). Φ function minimization applying gradient methods is performed computing its derivatives regarding the control variables (for the gradient components and searching direction) and regarding the state variables (for the Lagrange multipliers). The expressions of these derivatives are presented in [11], [12].

$$\begin{aligned} \Phi = & \sum_{i \in G} (a_i \cdot P_{gi}^2 + b_i \cdot P_{gi} + c_i) + \sum_{ij \in R} TP_{ij}(S_{ij} - S_{ij}^{**}) + \sum_{i \in N} (t_i \cdot \Delta P_{ci}^2 + v_i \cdot \Delta P_{ci}) + \sum_{i \in N\backslash e} \lambda_{pi} \cdot (P_i - P_{gi} - P_{ci}) + \\ & + \sum_{i \in C} \lambda_{qi} \cdot (Q_i - Q_{ci}) + r_{pe} \cdot (P_{ge} - P_{ge}^*)^2 + r_q \cdot \sum_{i \in G} p_{qi} \cdot (Q_{gi} - Q_{gi}^*)^2 + r_u \cdot \sum_{i \in C} p_{ui} \cdot (U_i - U_i^*)^2 + \\ & + r_p \cdot \sum_{ij \in R} p_{pij} \cdot (P_{ij} - P_{ij}^*)^2 + r_s \cdot \sum_{ij \in R} p_{sij} \cdot (S_{ij} - S_{ij}^*)^2 + \sum_{w \in W} I_w \end{aligned} \tag{9}$$

where $\lambda_{pi}, i \in N\backslash e$; $\lambda_{qi}, i \in C$ – Lagrange multipliers; r_{pe}, r_q, r_u, r_p, r_s – penalty coefficients; $p_{qi}, i \in G$; $p_{ui}, i \in C$; $p_{pij}, ij \in R$; $p_{sij}, ij \in R$ – weighting coefficients; P_{ge}^*; Q_{gi}^*, $i \in G$; U_i^*, $i \in C$, P_{ij}^*, P_{ji}^*, $ij \in R$; S_{ij}^*, S_{ji}^*, $ij \in R$ – are computed as presented in [11], [12].

3. DISTRIBUTION FACTORS METHOD

The distribution factors represent the relative power flow change on system element due to the generated and consumed power change. Generally, they depend on power system topology, operating condition (including constraints presented in Section 2) and power flow sense. Three factors are used [6], [12]: generation shift factors (A factors), generalized generation distribution factors (D factors) and generalized load distribution factors (C factors).

Generation Shift factors are determined by relation (10):

$$\begin{cases} \Delta P_{\ell,k} = A_{k,i} \cdot \Delta P_{gi} \\ \Delta P_{ge} + \Delta P_{gi} = 0 \end{cases}, \quad k \in R, \quad i \in N\backslash e \tag{10}$$

where: $\Delta P_{l,k}$ – real power flow change through the k network element; $A_{k,i}$ – generation shift factors through k network element, corresponding to generation change at bus i; ΔP_{gi} – generation change at bus i ($i \neq e$); ΔP_{ge} – generation change at slack bus.

Generalized generation distribution factors (D factors) are determining each generating unit impact on real power flow through the network elements. Generalized load distribution factors (C factors) are determining the contribution of each load to the network elements.

$$D_{k,i} = D_{k,e} + A_{k,i} = \frac{P_k^0 - \sum\limits_{i\in N\setminus e} (A_{k,i} \cdot P_{gi})}{\sum\limits_{i\in N} P_{gi}} + A_{k,i}$$

$$C_{k,j} = C_{k,e} - A_{k,j} = \frac{P_k^0 - \sum\limits_{j\in N} (A_{k,j} \cdot P_{cj})}{\sum\limits_{i\in N} P_{cj}} - A_{k,j} \qquad (11)$$

where: $P_{l,k}$ – real power flow through k network element; P_{gi} – i bus generated power; $D_{k,i}$ – k network element D factor, corresponding to the i bus generated power; P_{cj} – j bus consumed power; $C_{k,j}$ – k network element C factor, corresponding to the j bus consumed power; P_k^0 – power flow through the k network element from the previous iteration; e – slack bus.

K line transmission usage allocated to i generating unit or j consumer is determined based on D, respectively C factors.

$$UG_{ik} = \sum_{i\in N} (D_{k,i} \cdot P_{gi}), \quad k \in R$$

$$UD_{jk} = \sum_{i\in N} (C_{k,j} \cdot P_{cj}), \quad k \in R \qquad (12)$$

Transmission costs allocated to i bus generating unit [12] are determined based on the transmission tariffs for i PV bus, c_{gi} and transmission usage allocated to i generating unit, UG_{ik}. Similarly, transmission costs allocated to the j PQ bus are determined based on the transmission tariffs for j PQ bus, c_{cj} and transmission usage allocated to consumer j, UD_{jk}.

$$C^{Gi} = 0.2197 \cdot \sum_{k\in K} \sum_{i\in G} c_{gi} \cdot UG_{ik}$$

$$C^{Dj} = 0.7802 \cdot \sum_{k\in K} \sum_{j\in D} c_{cj} \cdot UD_{jk} \qquad (13)$$

where K – set of system lines.

4. SOFTWARE TOOL

The software tool has been designed in Mathematica environment [12] providing the graphical user interface characteristics specific to Microsoft Windows operating systems. It is linked with Powerworld software. The data base containing the power system topology, parameters and elements is extracted from Powerworld software. The flowchart is presented in Fig. 1. A script file, f_1, containing the topology, the parameters and the power system elements is used. The power flow computing results are extracted using a new script file, f_2. Input and output buses for power transfer are identified.

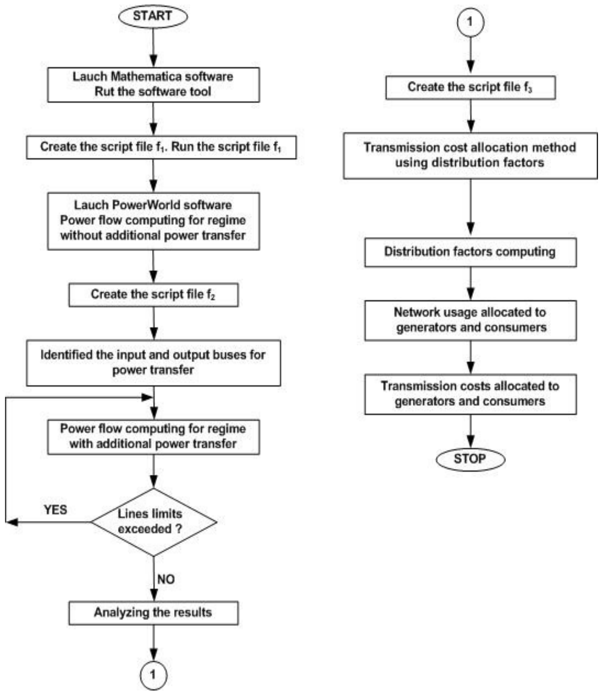

Fig. 1. Software tool flowchart

The opportunities for power transfer capacity expansion are identified and several technical possible solutions are developed. The additional power transfer operating condition is analysed using mathematical model presented in Section II.

Optimal operating condition is obtained and two possibilities are identified regarding the objective function:

- none of the last two terms is “activated”: the obtained operating condition is the final one. The analysis is completed and the power transfer is able to be achieved;
- at least one of the last two terms is “activated”: the obtained operating condition is not the final and the computing process has to be continued. In this case, it must return to power flow computing, to identify other opportunities for further investments.

All the analyses are repeated for “opposite direction” power transfer cases. The third script file, f_3, contains transfer variant analyzed data. Transmission cost is computed using distribution factor method once the data are loading.

5. CASE STUDY AND NUMERICAL RESULTS

The case study is performed for the Western and South-Western side of the Romanian Power System. It has 88 buses, 107 branches, 35 PV buses and 42 PQ buses. Within the power system the medium voltage buses (real generating units), 220 kV, 400 kV are represented. System hourly cost is 202543.97 €/hr. Slack bus is located on Sibiu bus. Real power losses are 71.28 MW. The operating condition for the considered case study [11], [12] is presented in Fig. 2.

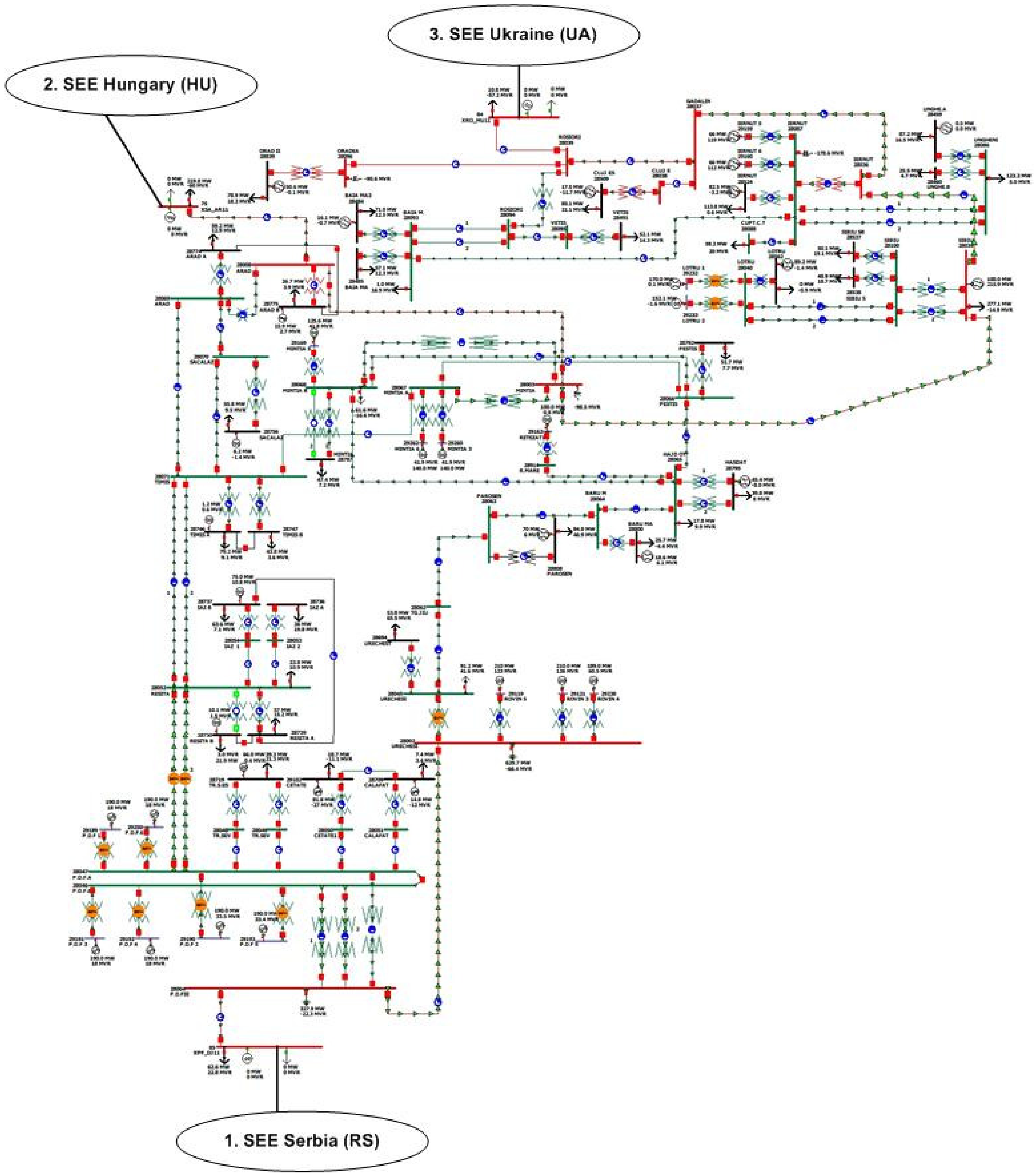

Fig. 2. Western power system being interconnected between the Serbia, Hungary and Ukraine power systems

Buses XPF_DJ11, XSA_AR11 and XRO_MU11 are representing tie-line connections with the neighbouring power systems (Serbia, Hungary and Ukraine). They are considered as inputs and outputs for real power transfers in both directions. In this paper two transfer variants are analyzed: Serbia - Hungary (RS-HU) and Hungary-Serbia (HU-RS). Real transferred power is 500 MW and 600 MW respectively.

The operating condition (Fig. 2) is very similar with the one used by the National Power Dispatcher. It is a peak-evening-winter operating condition.

The power transfer different cases analysis considering the congestion management is already presented in [2], [3]. Authors are focusing on transmission corridors analysis used by generating units and consumers. Real power transferred on 220 kV transmission corridors Iron Gates-Resita and 400 kV Sibiu-Iernut is presented in Table 1.

Table 1. Transmission corridors real power

Transfer	Iron Gates –Resita (MW)	Sibiu-Iernut (MW)
Based case	508	481.3
RS-HU	561.4	481.3
HU-RS	-140.8	412.2

In the following, the results are summarized. The real generated power once the transfer cases congestion management is finished is presented in Fig. 3. The great majority of the generating units have the same value for both cases, excepting the following ones: Mintia 3 (176 MW, 185 MW), PDF 5 (110 MW, 100 MW), Lotru 3 (170 MW, 150 MW), Iernut 6 (66 MW, 100 MW), Rovin 3 (210, 220 MW) and Sibiu (200.6 MW, 159 MW).

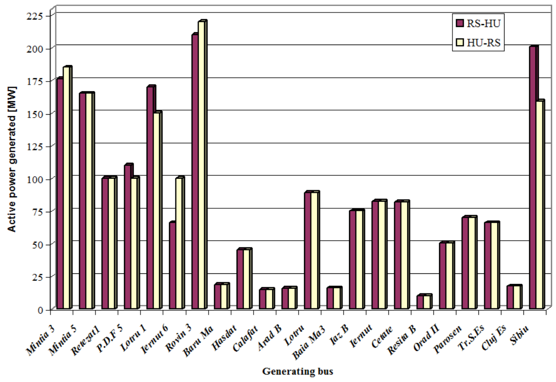

Fig. 3. RS-HU and HU-RS real generated power transfer

The transmission usage values allocated to generating units on transmission corridor Iron Gates-Resita and Sibiu-Iernut using distribution factors allocation method are presented in Fig. 4-5. Differences between the obtained values in both cases are highlighted. e.g. real power flow on Iron Gates-Resita transmission corridor is 561.4 MW (transfer RS-HU) and -140.8 MW (transfer HU-RS). Mintia 5 generating unit produces 165 MW in both cases. But, transmission usage values (Fig. 4) are -584 MW (transfer SR-HU) and 114 MW (transfer HU-RS). The same comment is available for Sibiu-Iernut transmission corridor, in case of the same generating unit. In case of RS-HU transfer, transmission usage allocated to Mintia 5 generating unit is 90.37 MW and for HU-RS, 93.68 MW (Fig. 5).

The Iernut generating unit case is considered as an example. Real Iron Gates-Resita transmission corridor power flow is 561.4 MW (transfer RS-HU), respectively -140.8 MW (transfer HU-RS). Transmission usage allocated to Rovin 3 generating unit is 702.06 MW and -280.81 MW. In case of Sibiu-Iernut transmission corridor the power flow sense is the same for both transfer cases (108.26 MW and 111.41 MW), and transmission usage allocated to Iernut 6 generating unit is negative in both transfer cases: -280.8 MW and -357.37 MW.

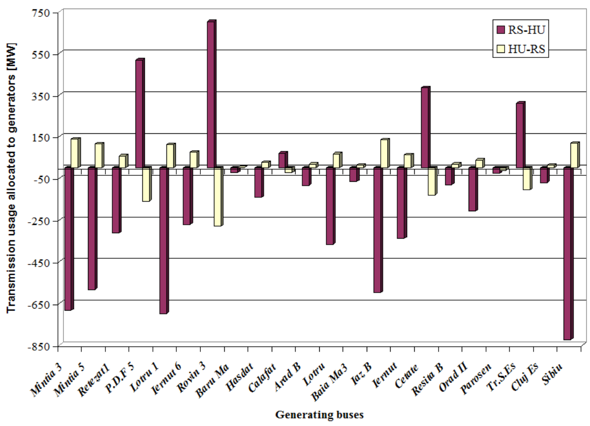

Fig. 4. Transmission usage allocated to generating units on Iron Gates-Resita transmission corridor using distribution factors method

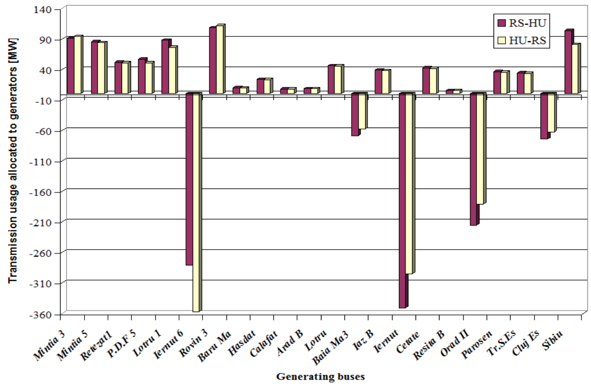

Fig. 5. Transmission usage allocated to generating units on Sibiu-Iernut transmission corridor using distribution factors method

According to Fig. 6 consumers present the same value for transfer cases, excepting the buses that have input and output role for real power transfers: 500 MW (bus XPF_DJ11) and 600 MW (bus XSA_AR11).

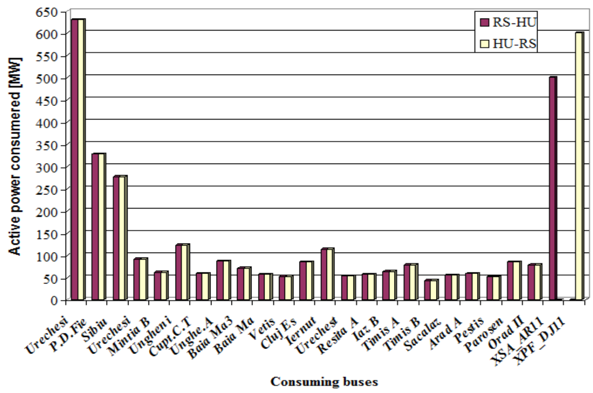

Fig. 6. Real consumed power in case of RS-HU and HU-RS power transfers

Transmission usage allocated to consumers on Iron Gates-Resita and Sibiu-Iernut transmission corridors using allocation method is presented in Figs. 7 and 8.

Consumer Urechesi has the highest value (629.7 MW), only for RS-HU transfer. Thus, for Iron Gates-Resita transmission corridor (Fig. 7) the following values have been obtained: 3389.48 MW (RS-HU transfer) and -699.24 MW (HU-RS transfer). According to fig. 8 transmission usage allocated to consumer Urechesi is 723.42 MW for RS-HU transfer and 602.12 MW for HU-RS transfer.

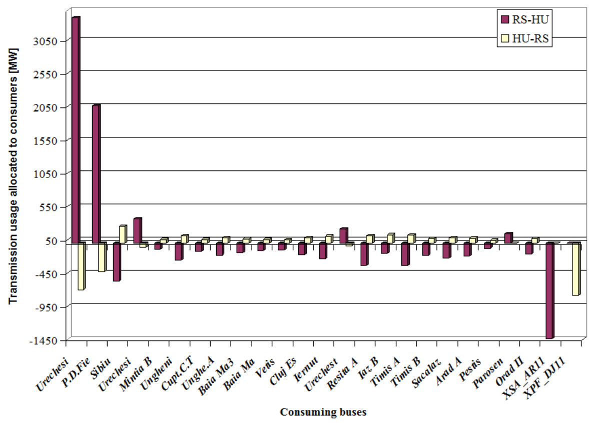

Fig. 7. Transmission usage allocated to consumers on Iron Gates-Resita transmission corridor using distribution factors method

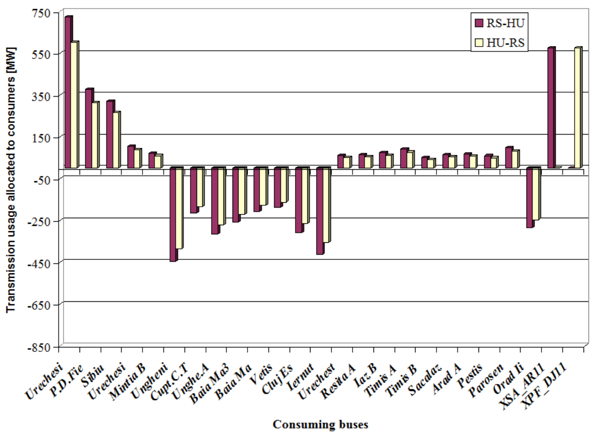

Fig. 8. Transmission usage allocated to consumers on Sibiu-Iernut transmission corridor using distribution factors method

Therefore transmission usage values allocated to generators and consumers using distribution factors method highlighted a unique behaviour due to the influence of system parameters, nodal susceptance matrix, generated and consumed power.

Transmission cost allocated to generating units and consumers are calculated using relation (13). Tariff values and the obtained ones are presented in Tables 2 and 3. The authors start from the assumption that negative values obtained with distribution factors method will be neglected. Significant differences are highlighted for RS-HU and HU-RS transfer cases.

Table 2. Transmission costs allocated to generating units

Bus name	Tariff value (€/MWh)		Transmission cost values (€/h)	
	RS-HU	HU-RS	RS-HU	HU-RS
Mintia 3	37.82	37.82	18653.1	23146.4
Retezat1	37.82	37.82	14258.7	15292.9
P.D.F 5	52.69	52.69	41760.	30681.7
Lotru 1	37.82	37.82	56127.1	46839.8
Iernut 6	25.59	25.59	10818.5	15799.7
Rovin 3	52.69	52.69	42138.3	30702.5
Baru Ma	37.82	37.82	3354.01	2057.68
Hasdat	37.82	37.82	4497.11	4965.28
Calafat	52.69	52.69	4113.23	3035.2
Arad B	37.82	37.82	1058.13	1921.22
Sacalaz	37.82	37.82	375.184	718.848
Lotru	37.82	37.82	26507.3	25465.9
Baia Ma3	25.59	25.59	2786.32	2662.41
Timis A	37.82	37.82	69.3472	136.597
Iaz B	37.82	37.82	7903.55	8915.95
Iernut	25.59	25.59	13504.6	13016.6
Cetate	52.69	52.69	23333.9	17387.7
Resita B	37.82	37.82	1031.97	1170.85
Orad Ii	37.82	37.82	13379.9	12778.1
Parosen	37.82	37.82	4730.96	5981.72
Tr.S.Es	52.69	52.69	16738.5	11909.7
Cluj Es	25.59	25.59	5506.52	5505.57
Unghe.A	25.59	25.59	81.8913	78.8752
Sibiu	37.82	37.82	38929.9	247.911
Xpf_Dj11	0.33	0	628.315	0
XSA_AR11	0	0.31	0	1243.1

Table 3. Transmission costs allocated to consumers

Bus name	Tariff value (€/MWh)		Transmission cost values (€/h)	
	RS-HU	HU-RS	RS-HU	HU-RS
XSA_AR11	0.04	0	307.389	0
XRO_MU11	0.08	0.08	17.8765	12.9529
XPF_DJ11	0	0.12	0	975.227
Urechesi	40.56	40.56	390467.	471827.
P.D.Fie	40.56	40.56	211936.	272117.
Sibiu	55.22	55.22	210190.	127383.
Urechesi	40.56	40.56	52984.	53492.4
Resita	52.56	52.56	22217.9	17837.3
Hajd Ot.	52.56	52.56	6029.25	3626.26
Mintia B	52.56	52.56	22578.8	11662.7
Ungheni	55.22	55.22	176397.	134858.
Cupt.C.T	55.44	55.44	108.745	79.8009
Baia M.	55.44	55.44	1262.16	2.06895
Unghe.A	55.22	55.22	290.813	280.102
Unghe.B	55.22	55.22	37310.	28712.7
Baia Ma3	55.44	55.44	94094.5	71211.7
Baia Ma	55.44	55.44	55721.6	42185.4
Vetis	55.44	55.44	66160.7	50241.2
Cluj Es	55.44	55.44	98954.9	71935.1
Iernut	55.22	55.22	144025.	105354.
Sibiu Sb	55.22	55.22	41036.5	26046.3
Sibiu S	55.22	55.22	39972.2	25361.8
Urechest	40.56	40.56	34080.7	34248.9
Calafat	40.56	40.56	7742.03	9081.73
Tr.S.Es	40.56	40.56	26508.7	32601.8
Resita A	52.56	52.56	56482.1	45975.8
Resita B	52.56	52.56	21707.	17670.5
Iaz A	52.56	52.56	26317.3	21931.3
Iaz B	52.56	52.56	24987.5	49494.3
Timis A	52.56	52.56	65762.4	37404.7
Timis B	52.56	52.56	36351.3	20668.6
Sacalaz	52.56	52.56	49970.9	26445.9
Arad A	52.56	52.56	42287.9	14514.4
Arad B	52.56	52.56	19037.6	6541.63
Mintia	52.56	52.56	20186.5	8930.41
Pestis	52.56	52.56	21134.3	13591.2
Hasdat	52.56	52.56	13477.2	8104.2
Baru Ma	52.56	52.56	11910.8	7307.23
Parosen	52.56	52.56	46979.8	34089.2
Orad Ii	55.44	55.44	95548.1	70452.8
Cetate	40.56	40.56	18692.3	22009.1

5. CONCLUSION

Within the paper the authors are proposing a mathematical model used for congestion management in case of indirect power transfers using an interconnected power system. Transmission corridors are considered very important in integration into a unique energy market and for this reason it is important to determine the generating units and consumers' transmission corridors usage and transmission costs allocated to generating units and consumers. Distribution factors method chosen by the authors is used for security and contingency studies. The case study is carried on a real power system modelled on the Western, South-Western and Northern parts of the Romanian Power System. The results have been obtained using the software tool developed in Mathematica environment. The existences of counterflow values obtained with distribution factors method require carefully interpretation. In this case it is necessary to perform a check of power flow to assess the accuracy of the calculation after the tracing buses contribution. The results obtained for both cases are very different. Also, transmission cost allocated to system generating units and consumers presents significant differences.

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