# INTERCONNECTED CAPACITIES ALLOCATION USING TRANSMISSION COSTS ALLOCATION METHODS

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**Abstract - The interconnected capacity and transmission cost allocation is tackled in this paper. Two methods are involved: distribution factors and equivalent bilateral methods. For the beginning, the mathematical model, allocation methods and software tool are presented. In the following, a comparison between the two allocation methods is performed. Three power system operating conditions are analysed. Real large scale case study has been used. It has been modelled based on the Western, South-Western sides of the Romanian Power System. Useful results for interconnection capacities allocated to generators and their related cost have been provided.**

**Keywords:** distribution factors, transmission cost allocation, interconnected capacity.

## 1. INTRODUCTION

In Romania, the capacity allocation process on the interconnected lines is developed by Transmission System Operator. In case of Romanian border with neighboring countries (Hungary, Bulgaria, Serbia and Ukraine), the process of capacities' allocation is achieved through market mechanisms, settled between the Romanian TSO (Transmission System Operator) and neighboring TSO, obviously respecting the agreements and rules signed every year [1].

The export-import available border capacity values are offered in the auctions on long-term, annual, monthly, daily auctions. For Hungarian border, auctions are organized on long terms, daily and during the day actions [2]. Implicit cross-border available capacities offered in daily auction settled between Romanian TSO and Hungarian TSO are included in 4M Market Coupling project. In case of Ukraine border, the capacity allocation is realized on long term auctions. It specifies that annual and monthly values on the Ukrainian border are not guaranteed, it is possible that these values are changing. For the Serbian border capacity allocation is performed within yearly, monthly and daily auctions [3]. The auctions conducted to the border with Bulgaria are on long-term and respectively daily auctions [4].

Cross-border available capacity allocation and transmission costs allocation can be determined using different allocation techniques: pro rata method [5], Bialek & Kirschen method [6], distribution factors method [7], equivalent bilateral exchanges [8], [9], Z-bus method [10], [11]. [12].

The remaining sections of this paper are organized as follows. The 2nd one presents the two analyzed methods: distribution factors method and EBE method. The following section includes a software tool, developing in Mathematica environment. The 4th section is dedicated to the case studies. System data and topology were provided by TSO, as a result of agreement between the two institutions [14], [15]. Three operating conditions are analyzed, containing 88 buses. The interconnected lines from case studies are grouped in section 1, 2 and 3. Buses 85, 75 and 84 correspond to Djerdap (Serbia), Sandorfalva (Hungary) and Mukacevo (UA) buses.

## 2. ALLOCATION METHODS

### 2.1. Distribution factors method

Relations (1) defines generation Shift factors ($A$ factors) [13], [14], [15]:

$$\begin{cases} \Delta P_{\ell,jk} = A_{jk,i} \cdot \Delta P_{gi} \\ \Delta P_{ge} + \Delta P_{gi} = 0 \end{cases}, \quad jk \in R, \quad i \in N \setminus e \tag{1}$$

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

Generalized generation distribution factors ($D$ factors) determine the impact of each generator on real power flow on network elements (2), while generalized load distribution factors ($C$ factors) determine the contribution of each load to network elements (3).

$$D_{jk,i} = D_{jk,e} + A_{jk,i} = \frac{P_{jk}^{0} - \sum_{i\in N\setminus e} (A_{jk,i} \cdot P_{gi})}{\sum_{i\in N} P_{gi}} + A_{jk,i} \tag{2}$$

$$C_{jk,i} = C_{jk,e} - A_{jk,i} = \frac{P_{jk}^{0} - \sum_{i\in N\setminus e} (A_{jk,i} \cdot P_{ci})}{\sum_{i\in N} P_{ci}} - A_{jk,i} \tag{3}$$

where: $P_{gi}$ – generated power at bus $i$; $D_{jk,i}$ – $D$ factor of $jk$ network element, corresponding to generated power at bus $i$; $P_{ci}$ – generated power at bus $i$; $C_{jk,i}$ – $C$ factor of network element $jk$, corresponding to consumed power in bus $i$; $\mathrm{P}_{jk}^{0}$ – power flow on $jk$ network element from the previous iteration; $e$ – slack bus.

Generators' allocation on $jk$ network element, $UG_{ij}$, is obtained using $D$ factors. Consumers' allocation on $jk$ network element, $UC_{ij}$, is obtained using $C$ factors.

$$UG_{jk} = \sum_{i\in N} (D_{jk,i} \cdot P_{gi}), \quad jk \in R \tag{4}$$

$$UC_{jk} = \sum_{i \in N} (C_{jk,i} \cdot P_{ci}) , \quad jk \in R \qquad (5)$$

Transmission costs allocated to generators at bus $i$ and consumers at bus $i$ for all lines are:

$$C^{Gi} = \sum_{k \in K} \sum_{i \in G} c_{gi} \cdot UG_{ik} \ , \ C^{Di} = \sum_{k \in K} \sum_{i \in D} c_{ci} \cdot UD_{ik} \qquad (6)$$

where: $c_{gi}$ – transmission tariff for the $i$ bus injected power [€/MWh]; $c_{ci}$ – transmission tariff for $i$ bus extracted power [€/MWh]; $K$ – set of system lines.

### 2.2. Equivalent Bilateral Exchanges method

This method is presented in detail in [6], [15], [16]. The relation of the bilateral exchange between generator and demand is (7), where total real consumed power is noted by (8).

$$GD_{ij} = \frac{P_{gi} P_{cj}}{P_{ctotal}} \qquad (7)$$

$$P_{ctotal} = \sum_{j \in C} P_{cj} \qquad (8)$$

Generators' allocation $P_{gi}$ on network element $k$ and consumers' allocation $P_{cj}$ on network element $k$ is determined by the following expressions:

$$UG_{ik} = \sum_{j \in C} \left| A_{k,i} \right| GD_{ij} \qquad (9)$$

$$UC_{jk} = \sum_{i \in G} \left| A_{k,i} \right| GD_{ij} \qquad (10)$$

where: $A_{k,i}$ – generation shift factors through network element $k$, corresponding to change in generator at bus $i$.

Transmission costs allocated to generators at bus $i$ and consumers at bus $i$ for all lines are calculated in same manner as in case of distribution factors method.

### 2.3. Comparative analysis of the two methods

Both methods are based on the preliminary calculation of A factors for all network elements and all system buses. This is the similarity of both methods. Obviously, the existence of counter flows on networks elements will also be reflected in the values of A factors.

The difference between the two methods refers to the different premises for determining the allocation of generators and consumers on network elements (relations (4)-(5) and (9)-(10)). In equivalent bilateral exchange methods, the term $|A_{k,i}|$ from relation (9) and (10) changes the sign "–" of counter flows. Also, relation (7) defines the bilateral exchange between a generator and a consumer.

In this case, it is natural for transmission costs allocated to generators and consumer to be different in comparison with the other method. Values corresponding to allocation of generators and consumers on network elements from distribution factors methods are calculated according to D factors and C factors. The results will have positive and negative sign. In case of transmission costs computing, only the positive values of $UG_{ik}$ and $UD_{ik}$ will be used. The negative values of these terms will be considered zero.

## 3. SOFTWARE TOOL

The software tool was created in Mathematica 9 environment, that can handle files with different extensions, such as *.xls. These files are exported from PowerWorld program. The software flowchart is presented in fig.1..

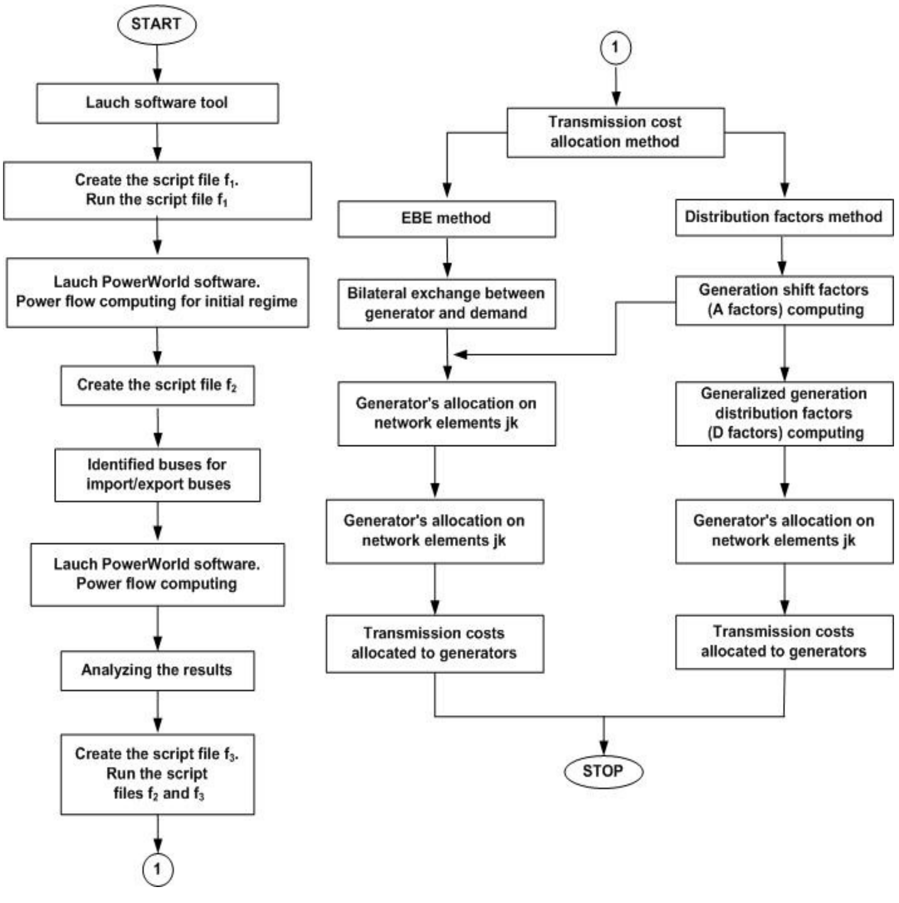


**Fig. 1 - Software tool flowchart**

The script file $f_1$ contains the information related to topology, parameters and system elements. After determining the power flow, the following results are extracted in script file $f_2$: bus data (real generated power, real consumed power, etc.) and data regarding power flow on system elements. System buses, that will have role as power importing / exporting buses are identified. Power flow computing is performed for each of the two operating conditions. The obtained values being loaded in script file $f_3$. The script file $f_2$ and $f_3$ will be used for transmission costs' computing using distribution factors and equivalent bilateral (EBE) methods

## 4. CASE STUDY

The power system based on the Western and South-Western side of the Romanian Power System has 35 sources and 42 consumers. The voltage level for 13 buses is 400 kV, 29 buses are at 220 kV, 29 buses at 110 kV, 3 buses at 24 kV and 14 buses at 15 kV. System hourly cost is 100592.76 €/hr. The real power losses are 73.10 MW.

The operating condition is presented in Fig. 2. Two situations have been considered.

For the 1st situation, real power is imported from Hungary (451 MW) on 400 kV overhead line 28008-75 (OHL) and from Ukraine (50 MW) on 400 kV 28039-84 OHL. The real power has been considered to be exported to Serbia (300 MW) on 400 kV 28004-85 OHL (Fig. 3).

For the 2nd case, presented in Fig. 4, real power is exported to Hungary (364 MW) and Ukraine (10 MW) and 654 MW are imported from Serbia. The values of interconnected available capacity are extracted from monthly auctions for November 2016, available on OTS websites (Table 1).

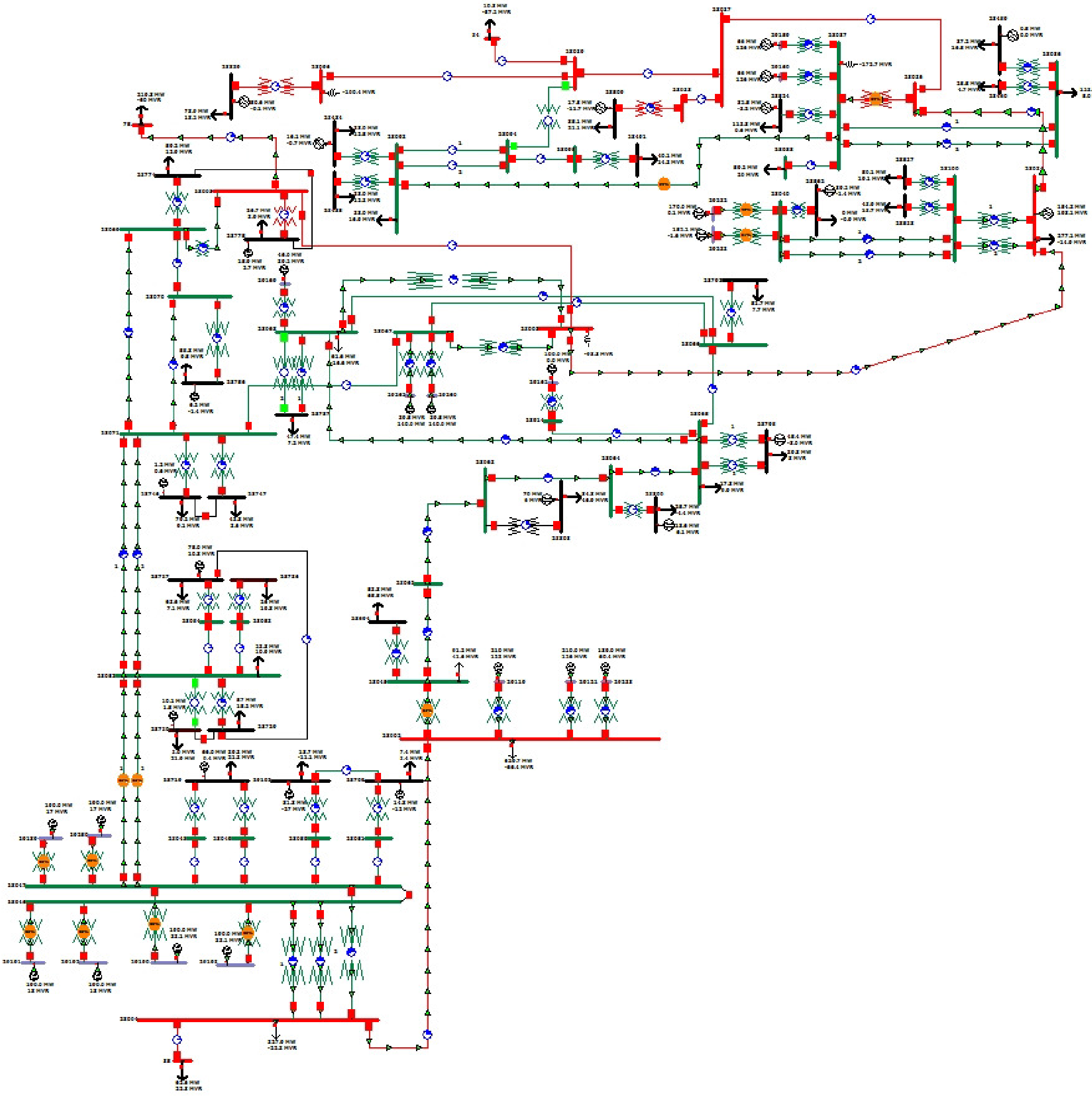


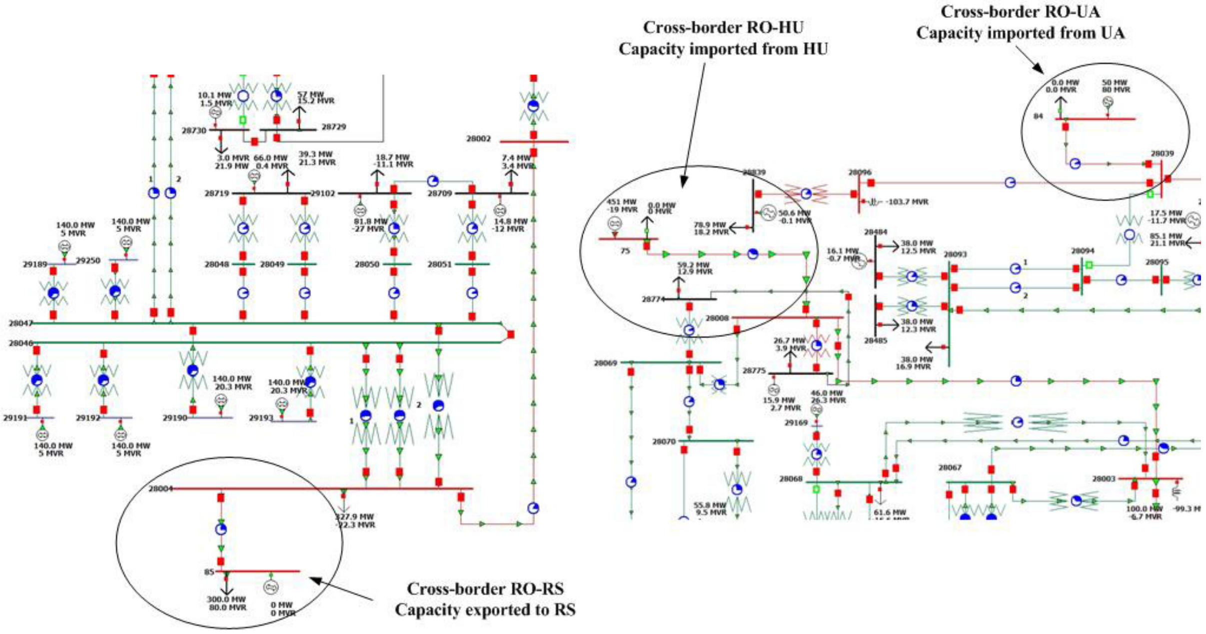
**Fig. 2 - One-line diagram for the power system considered as case study**

**Table 1. Data monthly auction November 2016**

| Border Direction | ATC [MW] | Marginal price/ [€ / MWh] |
|---|---|---|
| Hungary -Romania | 451 | 0.06 |
| Romania – Hungary | 364 | 3.48 |
| Serbia – Romania | 654 | 3.7 |
| Romania - Serbia | 300 | 0 |
| Ukraine - Romania | 50 | 0 |
| Romania – Ukraine | 10 | 0.17 |

**Table 2. Values of real power flow for interconnected lines**

| Cross-border OHL | Power transfers [MW] | | |
|---|---|---|---|
| | Base operating condition | Direction HU-RO, UA-RO, RO-RS | Direction RO-HU, RO-UA, RS-RO |
| 400 kV 28008–75 OHL | 219.8 | -451 | 364 |
| 400 kV 28039–84 OHL | -10.8 | -50 | 10 |
| 400 kV 28004–85 OHL | -62.6 | 300 | -654 |

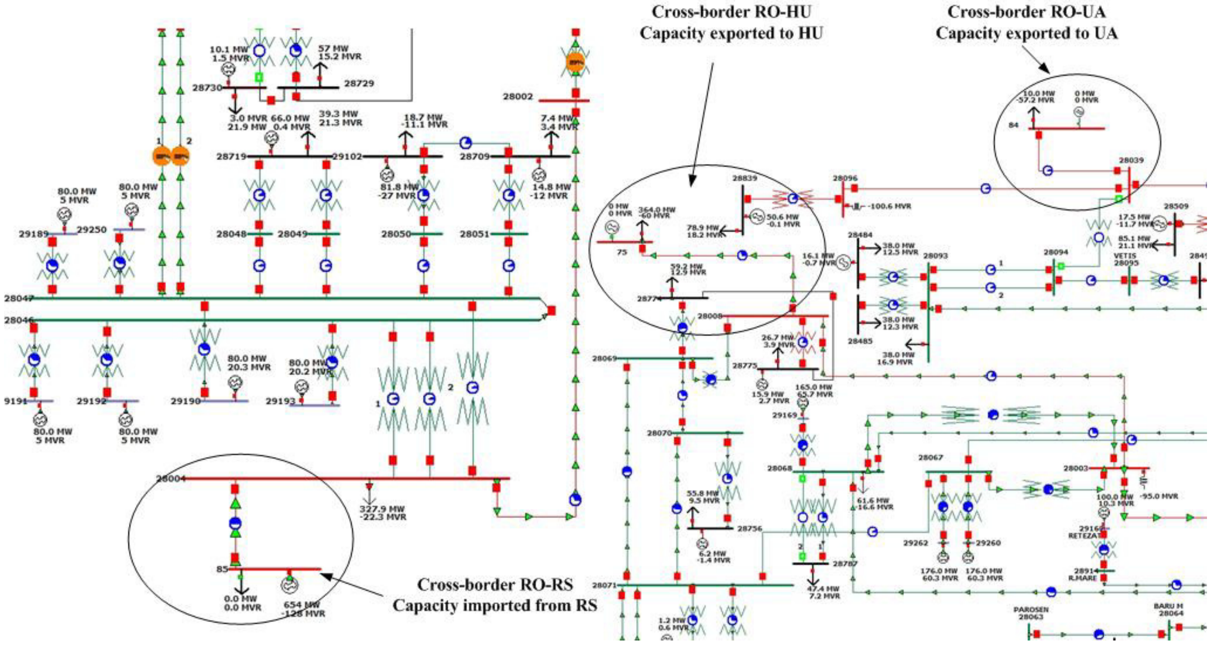


Cross-border RO-HU
Capacity imported from HU

Cross-border RO-UA
Capacity imported from UA

Cross-border RO-RS
Capacity exported to RS

**Fig. 3 - Cross-borders power transfers for HU-RO, UA-RO, RO-RS**



Cross-border RO-HU
Capacity exported to HU

Cross-border RO-UA
Capacity exported to UA

Cross-border RO-RS
Capacity imported from RS

**Fig. 4 - Cross-borders power transfers for RO-HU, RO-UA, RS-RO**

The real power flows through interconnected lines are presented in Table 2. The real generated power is presented in Fig. 5. The highest values of real generated power are recorded on generated groups including buses 29189, 29190, 29191, 29192, 29193 and 29250 for base operating condition (1140 MW). In case of HU-RO, UA-RO, RO-RS border direction the same group generates the greatest value (840 MW).

Transmission costs allocated to generators are determined considering the values of marginal prices (Table 1). Fig. 6, 7 and 8 present a comparison of values obtained on the three analyzed OHL: 400 kV 28008-75, 400 kV 28039-84, respectively 400 kV 28004-85. For the first OHL marginal prices are available on both transfer senses, HU-RO, respectively RO-HU.

Transmission costs have been calculated for both allocation methods. The analysis considers only the last two operating conditions.

From the four distinct situations obtained in case of the line 400 kV 28008-75 OHL, most significant transmission costs have been obtained for border direction RO-HU, RO-UA, RS-RO, using EBE method. Highest transmission costs' values are recorded for sources from Serbia (636.09 €/MWh) and generated groups including buses 29119, 29121 and 29238 from Romania (395.33 €/MWh). In case of border direction HU-RO, UA-RO, RO-RS, marginal cost used to determine the transmission costs is 0.06 €/MWh, much lower compared to 3.48 €/MWh. Therefore, very small values of transmission costs are able to be observed (Fig. 6).

On 400 kV 28004-85 OHL, transmission costs are determined only for RO-HU, RO-UA, RS-RO border directions. Comparing the two allocation methods, significant values have been obtained for distribution factors method (Fig. 7). For example, generating groups from Serbia and three Romanian generating groups have the transmission costs: 645.53 €/MWh (generating groups including buses 29119, 29121, 29238), 375.78 €/MWh (generating groups including buses 29260, 29262, 29169), 319.01 €/MWh and 296.18 €/MWh (generating groups including buses 29189, 29190, 29191, 29192, 29193 and 29250).

The marginal cost established for RO-UA is 0.17 €/MWh. Available interconnected capacity is 10 MW, leading to values of transmission costs below 0.5 €/MWh. Studying Fig. 8, it can be observed that generators from Serbia exported a significant amount of real power, transmission cost being 0.315 €/MWh. This value is obtained for distribution factors method. In case of EBE method, reduced transmission costs have been recorded.

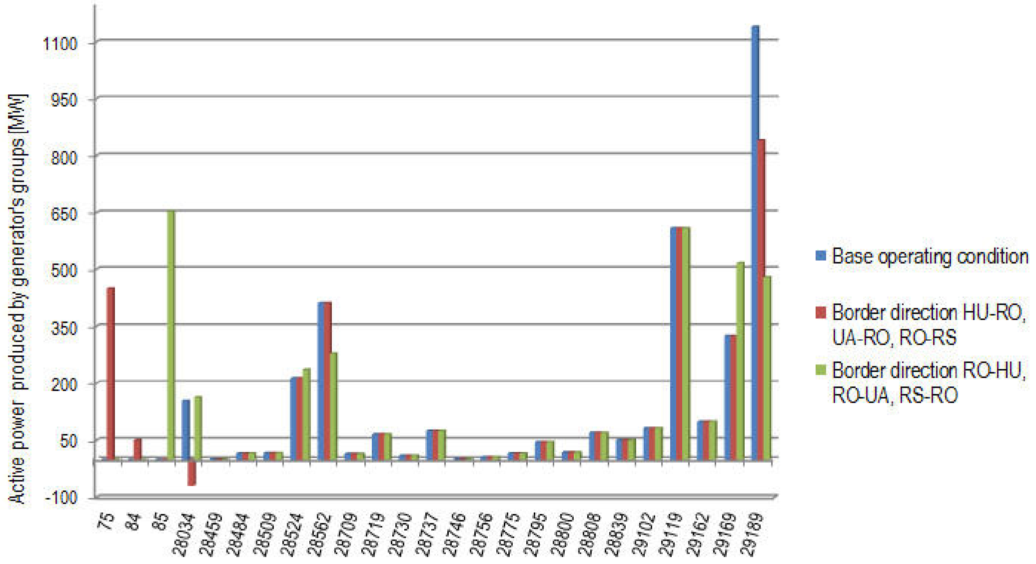


**Fig. 5 - Real generated power**

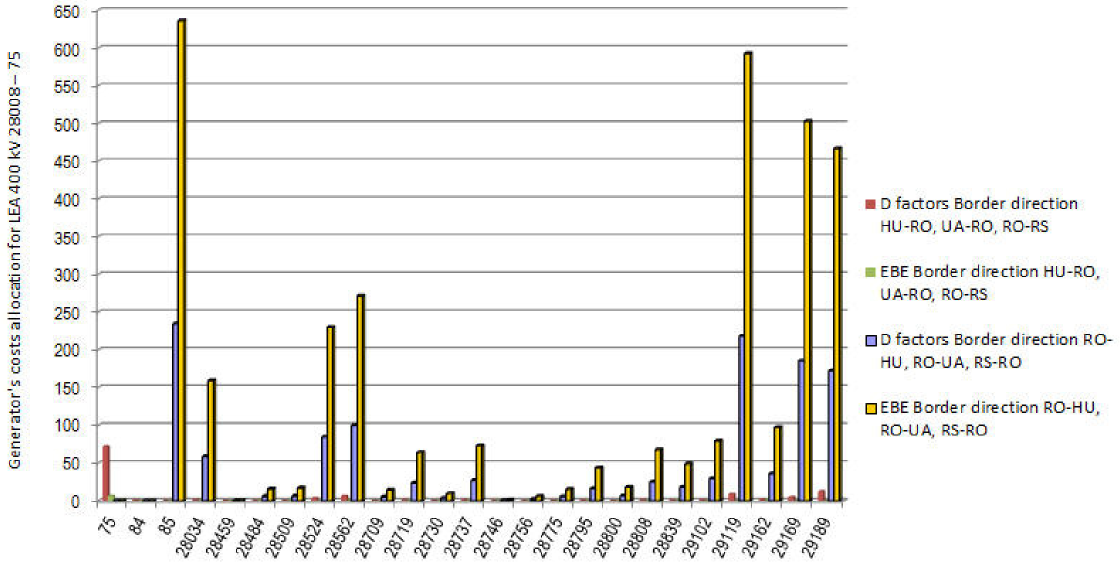


**Fig. 6 - Transmission costs allocation on 400 kV 28008-75 OHL**

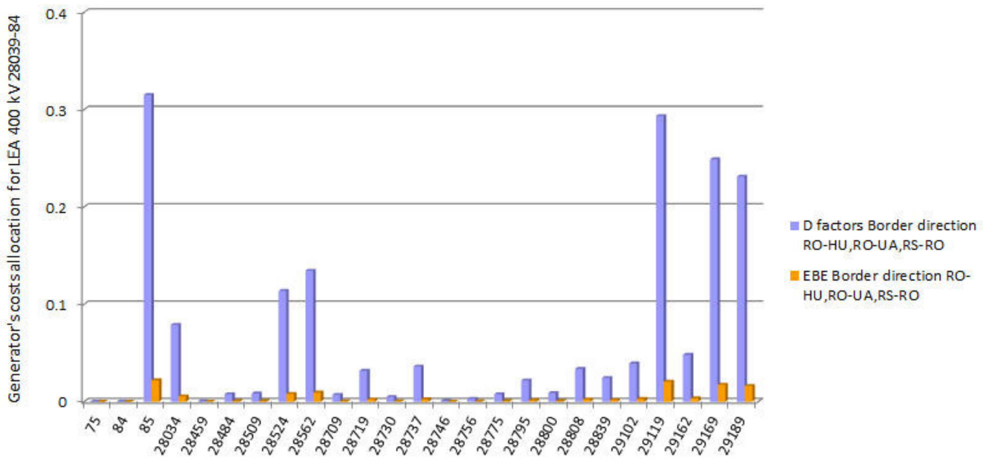


**Fig. 7 - Transmission costs allocation on 400 kV 28039-84 OHL**

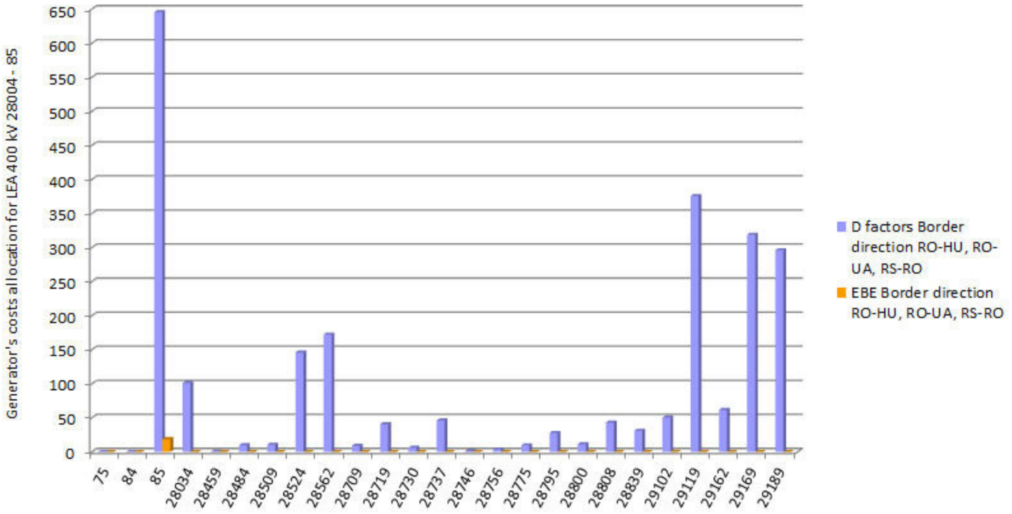


**Fig. 8 - Transmission costs allocation on 400 kV 28004 - 85 OHL**

## 5. CONCLUSION

This paper examines the allocation cross-border capacity on three interconnected OHLs that connects Romanian power system with neighboring states power systems. Two allocation methods (distribution factors and equivalent bilateral exchanges) have been applied to a part of the national power system using real operating conditions.

Both allocation methods take into account the existence of counter flows of network elements and A factors on system elements. These methods have different premises. Allocation of generators and consumers on network elements is determined in different manner. Equivalent bilateral exchanges method defines bilateral exchanges between a generator and a consumer. Distribution factors method contains generalized generation distribution factors (D factors) and generalized load distribution factors (C factors).

In case of generators' allocation on network elements, the authors noted a number of comments for both analyzed methods. To highlight the difference between the two methods, there are presented the significant results belong especially to groups that produce high value of generated power, meaning buses groups 29189, 29190, 29191, 29192, 29193 and 29250, buses groups 29119, 29121, 29238 and buses groups 29260, 29262, 29169 and generated groups from neighboring power systems from Serbia and Hungary. The transmission costs allocated to generators have been analyzed on three cross-border OHLs and complete the accentuating of differences between methods. Higher values have been obtained in case of RO-HU, RO-UA, RS-RO border direction on 400 kV 28008-75 OHL (distribution factors method) and 400 kV 28004 - 85 OHL (EBE method).

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