Mixed Method for Transmission Loss Allocation

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***Abstract*—The paper presents a method for transmission loss allocation developed as a mix of Zbus transmission cost allocation method and power summation method for loss allocation. Zbus method is used to decompose the power flows through the branches in the network and to calculate the participation of each network user (node power injection) in the active and reactive power flow at each branch of the network. When this information is obtained, power summation method principle with quadratic allocation of crossed terms of active and reactive power is used for allocation of losses of each branch to network users (node power injections). Sum of allocated losses to network users (nodes) from all branches in the network presents total loss allocation to each node. This is the reason why the method is called mixed method. The method is tested on real data individual model of power system of North Macedonia for future planning purposes. The model is with high presence of renewables (PV and WIND). The results are presented and discussed.**

Keywords— loss allocation, transmission, renewables.

I. INTRODUCTION

The costs of losses in the electricity networks are one of the main elements for determination of transmission and distribution tariffs for generators and/or consumers. However, calculation of allocation of losses to generators and consumers is complex, and in practice, mainly losses are allocated evenly to all network users. Nowadays we evident very high prices of electrical energy on the markets, and very high costs of losses in the networks due to high electricity prices. Main issues for fair competition are open access on non-discriminatory basis to transmission and distribution networks, and setting adequate price for network services. These events actualize the loss allocation problem in transmission and distribution networks. The impact of losses costs on transmission and distribution tariffs become serious and actualize fair and equitable allocation of losses as an economic signal to network users.

There are three basic approaches for allocation of losses: 1) Marginal; 2) Average; 3) Actual [1]. The adopted approach for allocation of losses must be adequate to electricity market design and it must be clear to detect that losses are part of market design. Marginal approach is mainly focused on the increase effect of each generator on the losses in the system. This implies detailed calculation of the impact of each generator unit on the losses. Average approaches treatment of losses is homogenized. The effect and identity of each generator and load is masked. The total losses in the system are estimated or measured and after that applied on each generator (and/or load) on a pro rata basis. Actual approach includes calculation of total actual losses in the system and determination of the participation and impact of the injected power of each generator or evacuated power of each load on the losses. In the basis of actual approach for loss allocation, power flow solution is implemented. Mainly all methods from this approach are based on power flow decomposition in each individual line or transformer in the network. The core of this paper is to present a new mixed method based on actual approach for allocation of losses in transmission networks.

Namely, the paper presents a new method for transmission loss allocation developed as a mix of Zbus transmission cost allocation method [2] and power summation method for loss allocation [3, 4]. Zbus transmission cost allocation method is used for power flow decomposition in the branches of the network and to calculate the participation of each network user (node power injection) in the active and reactive power flow at each branch of the network. When this information is obtained, power summation method principle with quadratic allocation of crossed terms of active and reactive power is used for allocation of losses of each branch to network users (node power injections). The sum of allocated losses to network users (nodes) from all the branches in the network presents total loss allocation to each node.

The results obtained with the method are tested on real future planning model of power system of North Macedonia. This future model contains high presence of renewables and calculations are performed on winter and summer maximum load and generation data. Allocation of losses from specific lines to network nodes is also presented The results are presented and discussed for method efficiency testing. Conclusions are elaborated at the end of the paper.

II. THE METHOD

Zbus transmission cost allocation method [2] is based on decomposition of complex power flow at both ends of each branch of the network. Fig. 1 depicts complex power flows at π equivalent of line *j-k*. According to Zbus allocation method, the complex power flow of each branch *j-k* can be expressed as a function of node voltage *j* and current injections at each node *i*:

$$\underline{S}_{jk} = \underline{U}_j \cdot \sum_{i=1}^{n} \left(\underline{a}_{jk}^{i} \cdot \underline{I}_i \right)^* = \sum_{i=1}^{n} \underline{U}_j \cdot \underline{a}_{jk}^{i\,*} \cdot \underline{I}_i^* \qquad (1)$$

where: $\underline{a}_{jk}^{i} = \left(\underline{z}_{ji} - \underline{z}_{ki} \right) \cdot \underline{y}_{j-k} + \underline{z}_{ji} \cdot \underline{y}_{j-k}^{sh}$ is a complex coefficient that provides the electrical distance between node *i* and branch *j-k* ($\underline{z}_{ji}$ and $\underline{z}_{ki}$ are the elements j_i and k_i of the

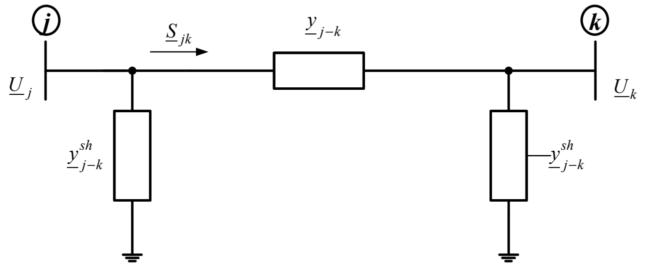

Fig. 1. Line π equivalent

system impedance Zbus matrix, $\underline{y}_{j-k}$ and $\underline{y}^{sh}_{j-k}$ are the series and shunt line admittance of the π equivalent of line *j-k*); $\underline{U}_j$ is the complex voltage of node *j* and $\underline{I}_i$ is the current injection at node *i*.

The active and reactive power flow through branch *j-k* at side *j* are derived from (1):

$$P_{jk} = \mathrm{Re}\left\{\sum_{i=1}^{n} \underline{U}_j \cdot \underline{a}^{i}_{jk}{}^{*} \cdot \underline{I}_i^{*}\right\} \tag{2}$$

$$Q_{jk} = \mathrm{Im}\left\{\sum_{i=1}^{n} \underline{U}_j \cdot \underline{a}^{i}_{jk}{}^{*} \cdot \underline{I}_i^{*}\right\} \tag{3}$$

The active and reactive power flow through any line can be split and associated to the nodal currents in a direct way. Then, the active and reactive power flow through line *j-k* associated with nodal current *i* are:

$$P^{i}_{jk} = \mathrm{Re}\left\{\underline{U}_j \cdot \underline{a}^{i}_{jk}{}^{*} \cdot \underline{I}_i^{*}\right\} \tag{4}$$

$$Q^{i}_{jk} = \mathrm{Im}\left\{\underline{U}_j \cdot \underline{a}^{i}_{jk}{}^{*} \cdot \underline{I}_i^{*}\right\} \tag{5}$$

Let us consider one branch *j-k* depicted on Fig. 2, in which the active and reactive power flow through line *j-k* are associated with nodal currents of two nodes *i*, *m* ($i \neq m$) (P^{i}_{jk}, P^{m}_{jk} and Q^{i}_{jk}, Q^{m}_{jk}) obtained with (4) and (5), appropriately.

Calculation of complex losses in branch *j-k* can be performed as follows [3]:

$$\begin{aligned}\Delta P_{jk} + \mathrm{j}\Delta Q_{jk} &= \Delta P^{i}_{jk} + \Delta P^{m}_{jk} + \mathrm{j}\left(\Delta Q^{i}_{jk} + \Delta Q^{m}_{jk}\right) = \\ &= \frac{Z_{jk}}{U_j^2} \cdot (P^{i}_{jk}{}^{2} \pm 2 \cdot P^{i}_{jk} \cdot P^{m}_{jk} + Q^{i}_{jk}{}^{2} \pm 2 \cdot Q^{i}_{jk} \cdot Q^{m}_{jk} \\ &\quad + P^{m2}_{jk} \pm 2 \cdot P^{m}_{jk} \cdot P^{i}_{jk} + Q^{m2}_{jk} \pm 2 \cdot Q^{m}_{jk} \cdot Q^{i}_{jk})\end{aligned} \tag{6}$$

where ΔP^{i}_{jk}, ΔP^{m}_{jk} and ΔQ^{i}_{jk}, ΔQ^{m}_{jk} are active and reactive power losses of branch *j-k* allocated to nodes *i* and *m* that are subject of determination.

It is clear that the components in expression in brackets in (6) $P^{i}_{jk}{}^{2}$ and $Q^{i}_{jk}{}^{2}$ are associated with allocated losses to

Fig. 2. Allocation of crossed terms

node *i* ΔP^{i}_{jk} +j ΔQ^{i}_{jk}. However, the terms of the expression in brackets $2 \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ and $2 \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}$ represent the losses generated by (P^{i}_{jk}, P^{m}_{jk} and Q^{i}_{jk}, Q^{m}_{jk}). These terms has to be split on two parts allocated appropriately to ΔP^{i}_{jk} +j ΔQ^{i}_{jk} and ΔP^{m}_{jk} +j ΔQ^{m}_{jk}. The idea from [3, 4] will be used for the splitting process. Namely, the part of $2 \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ and $2 \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}$ allocated to ΔP^{i}_{jk} +j ΔQ^{i}_{jk} will be $\beta^{Pi}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ and $\beta^{Qi}_{jk} \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}$. On the other hand the part allocated to ΔP^{m}_{jk} +j ΔQ^{m}_{jk} will be $\beta^{Pm}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ and $\beta^{Qm}_{jk} \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}$. According to these definitions, follows:

$$\beta^{Pi}_{jk} + \beta^{Pm}_{jk} = 2,\ \beta^{Qi}_{jk} + \beta^{Qm}_{jk} = 2 \tag{7}$$

Following the logic from [3, 4], it can be adopted that the ratio between $\beta^{Pi}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ and $\beta^{Pm}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk}$ (practically the ratio between $\beta^{Pi}_{jk} / \beta^{Pm}_{jk}$), is equal to the ration between the squares of the active power flows through line *j-k* associated with nodal currents i and m. The same analogy can be followed for reactive power flows. So, it can be written that:

$$\frac{\beta^{Pi}_{jk}}{\beta^{Pm}_{jk}} = \frac{P^{i}_{jk}{}^{2}}{P^{m2}_{jk}},\ \frac{\beta^{Qi}_{jk}}{\beta^{Qm}_{jk}} = \frac{Q^{i}_{jk}{}^{2}}{Q^{m2}_{jk}} \tag{8}$$

According to (7) and (8), coefficients for crossed terms allocation are as follows:

$$\beta^{Pi}_{jk} = \frac{2 \cdot P^{i}_{jk}{}^{2}}{P^{i}_{jk}{}^{2} + P^{m2}_{jk}},\ \beta^{Pm}_{jk} = \frac{2 \cdot P^{m2}_{jk}}{P^{i}_{jk}{}^{2} + P^{m2}_{jk}} \tag{9}$$

$$\beta^{Qi}_{jk} = \frac{2 \cdot Q^{i}_{jk}{}^{2}}{Q^{i}_{jk}{}^{2} + Q^{m2}_{jk}},\ \beta^{Qm}_{jk} = \frac{2 \cdot Q^{m2}_{jk}}{Q^{i}_{jk}{}^{2} + Q^{m2}_{jk}} \tag{10}$$

Finally, components of losses of line *j-k* allocated nodes *i*, and *m*, are as follows:

$$\Delta P^{i}_{jk} + \mathrm{j}\Delta Q^{i}_{jk} = \frac{Z_{jk}}{U_j^2} \cdot \left(P^{i}_{jk}{}^{2} + \beta^{Pi}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk} + Q^{i}_{jk}{}^{2} + \beta^{Qi}_{jk} \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}\right) \tag{11}$$

$$\Delta P^{m}_{jk} + \mathrm{j}\Delta Q^{m}_{jk} = \frac{Z_{jk}}{U_j^2} \cdot \left(P^{m2}_{jk} + \beta^{Pm}_{jk} \cdot P^{i}_{jk} \cdot P^{m}_{jk} + Q^{m2}_{jk} + \beta^{Qm}_{jk} \cdot Q^{i}_{jk} \cdot Q^{m}_{jk}\right) \tag{12}$$

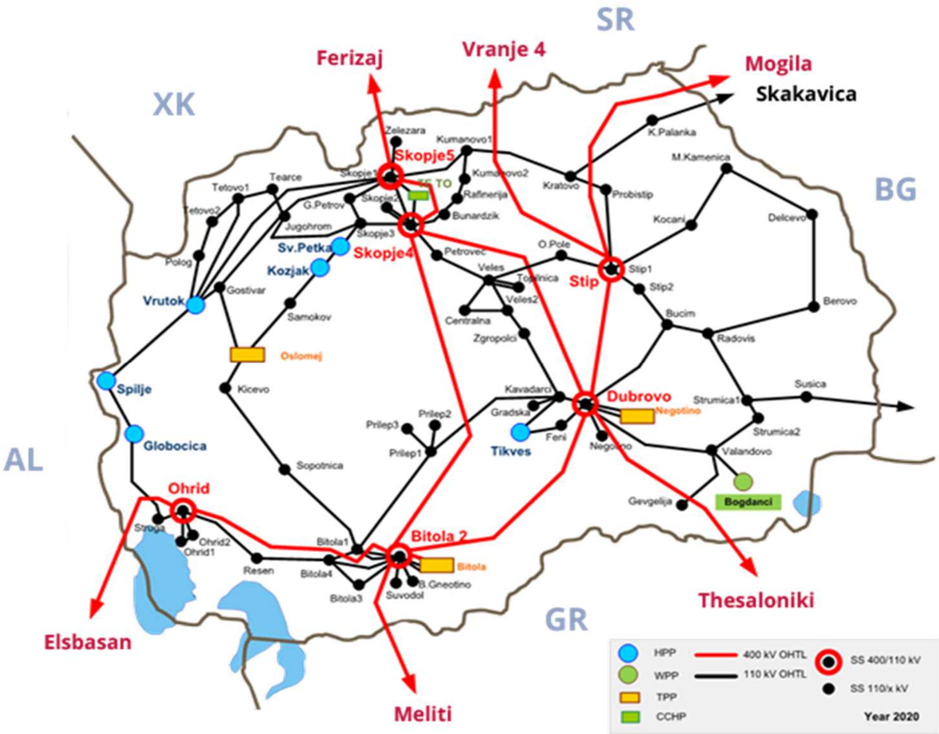

Fig. 3. Considered power system model of North Macedonia

In general, according to (11) and (12), the component of losses of branch *j*-*k*, allocated to any node *i*, can be calculated with the following general formula:

$$\Delta P_{jk}^{i} + \mathrm{j}\Delta Q_{jk}^{i} = \frac{Z_{jk}}{U_j^2}\cdot\left({P_{jk}^{i}}^{2} + {Q_{jk}^{i}}^{2} + P_{jk}^{i}\cdot\sum_{\substack{m=1\\ i\neq m}}^{N}\beta_{jk}^{Pi}\cdot P_{jk}^{m} + Q_{jk}^{i}\cdot\sum_{\substack{m=1\\ i\neq m}}^{N}\beta_{jk}^{Qi}\cdot Q_{jk}^{m}\right) \tag{13}$$

where N is the total number of nodes in the network.

Total losses allocated to each node i will be a sum of allocated losses to node i from all branches in the network, calculated with (13):

$$\Delta P^{i} = \sum_{l=1}^{nb}\Delta P_{l}^{i} \tag{14}$$

where nb is the total number of branches in the network.

Total losses in the network are a sum of allocated losses to network nodes:

$$\Delta P = \sum_{i=1}^{N}\Delta P^{i} \tag{15}$$

The explained calculation procedure of the method is for side j of each branch *j*-*k* in the network. However, it is completely the same for the other side k of each branch *j*-*k*, only in the formulas node voltage Uk has to be used and power flow S_{kj} will be decomposed, (P_{kj}, Q_{kj}). There are minor differences between the results. This is because electrical distance parameters are not generally symmetrical with respect to line indexes $\underline{a}_{jk}^{i} = \underline{a}_{kj}^{i}$ [2]. The same technique proposed by the authors in [2], can be used here to resolve the minor differences between allocated losses to nodes (generators and loads). Namely, the calculation is done in three steps:

- First step the allocation of losses is performed by decomposing power flow S_{jk} on side j of each branch *j*-*k* in the network;
- Second step the allocation of losses is performed by decomposing power flow S_{kj} on side k of each branch *j*-*k* in the network;
- Average value of allocated losses to nodes from previous two steps is calculated.

This approach reduces the trends of allocating higher or lower losses to generators versus loads [2].

III. RESULTS

The method is tested on real data individual model of power system of North Macedonia for future planning purposes. The model is with high presence of renewables (PV and WIND). Fig. 3 depicts the network topology of the power system model. This future planning model is mainly based on renewables generation and many renewable energy sources planned in the future are presented on the Fig. 3. Loading and generation scenarios for winter and summer maximum are considered [10,11,12]. Load flow and loss allocation calculations are performed with a specially developed computer program in Python. The network models for future winter and summer maximum in PSS/E .raw format are an input file for the developed computer program. Input files are obtained from MEPSO (North Macedonia Transmission System Operator). The computer program in first phase reads

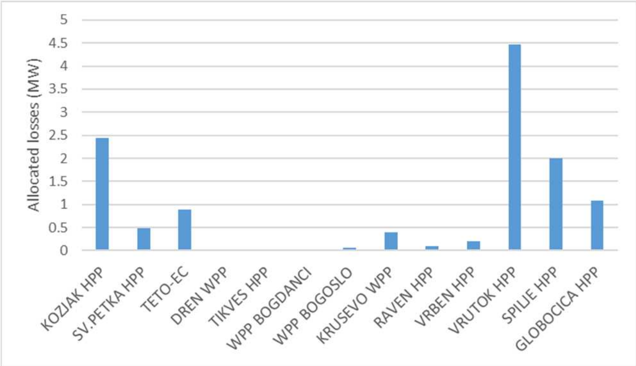

Fig. 4. Allocation of losses to separate generators for winter maximum

TABLE I. SUMARRY OF ALLOCATION OF LOSSES FOR WINTER MAXUMUM

ELEMENTS	Allocated losses (MW)
GENERATORS	12.15
LOADS	7.07
EXCHANGE	3.39
SUM	**22.61**

the network model from a .raw file, in the second phase it solves load flow using Newton-Raphson method and in the third phase, it calculates allocation of losses using the proposed mixed method.

Table I summarizes the allocation of losses with the proposed mixed method to network users for winter maximum scenario. Total calculated and allocated losses with power flow and with the proposed method are 22.61 MW. Allocation of losses to generators is 12.15 MW (53.7 %), to loads is 7.07 MW (31.3 %) and to power system exchange on borders with neighbors is 3.39 MW (15 %).

Fig. 4 depicts the allocation of losses to separate generators for winter maximum scenario. Hydro power plant HPP Vrutok has highest allocation of losses (4.48 MW) and HPP Tikves lowest allocation of losses (0.01 MW).

Fig. 5 depicts the allocation of losses to loads for winter maximum scenario. It is evident that some of the loads have negative loss allocation. Negative sign of allocated losses can be treated as a reward for the network user.

Fig. 6 illustrates the allocated losses to nodes from line 110 kV "Kozjak – Sv. Petka". This line evacuates the generated power from Kozjak to load centers Skopje 3 and Skopje 4. It is obvious that HPP Kozjak has highest allocation of losses from this line, since the power flow through this line mainly belongs to these power plants. Generators Sv. Petka and TETO and some of the loads (Tetovo 1 and 2, Kicevo and Gostivar) have negative loss allocation from this line as a reward for reducing losses in line "Kozjak-Sv. Petka".

Fig. 7 depicts the allocated losses to nodes from line 110 kV "Dubrovo - Valandovo". Since this line supplies the power for loads Gevgelija and Strumica 1 and 2 and Valandovo, these loads have maximum allocation of losses from the line.

Table II summarizes the allocation of losses with the proposed mixed method to network users for summer maximum scenario. Total calculated and allocated losses with power flow and with the proposed method are 33.60 MW.

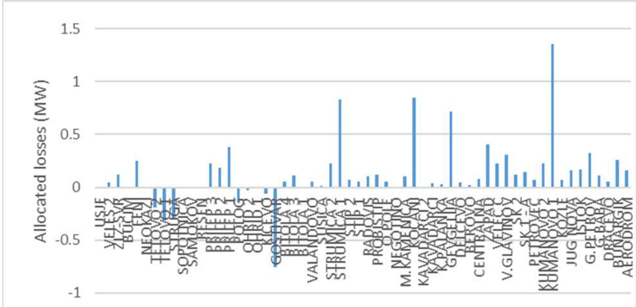

Fig. 5. Allocation of losses to separate loads for winter maximum

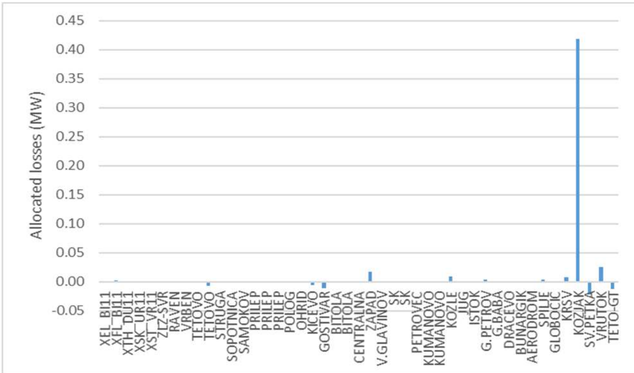

Fig. 6. Allocation of losses from line 110 kV "Kozjak – Sv. Petka" for winter maximum (losses 0.43 MW)

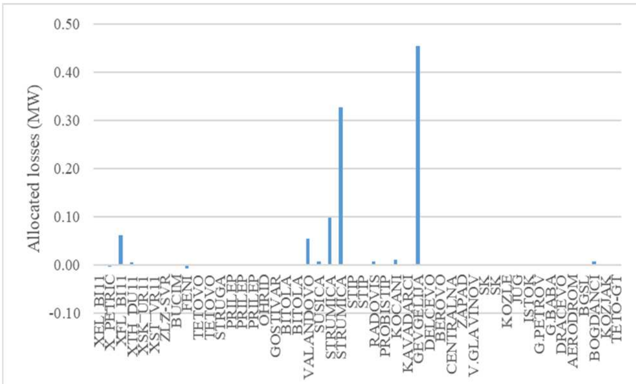

Fig. 7. Allocation of losses from line 110 kV "Dubrovo – Valandovo" for winter maximum (losses 1.02 MW)

Allocation of losses to generators is 23.78 MW (70.8%), to loads is 7.16 MW (21.3 %) and to power system exchange on borders with neighbors is 2.66 MW (7.9%).

Fig. 8 illustrates the allocation of losses to separate generators for summer maximum scenario. Photovoltaic power plants PV OSLOMEJ has highest allocation of losses (7.2 MW). Fig. 9 depicts the allocation of losses to loads for summer maximum scenario. It is evident that some of the loads have negative loss allocation.

Fig. 10 illustrates the allocated losses to nodes from line 110 kV "Sv. Petka – Skopje 3". This line is one of the lines with highest loading in summer maximum scenario, 89% from its rated thermal power, and it evacuates the generated power from HPP Sv. Petka, PV Oslomej and HPP Kozjak to load centers Skopje 3 and Skopje 4. It is obvious that HPP Sv. Petka, HPP Kozjak and PV Oslomej have highest allocation of losses from this line, since the power flow through this line mainly belongs to these power plants. Power plant TETO has

TABLE II. SUMARRY OF ALLOCATION OF LOSSES FOR SUMMER MAXUMUM

ELEMENTS	Allocated losses (MW)
GENERATORS	23.78
LOADS	7.16
EXCHANGE	2.66
SUM	**33.60**

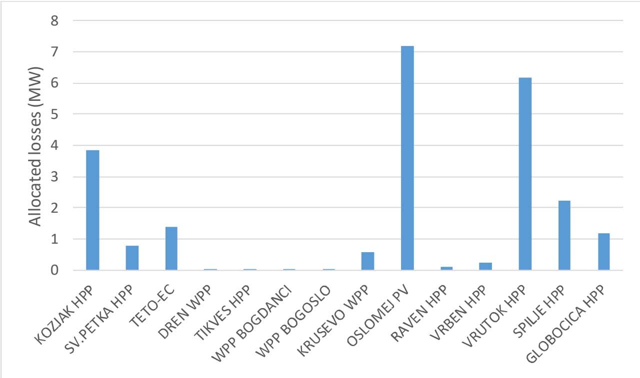

Fig. 8. Allocation of losses to separate generators for summer maximum

negative loss allocation from this line as a reward for reducing losses in line “Sv. Petka – Skopje 3”.

IV. CONCLUSION

In the paper a new method for allocation of losses in transmission networks has been proposed. The method is a mix of Zbus transmission cost allocation method and power summation method for loss allocation. Zbus method is used to decompose the power flows through the branches in the system and power summation method with allocation of crossed terms of active and reactive power is used for branches losses allocation.

The obtained results have shown that the allocated losses vary in time and space. Implementation of the method can be on ex-post basis which is more accurate approach, because it reflects the impact on losses of each user in real time.

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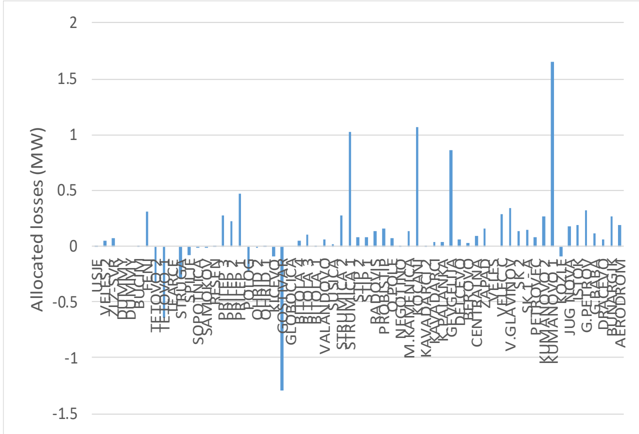

Fig. 9. Allocation of losses to separate loads for summer maximum

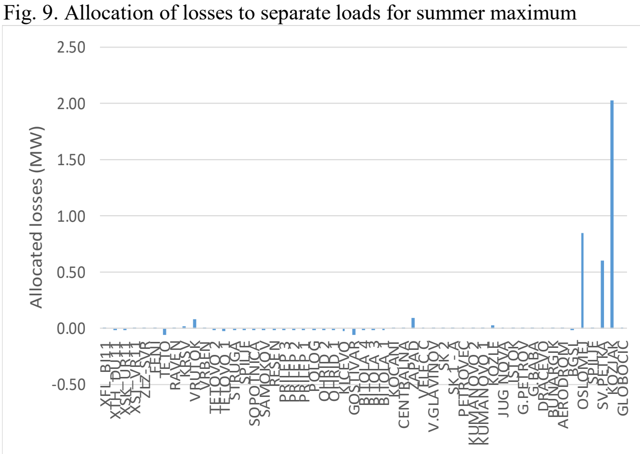

Fig. 10. Allocation of losses from line 110 kV “Sv. Petka – Skopje 3” (losses 3.59 MW) summer maximum

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