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OPERATIONAL MEASURES BASED ON ELECTRICAL DISTANCE MATRIX APPROACH FOR MITIGATING TRANSMISSION AND DISTRIBUTION LINE OVERLOADING

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Abstract: The time equivalent availability of maximum power for photovoltaics (PVs) is approximately 1500 h per year, and for the wind power plants (WPPs) it is about 3000 h per year. The maximum power generation of PVs and WPPs will occur in several hours per day depending on the season, and for the rest of the day the power will be lower or zero. As a result, the transmission and distribution lines will be highly loaded or overloaded for the previously mentioned specific hours, while during the rest of the year the loading will be lower. In order to overcome the problem of unnecessary reinforcement of lines, this paper proposes less costly operational measures using load and generation flexibility based on electrical distance. According to the Zbus matrix allocation method, the complex power flow of each branch j-k can be expressed as a function of the voltage at node j and the current injections at each node. The electrical distance coefficient matrix represents the electrical distance of the bus i from the branch j-k and it measures the impact of the bus injection on the branch j-k complex power flow. Namely, higher value of electrical distance coefficient means higher impact of the bus i injection on the power flow. The proposed algorithm in this paper uses the electrical distance and load flexibility or generation re-dispatch for solving the overloads in the network. Firstly, power flow is solved, which enables to detect the overloads in the network. After that, the Zbus matrix and the electrical coefficients matrix are calculated. We are observing the row of electrical distance coefficient matrix that corresponds to the overloaded branch(es). The maximum electrical coefficient is detected in that row and load or generator in the corresponding bus is scaled (+ or -) appropriately to solve the overloading(s). The proposed methodology will be tested on distribution and transmission network. The results will be presented and discussed.

Keywords: Zbus matrix, cost allocation method, line overloading, electrical distance matrix.

INTRODUCTION

As a result of coordinated policy and financial support measures [1], renewable energy source (RES) production has increased its share in the overall electricity production in many European Union (EU) countries. According of the state-of-the-art technology development, WPPs and PVs have a dominant role from all RES technologies and their further deployment is expected [2], [3]. The continuous support measures and the development and integration of electricity markets has led to high installed RES capacities across number of EU countries. In 2023, renewable energy represented 24.5% of energy consumed in the EU [4]. Consequently, during limited time periods almost all of the load in some of these countries has been supplied by electricity produced from RES.

Main characteristic of WPP and PV is intermittent power generation during the day and season. The time equivalent availability of maximum power for PV power plants is 1500 h per year and for the WPP it is about 3000 h per year. According to this, it can be concluded that maximum power generation of PV and WPP will occur in several hours per day depending from the season, and for the rest of the day it will be lower or zero. The relevant season for WPP maximum power generation is winter, especially in the night hours and for PV, the relevant season is summer in the near noon hours. The transmission and distribution lines evacuating PV or WPP power will be highly loaded or overloaded for the previously mentioned specific hours. In order to overcome the problem of unnecessary reinforcement of lines or usage of conductors with larger cross section, this paper proposes less costly operational measures using load and generation flexibility impact based on electrical distance for solving overloads.

Zbus transmission cost allocation method [5] is based on decomposition of complex power flow at both ends of each branch of the network. Practically, this 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.

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Namely, the complex power flow of each branch j-k can be expressed as a function of the voltage at node j and the current injections at each node. The electrical distance coefficient matrix represents the electrical distance of the bus i from the branch j-k and it measures the impact of the bus injection on the branch j-k complex power flow. Higher value of electrical distance coefficient means higher impact of the bus i injection on the power flow. The proposed algorithm in this paper uses the electrical distance and load flexibility or generation re-dispatch for solving the overloads in the network. Firstly, a power flow is solved, making it possible to identify network overloads. The electrical coefficients matrix and the Zbus matrix are then computed, which allows to observe the electrical distance coefficients matrix row corresponding to the overloaded branches. The load or generator in the relevant bus is scaled (+ or -) suitably to solve the overloading(s) after the maximum electrical coefficient in that row is identified.

The paper is composed of five sections. After the introductory section, the second section elaborates the proposed methodology. In the third section, the proposed methodology is tested on distribution and transmission network, followed by discussion of results. The last sections contain the conclusions and references.

1. METHODOLOGY

Zbus transmission cost allocation method [5], [6] is based on decomposition of complex power flow at both ends of each branch of the network. Figure 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:

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

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 system impedance Zbus matrix; $\underline{y}_{j-k}$ and $\underline{y}_{j-k}^{sh}$ 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 I_i is the current injection at node i.

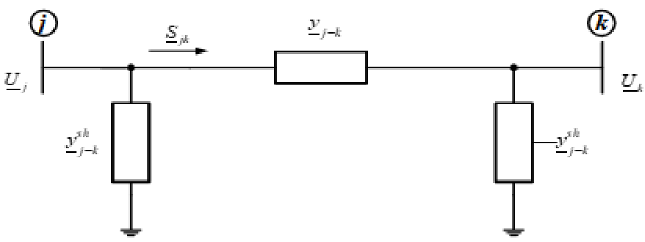

Figure 1: Line π equivalent

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

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

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

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:

$$P_{jk}^{i} = \mathrm{Re}\left\{ \underline{U}_j \cdot \underline{a}_{jk}^{i\,*} \cdot \underline{I}_i^* \right\} \quad (4)$$

$$Q_{jk}^{i} = \mathrm{Im}\left\{ \underline{U}_j \cdot \underline{a}_{jk}^{i\,*} \cdot \underline{I}_i^* \right\} \quad (5)$$

It is obvious from equations (4) and (5) that the impact of each nodal injection i, on active and reactive power flow through branch j-k, depends on a_{jk}^{i} the electrical distance between node i and branch j-k. Higher value of electrical distance coefficient means higher impact of the bus i injection on the power flow.

The described methodology uses the electrical distance and load flexibility or generation re-dispatch for solving the overloads in the network. Firstly, the power flow is solved, which enables to detect the overloads in the network. After that, the Zbus matrix and the electrical coefficients matrix are calculated. Following these calculations, the row of electrical distance coefficient matrix that corresponds to the overloaded branches is observed. The electrical coefficient with maximum value is detected in the observed row and load or generator in the corresponding bus is scaled (+ or -) appropriately to solve the overloading(s). After scaling, the power flow is calculated once again to check if the overload is mitigated.

2. STUDY CASES AND 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). Figure 2 depicts the network topology of the power system model. This future planning model is mainly based on RES generation. Loading and generation scenarios for winter and summer maximum are considered [7], [8]. Load flow and loss allocation calculations are performed with a computer program developed for this purpose in Python. The network models for future summer maximum in PSS/E .raw format are inputs for the developed computer program. Input files are obtained from MEPSO (North Macedonia Transmission System Operator). The computer program follows these steps: 1) the first step includes reading the network model from a

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.raw file; 2) the second step solves the load flow for the particular model using the Newton-Raphson method; and 3) the third step solves the potential overloading using the described electrical coefficient approach. For the calculations, the N scenario and N-1 contingency analysis scenarios are considered.

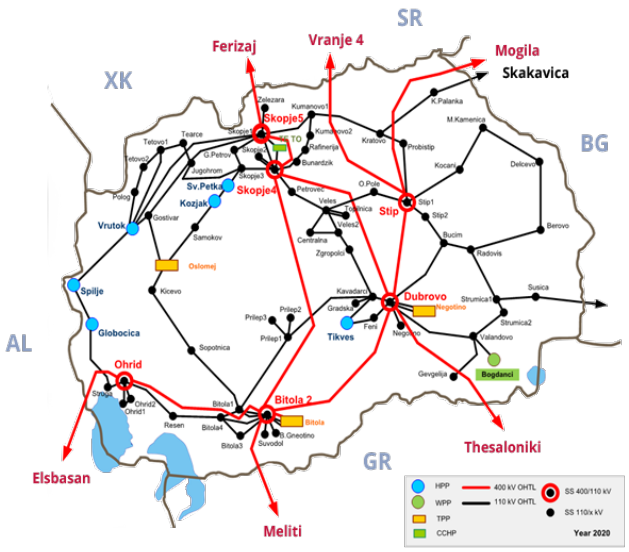

Figure 2: Considered power system model of North Macedonia

Visualization of full complex electrical coefficients matrix of Macedonian power system is depicted on Figure 3.

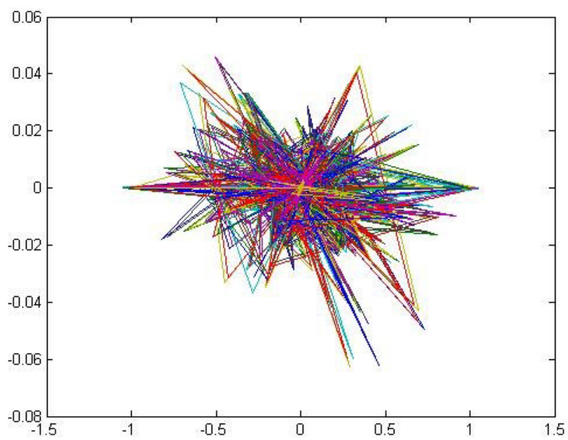

Figure 3: Visualization of complex electrical coefficients matrix of the power system of N. Macedonia

Under the N scenario, the power flow solution reports that the most loaded branch in the observed network is the line Skopje 3 – Sv. Petka. Figure 4 depicts the highest values of the electrical coefficients of the nodes for the observed branch. According to Figure 4, scaling down the production of the generators in the Hydro Power Plant (HPP) Sv. Petka and/or HPP Kozjak will have the maximum impact on the load decrease of the line Skopje 3 - Sv. Petka. Similarly, the increase of the load at node Samokov will have maximum impact on the load decrease of the observed line. Table I summarizes the changes at the Sv. Petka and Samokov nodes. These changes allow decrease of the loading of the critical branch to 90%.

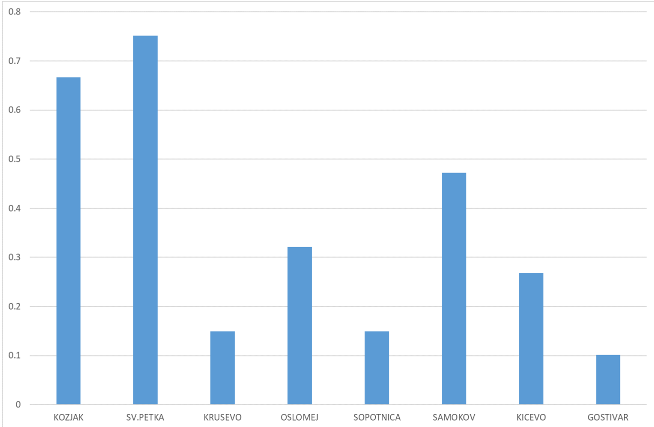

Figure 4: Nodes with highest electrical coefficients for line Skopje 3 – Sv. Petka

Namely, if the target is to decrease the loading of the line Skopje 3 – Sv. Petka to 90%, the production of the generators in Sv. Petka should be scaled down by 3 MW. For the same effect, the load in Samokov should be scaled up by 6 MW for the same power factor.

Table I: Line Skopje 3– Sv. Petka loading before and after generator or load scaling

node	Scaling (+/-)	Line loading before scaling (%)	Line loading after scaling (%)	Sensitivity (%/MW)
Sv. Petka	–3 MW	92	90	0.7
Samokov	+6MW	92	90	0.33

The contingency analysis under the N-1 scenario is very interesting for consideration, since several overloaded lines can be observed. For example, following the contingency when Kicevo – Oslomej line is out of service, two lines are overloaded in the network, i.e. Skopje 3 – Sv. Petka (102.5%) and Kozjak – Sv. Petka (102%). Figure 5 depicts the highest values of the electrical coefficients of

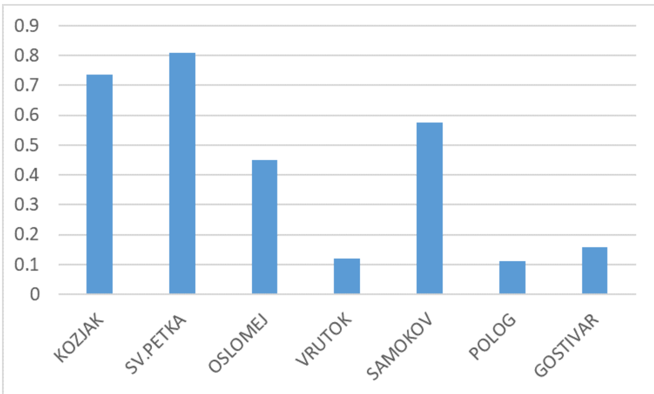

Figure 5: Nodes with highest electrical coefficients for the line Kozjak – Sv. Petka

the nodes for to the most loaded branch Skopje 3 – Sv. Petka (102.5%) and Table II presents the loading before and after implementing mitigation measures

Table II: Line Skopje 3– Sv. Petka loading before and after generator or load scaling

node	Scaling (+/-)	Line loading before scaling (%)	Line loading after scaling (%)	Sensitivity (%/MW)
Sv. Petka & Kozjak	–6 MW (–12 MW in total)	102	97	0.42
Samokov	+15MW	102	97	0.33
Gostivar	+17 MW	102	97	0.29

The overloads in this case can be resolved with scaling down the production of the generators in Sv. Petka and Kozjak in total of 12 MW (6 MW in each HPP). The same effect can be achieved if the load in Samokov is increased for 15 MW, considering the same power factor. Another option is to increase the load at node Gostivar for 17 MW for the same power factor.

For further validation of the methodology efficency, simulation analysis is performed on a test radial distribution network depicted in Figure 6 [9]. For the analysis, the voltage limits of the distribution network nodes are set at 1.1 p.u.–0.9 p.u., while the current capacity of the lines is set to 145 A.

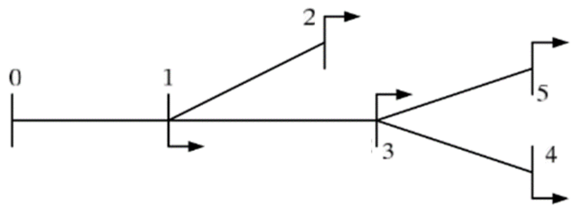

Figure 6: Radial distribution network

PV power plant should be integrated in bus 2 with maximum power of 2.9 MW. It will cause overloading of line 1-2 (100.64%). Electrical distance coefficient matrix is calculated as follows:

Table III: Electrical Distance Parameters in p.u.

Line	Bus					
	0	1	2	3	4	5
0-1	1.00	0.00	0.00	0.00	0.00	0.00
1-2	0.05	0.05	0.95	0.05	0.05	0.05
1-3	0.70	0.70	0.70	0.30	0.30	0.30
3-4	0.04	0.04	0.04	0.04	0.96	0.04
3-5	0.06	0.06	0.06	0.06	0.06	0.94

It is obvious that that the load at node 2 is electrically close to the line 1-2 and the participation of the consumer at node 2 in demand response will yield to solving overload problem. Demand response (flexibility) of load with +30% will resolve the overload and the branch loading will decrease to 98%.

3. CONCLUSION

In this paper, a new approach for resolving overloads in transmission and distribution networks is proposed. The approach provides adequate mitigation measures using the electrical distance coefficients matrix, which is developed on the basis of the Zbus matrix of the network. In other words, considering the highest electrical distance coefficient, adequate and effective load flexibility or generation re-dispatch measures for solving the overloads in the network can be proposed. For testing the applicability and efficiency of the proposed method, the individual model of the power system of North Macedonia for planning purposes has been used. The model considers high penetration of PV and wind generation. The presented results have shown the efficiency of the proposed methodology for resolving overloads in the network with selection and scaling up and down of loads and generators in the buses with highest electrical distance coefficient corresponding to overloaded branch. The methodology efficiency is also presented on simple test radial distribution network. In addition, it should be emphasized that the method can be implemented for larger, meshed grids or multiple simultaneous overloads.
Direct control is envisioned to be implemented using standardized communication protocols, enabling the translation of load flexibility or re-dispatch signals into actual operational commands. Under this approach, centralized platforms would issue real-time instructions directly to controllable assets using established protocols. These protocols facilitate secure and reliable communication, ensuring precise and immediate responses from connected devices. The operational commands would automatically trigger asset adjustments, based on predefined contractual agreements, eliminating the need for market-based interactions.

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BIOGRAPHY

Metodija Atanasovski was born in 1977 in Bitola. He received his Dipl. Ing., M.Sc. and Dr. sc. degrees all in Electrical Engineering at University "Ss. Cyril and Methodius" in Skopje in 2001, 2005 and 2011 respectively. During the period 2001-2002 he worked at the Institute for En-ergy in Skopje. In 2003 he joined Faculty of Technical Sciences, University "St. Kliment Ohridski"- Bitola. Presently he is a full professor in several subjects from power systems scientific area. His subjects of interest are distributed energy resources and their technical and economic influence in distribution networks and loss allocation. He has participated in several research projects financed by various programs of the European Commission as a member of the UKLO research teams, amongst which most important are TRINITY H2020 project, IPA Adrion CIRASIM project and InnoFEIT EDIH Digital Europe project. He is a member of IEEE and CIGRE.

Goran Veljanovski was born in 1996, in Bitola. He completed his undergraduate studies at the Faculty of Technical Sciences Bitola, in the field of Electrical Power Systems, in 2019. After graduating, he continued with master's studies at the Faculty of Technical Sciences Bitola and obtained his master's degree in 2021. In parallel with his postgraduate studies at the faculty, he also worked as a demonstrator at the same faculty until 2022. In 2022, he enrolled in doctoral studies at the Faculty of Electrical Engineering and Information Technologies (FEEIT) at the Ss. Cyril and Methodius University, at the Institute of Power Transmission Systems. In 2023, he was appointed as a teaching assistant at the Faculty of Technical Sciences Bitola, where he still works. His areas of scientific and research interest include battery energy storage systems, with a special focus on their optimal sizing and management to provide a range of services, electricity markets, and distribution networks.

Pande Popovski was born in 1996 in Bitola. He received his B.Sc. degree in Electrical Power Systems from the Faculty of Technical Sciences, Bitola, in 2019, and his M.Sc. degree from the same institution in 2021. During his postgraduate studies, he also worked as a demonstrator at the Faculty of Technical Sciences until 2022. In 2023, he commenced his doctoral studies at the Faculty of Electrical Engineering and Information Technologies (FEEIT), Ss. Cyril and Methodius University in Skopje, within the Institute of Power Plants and Substations. Since 2023, he has been employed as a Teaching Assistant at the Faculty of Technical Sciences, Bitola. His research interests include power system operational planning, with emphasis on the optimization of unit commitment and economic dispatch problems in diverse generation portfolios comprising renewable, conventional, and energy storage systems.

Aleksandra Krkoleva Mateska was born in Skopje in 1979. She has received Dipl. Ing., M.Sc. and Dr. sc. degrees all in Electrical Engineering at University "Ss. Cyril and Methodius" in Skopje (UKIM). She is with UKIM and works in the field of power systems, focusing on Smart Grids, renewable sources integration in distribution grids and Microgrids, electricity markets and regulation related to these areas. She has participated in several research projects financed by various programs of the European Commission as a member of the UKIM research teams. As a representative of the CROSSBOW and R2D2 projects, she participated in the BRIDGE Regulation Working Group. She is a member of IEEE and CIGRE.

Petar Krstevski was born in 1988 in Bitola. He has received B.Sc., M.Sc. and Ph.D. degreed at Ss Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies (UKIM/FEIT) in 2010, 2012 and 2018. Currently he is holding the position of Associate Professor at UKIM/FEIT. He works in the field of power systems, and his areas of investigation are the regional integration of electricity markets and ancillary services markets, cross-border coordination in power system operation, integration of generation from renewable energy sources in electricity markets and the regulation related to these areas. He has actively participated in multiple international projects financed by the European Commission and the Kingdom of Norway, amongst which most important are CROSSBOW, R2D2 and TRANSIT, as well as several national studies in his areas of expertise.