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Professional paper

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INTEGRATION OF SOLAR PHOTOVOLTAIC POWER PLANTS INTO THE POWER TRANSMISSION SYSTEM OF BOSNIA AND HERZEGOVINA LOAD AND VOLTAGE CONDITIONS ANALYSIS

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Abstract: Governments in the region are actively trying to decentralize production in the energy sector by encouraging the construction of power plants using renewable energy resources. The Network Code [1] and the Connection Regulation [2]-[4] define the procedure for issuing connection conditions to the power transmission network in Bosnia and Herzegovina. This paper will demonstrate the necessary approach to assessing the possibilities of connection and placement of the produced power and energy at a specific connection point in the early stages of planning, using the example of an 80 MW photovoltaic power plant planned for construction in the municipality of Tomislavgrad. The connection of the power plant is planned on a 110 kV voltage level network, by connecting it to the target 110 kV overhead transmission lines, following the principle of input-output.

Keywords: photovoltaic power plants, renewable energy sources, connection

INTRODUCTION

The construction of the proposed Photovoltaic Power Plant (PVPP) is planned in the municipality of Tomislavgrad. The PVPP is near the overhead transmission lines (TL): 110 kV Tomislavgrad – Kupres line, 110 kV Livno – Tomislavgrad line, and 110 kV Jelovača - Tomislavgrad line, all owned by the Power Transmission Company ELEKTROPRENOS BiH. The plan involves intersecting the selected 110 kV TL, which will be constructed at the PVPP connection point following the input-output principle.

The Southwest Bosnia and Herzegovina region, in terms of the exploitation of power transmission lines and substations, is organized under the company Elektroprenos BiH - Operational Area Mostar. Territorial Unit (TU) Mostar covers the area from Neum to the northwest of Bosnia and Herzegovina. TU Mostar is responsible for approximately 1330 km of transmission lines of various voltage levels, including 525 km of 220 kV transmission lines, 669 km of 110 kV transmission lines, and few transformer substations (TS), such as TS 400/220/110/35/10 kV Mostar 4, RP 220 kV Mostar 3, RP 220 kV Jablanica, and the following TS 110/35/10 kV: Mostar 1, Mostar 2, Mostar 5, Mostar 6, Mostar 7, Mostar 9, Čitluk, Čitluk 2, Grude, Široki Brijeg, Posušje, Čapljina, Neum, Ljubuški, Stolac, Tomislavgrad, Livno, Kupres, Jablanica, Konjic, Uskoplje, Rama, and Glamoč [5].

According to the information from [6], the TS with the highest installed capacity is TS 400/220/110/35/10 kV Mostar 4, the interconnection of the transmission network at 400 kV, 220 kV, and 110 kV in the mentioned area with the Republic of Croatia (HR) and Montenegro (MNE) is achieved through the following transmission lines: 400 kV Mostar 4 – Konjsko line, 400 kV Trebinje – Lastva line, 220 kV Mostar 4 – Zakučac line, 220 kV Trebinje – Perućica line, and 220 kV Trebinje – Plat line. The connection with neighbouring systems at 110 kV voltage is achieved through the following lines: 110 kV Grude – Imotski (HR) line, 110 kV Ljubuški – Vrgorac (HR) line, 110 kV Čapljina – Opuzen (HR) line, 110 kV Neum – Opuzen (HR) line, 110 kV Neum – Ston (HR) line, 110 kV Trebinje – Komolac (HR) line, 110 kV Bileća – Nikšić (MNE) line, 110 kV Trebinje – Herceg Novi (MNE) line, and 110 kV Livno – Buško Blato line [6].

The following observations are made based on the collected data from [6]-[8] regarding the treatment of the 110 kV transmission line load in the relevant area, both the past and current status, and the projected situation. Among the 110 kV transmission lines in the area, the following lines are recognized as the most heavily loaded, especially during deviations from normal operational states and for power flow conditions before the construction of the Wind Power Plant (WPP) in the relevant region: 110 kV Mostar 4 – Široki Brijeg line and 110 kV Široki Brijeg – Grude line. Line 110 kV Mostar 4 – Široki Brijeg consisting of Al/Fe

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240/40 mm^2 conductors and Cu 95 mm^2 conductors. This line experiences high loads even when all branches are fully operational, and it is at risk of overloading when there are specific outages in the Hydro Power Plant (HPP) Jablanica – TS Jablanica line, Jablanica – Rama line, or Rama – Tomislavgrad lines during dry hydrological conditions. In the event of a failure in the aforementioned line, there is a risk of overloading the 110 kV Čapljina – Opuzen line, leading to further overloads in the network. 110 kV Široki Brijeg – Grude line, using Al/Fe 240/40 mm^2 and Cu 95 mm^2 conductors, with a length of 16 km, is at the brink of overloading during wet hydrological conditions and power export, particularly when 110 kV HPP Jablanica – Jablanica line is out of operation. Besides the mentioned lines, the most heavily loaded 110 kV transmission lines in the area are Š.Brijeg – Grude (81%), Grude – Imotski (34%), Mostar 4 – Čitluk (69%), Čitluk – Ljubuški (53%), Ljubuški – Čapljina (34%), Mostar 1 – Mostar 6 (58%), and Mostar 2 – HPP Jablanica (61%) [7]. These lines are heavily loaded when supplying power to the areas of Š. Brijeg, Grude, Posušje, Tomislavgrad, Čitluk, Ljubuški, Čapljina, and various sections within Mostar and between Mostar and Jablanica [7]. However, it should be noted that these observations are based on documents reflecting previous operational states and are primarily associated with power flow conditions before the construction of the WPP in the relevant region. Once the WPP is operational, the load on the mentioned 110 kV lines will decrease.

For this analysis, taking into consideration the current and prospective state of the Electrical Power System (EPS) in the relevant area, technical data on all substations in the area, as well as 110/x kV TS, existing 400/x kV, and 220/x kV TS, were collected and selectively compiled to form a model for calculations. Subsequently, power flow calculations were performed in the relevant area for various scenarios and system loads, both with and without the considered PVPP. The section Model and Calculation Results briefly presents the results of the conducted calculations. The Discussion section provides discussions based on the obtained results. The conclusions derived from the analysis are presented in the Conclusions section.

1. MODEL AND CALCULATION RESULTS

As previously stated, to prepare this study, technical data on all TS in the relevant area, as well as 110/x kV TS, existing 400/x kV, and 220/x kV TS, were collected, and carefully selected. Based on this data, databases containing essential technical information and corresponding electro-energetic parameters of the relevant TL and TS and equipment were formed, considering three response levels to overloads. Subsequently, the TS 110/x kV and the corresponding connecting 110 kV transmission lines within the power transmission area of the Operational Unit Mostar and surrounding TS 110/x kV for the project coverage area were modelled using the specialized software package CASE. To ensure accurate calculations, the main 110 kV connections and lines from other regions, as well as interconnections with neighbouring countries, and 400/x kV and 220/x kV transformations relevant to the calculation were added to the model. The used software package allows for manual and automatic voltage regulation in the model, by manually adjusting the voltage regulator through manual adjustment of the control switch, or automatically adjusting the control switch of the 110/x kV transformer to maintain the voltage within specified values, e.g., in the range of 0.95 to 1.05 per unit. Automatic voltage regulation on transformers in the model can be performed both at the local and systemic levels. In reality, the transformer must have an automatic voltage regulator for such voltage regulation. According to the data collected for this study's preparation, many substations have fully functional automatic voltage regulators on their transformers. Additionally, the mentioned software package enables the regulation of voltage conditions in the considered system by regulating the generator in the following manner: During the power flow and voltage condition calculations, the generator maintains the voltage at a specified value or within a certain range at the node to which it is connected, and even at a node to which the generator is not directly connected. This is known as remote or secondary voltage regulation. During this process, the power generated by the power plants in the EPS corresponds to the displayed committed power of power plants in the document [6]. It should be noted that during the simulation, the power generation of power plants from the Republic of Croatia, which supply electrical energy via the 110 kV transmission line Buško Blato - Livno, is aligned with the data presented in document [6]. In the model, simulations were conducted for normal operating conditions in the power system, as well as for simulated outages of specific transmission lines of interest, considering maximum, average, and minimum system loads both with and without the connection of the subject PVPP. Additionally, the issue of connecting the subject PVPP from the perspective of its contribution to short-circuit currents was addressed without knowledge of the specific equipment to be installed. The following text highlights only basic data for TS 110/x kV Tomislavgrad, TS 110/x kV Kupres, and TS 110/x kV Livno, along with the relevant transmission lines converging at these substations. Detailed graphical representations of bus voltages, expressed in magnitude and phase angle, as well as the results of calculations for active and reactive power flows, are presented.

Figure 1 is a graphical representation of the calculation results for power flows in the 110 kV transmission lines of the subject area, along with voltage conditions at the 110 kV busbars of the TS 110/x kV substations, under the condition of average maximum load achievable during the previous ten-year period, without the subject PVPP. The voltage at the 110 kV busbars of TS 110/x kV Tomislavgrad

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is 117.27 kV with a phase angle of 1.67 degrees, at TS 110/x kV Livno is 117.74 kV with a phase angle of 2.97 degrees, and at TS 110/x kV Kupres is 116.93 kV with a phase angle of 1.11 degrees. The load of the 110 kV Livno-Tomislavgrad line is 27.92 MW (21.46%), 110 kV Jelovača-Tomislavgrad line is 18.49 MW (16.03%), 110 kV Mesihovina-Tomislavgrad line is 16.20 MW (13%), 110 kV Tomislavgrad-Kupres line is 42.02 MW (32.08%), and 110 kV Kupres-Bugojno line is 38.89 MW (29.80%).

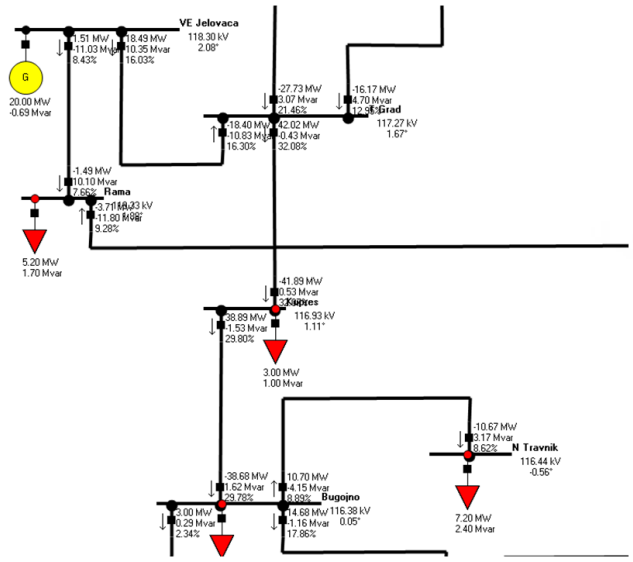


Figure 1: Graphical representation of calculation results for the average maximum load achievable during the previous ten-year period, without the connected PVPP

Figure 2 is a graphical representation of calculation results for power flows in the 110 kV transmission lines of the subject area, along with voltage conditions at the 110 kV busbars of the TS 110/x kV substations, for the maximum load reached in 2021 and with the connected subject PVPP with a capacity of 80 MW, on the 110 kV Tomislavgrad-Kupres line. The voltage at the 110 kV busbars of TS 110/x kV Tomislavgrad is 117.28 kV with a phase angle of 6.63 degrees, at TS 110/x kV Livno is 117.50 kV with a phase angle of 7.94 degrees, and at TS 110/x kV Kupres is 116.95 kV with a phase angle of 6.47 degrees. The load of the 110 kV Livno-Tomislavgrad line is 27.42 MW (21.57%), 110 kV Jelovača-Tomislavgrad line is 6.83 MW (13.35%), 110 kV Mesihovina-Tomislavgrad line is 4.98 MW (3.97%), 110 kV Tomislavgrad-PVPP line is -6.07 MW (10.73%), 110 kV PVPP-Kupres line is 73.93 MW (56.71%), and 110 kV Kupres-Bugojno line is 70.83 MW (54.49%).

Figure 3 is a graphical representation of calculation results for power flows in the 110 kV transmission lines of the area of interest, along with voltage conditions at the 110 kV busbars of the TS 110/x kV substations, for the maximum load in 2021, with the connected subject PVPP with a capacity of 80 MW on the 110 kV Tomislavgrad-Kupres line. During this simulation, an outage of the transmission line on the PVPP-Kupres section was performed. The voltage at the 110 kV busbars of TS 110/x kV Tomislavgrad is 117.45 kV a phase angle of 12.96 degrees, the voltage at the 110 kV busbars of TS 110/x kV Livno is 117.67 kV a phase angle of 14.26 degrees, and the voltage at the 110 kV busbars of TS 110/x kV Kupres is 113.53 kV a phase angle of 1.37 degrees. The load on the 110 kV Livno-Tomislavgrad line is 27.42 MW (21.57%), 110 kV Jelovača-Tomislavgrad line is -45.58 MW (39.65%), 110 kV Mesihovina-Tomislavgrad line is -12.23 MW (10.09%), and 110 kV Tomislavgrad-PVPP line is -79.63 MW (64.17%).

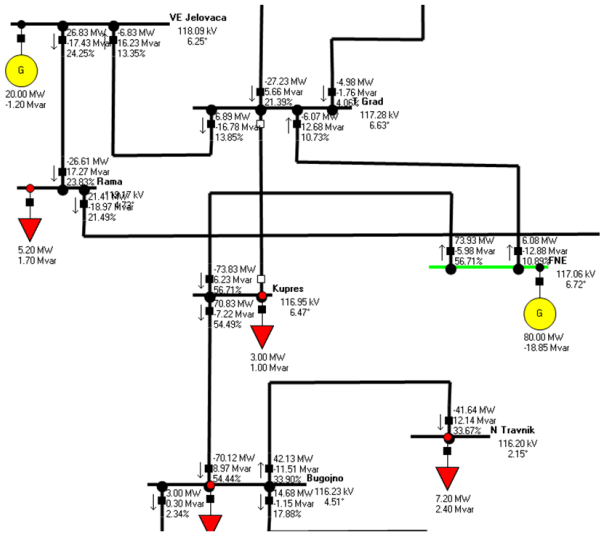


Figure 2: Graphical representation of calculation results for the maximum load in 2021, with the connected PVPP

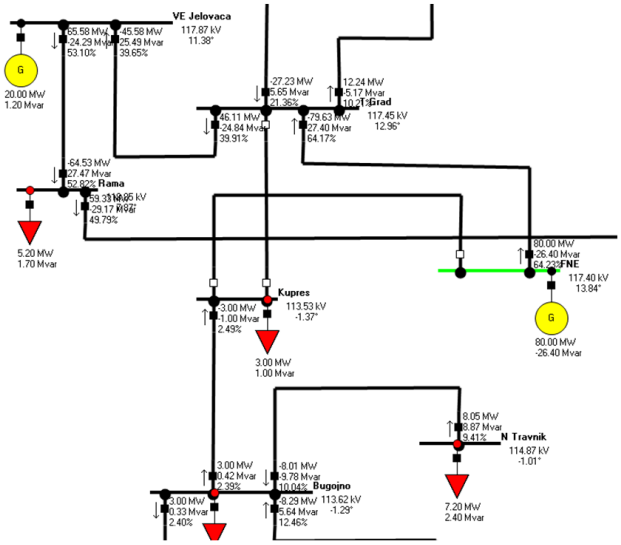


Figure 3: Graphical representation of calculation results for the maximum system load achieved in 2021, with the connected PVPP and simulated outage of the transmission line on the PVPP-Kupres section

Figure 4 is a graphical representation of calculation results for power flows in the 110 kV transmission lines of the area of interest along with voltage conditions at the 110 kV busbars of the TS 110/x kV, for the minimum load registered in 2019, with the connected subject PVPP with a capacity of 80 MW. The voltage at the 110 kV busbars of the TS 110/x kV Tomislavgrad is 117.53 kV a phase angle of 8.64 degrees, TS 110/x kV Livno is 118.17 kV a phase angle of 10.31 degrees, and TS 110/x kV Kupres is 116.99 kV a phase angle of 7.77 degrees.

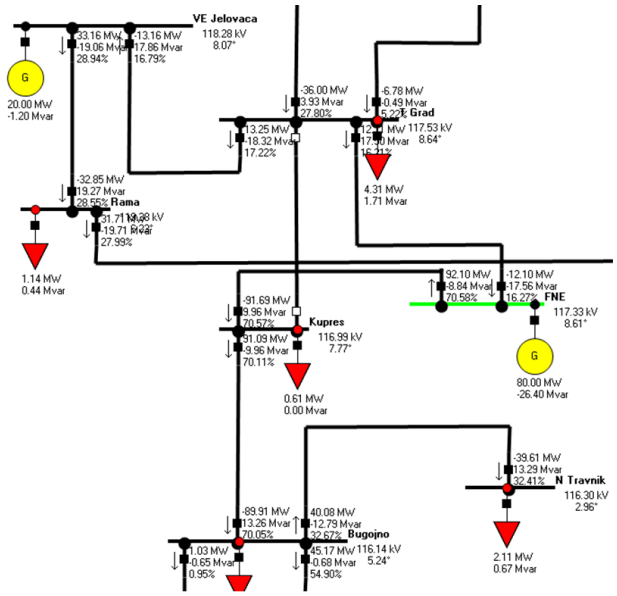


Figure 4: Graphical representation of calculation results for the minimum load registered in 2019, with the connected PVPP

2. DISCUSSION

Based on the data collected from development documents for [6] and [7], regarding the treatment of the 110 kV transmission lines' load in the area of interest, including the past, current, and prospective states, the following conclusions can be drawn: Low Load on 110 kV transmission lines: The results of the power flow calculations indicate that the 110 kV transmission lines in the target area have a low load, even during maximum system load conditions. The maximum load on any of the 110 kV transmission lines in such conditions does not exceed 36%. For example, the 110 kV Kupres-Tomislavgrad line is loaded at approximately 36%, the 110 kV Livno-Tomislavgrad line at around 23%, and the 110 kV Jelovača-Tomislavgrad line at about 15%.

Impact of PVPP Integration: The integration of the subject solar photovoltaic power plant with a capacity of 80 MW is not expected to endanger the thermal stability of the targeted transmission lines and their associated conductors and equipment. The simulations show that even with the presence of another PVPP with similar characteristics in the system, there are no thermal overloads on the transmission lines, both before and after the PVPP connection. A simulation, along with accompanying calculations, was conducted in the event of a partial outage on the 110 kV power line from Tomislavgrad to Kupres in the direction of Kupres, as illustrated in Figure 3. It's important to note that the operational conditions depicted here are considered the most unfavourable. Nevertheless, even under these extreme conditions, the thermal loads on the mentioned power line are not compromised, and there is no significant increase in voltage on the 110 kV busbars within the considered system. In the event of a disconnection towards the Kupres area, the generated power and energy are redistributed, allowing the system to resume its operation without significant alterations in voltage conditions. The Kupres and Bugojno regions, not visible in the displayed part of the system illustrated in Figure 3. but represented within the model's internal framework, are supplied with power and energy from the other side of the system. This reaffirms the points previously outlined and leaves room for the development of renewable energy facilities in the Kupres area, which would further contribute to the broader balancing of power flows within the electricity grid of Bosnia and Herzegovina in the considered region.

Voltage Conditions: The simulations show elevated voltage conditions on the power system's 400 kV and 220 kV voltage levels, compared to the 110 kV level. The voltage conditions are significantly higher during weekends compared to weekdays, and the voltage is closer to maximum permissible values in the broader area of interest. The voltage conditions are noticeably higher compared to nominal values and approach the maximum allowable limits on the broader observed area. It is important to note that this paper does not encompass an in-depth analysis of voltage conditions within the power transmission system, nor does it provide recommendations for the regulation of voltage conditions in the power transmission system, except in the context of demonstrating the feasibility of power and energy transmission from the discussed photovoltaic power plant. At this juncture, it is worth noting that the regulation could also be achieved through adjustments of the voltage regulators on transformers. The voltage at the terminals of transformers, or the nodes to which the transformer is connected, can be controlled by altering the tap position on the transformer. According to the data gathered for the purposes of this paper, a large number of substations are equipped with fully functional automatic voltage regulators on their transformers. The software package used enables the consideration of both manual and automatic voltage regulation within the model by manually adjusting the voltage regulator settings on the transformer or by automatically readjusting the tap settings of the 110/x kV transformer, ensuring that the voltage remains within the predefined values, what could be utilized for further elaboration in resolving the specific problem.

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Stability During Line Outages: Simulations were also performed for scenarios involving line outages, including the Tomislavgrad-Kupres line. However, even under such extreme conditions, the thermal loads on the targeted 110 kV transmission lines are not affected significantly, and there is no significant increase in voltage at the 110 kV busbars of the TS 110/x kV substations.

Short-Circuit Current Contributions: In accordance with the [1], the transmission network in BiH is designed to maintain short-circuit current levels at 31.5 kA within the 110 kV system. In the document [6], the calculated values of three-phase short-circuit currents at the 110 kV busbars in the observed area are provided. These values were taken into account during the preparation of this paper. Additionally, verifications were carried out based on the constructed model. The study considered the contributions of short-circuit currents resulting from the PVPP integration. It has been concluded that there is no risk of jeopardizing the projected short-circuit levels on the 110 kV system in the area of interest, both with and without the connected PVPP. It is known that PVPPs connected via inverters provide a limited contribution to short-circuit currents. In the literature, studies, and professional works, values around 110% of the nominal current are typically cited. The exact contribution of the three-phase short-circuit current by the discussed PVPP at the TS Tomislavgrad, TS Livno, TS Kupres, and the surrounding area will be determined once the specific equipment to be installed at the PVPP is identified.

In summary, the results of the calculations and simulations indicate that the integration of the solar photovoltaic power plant with a capacity of 80 MW in the targeted 110 kV transmission lines does not pose significant challenges to the thermal stability, voltage levels, or short-circuit current capabilities of the power system. This suggests that the integration of renewable energy sources like PVPP can be accommodated safely and effectively within the existing power system infrastructure.

3. CONCLUSION

The conclusion of this study can be summarized as follows.

The 110 kV transmission lines in the studied area have low levels of loading, even during peak system demand. The loading of all targeted 110 kV transmission lines is below 36%, indicating sufficient capacity reserves for the integration of new energy sources.

The integration of the subject 80 MW solar photovoltaic power plant (PVPP) will not jeopardize the thermal stability of the targeted 110 kV transmission lines or their associated equipment, regardless of the presence of other similar PVPPs in the nearby part of the system.

Voltage conditions at the 400 kV and 220 kV voltage levels show higher variations compared to the 110 kV level, particularly during weekends. However, the connection of the PVPP to the 110 kV voltage level will not significantly affect the regulation of voltage conditions in the transmission grid.

In the event of unexpected outages of transmission lines, even under extreme conditions, the thermal loading of the targeted 110 kV transmission lines remains stable, and the voltages at the 110 kV busbars do not show significant increases.
The contribution of short-circuit currents at the targeted 110 kV substations will not compromise the designed levels of short-circuit capacity, regardless of the presence of the PVPP.

All calculation and simulation results indicate that the integration of the subject 80 MW solar photovoltaic power plant is feasible and safe. Its connection to the existing transmission system will not significantly disrupt the system's operation or lead to overloading and compromising the stability of the transmission lines. The results clearly show that the operation of the subject solar power plant has a positive impact on voltage regulation through reactive power injection/absorption, contributing to the improvement of voltage conditions in the power system within the limits of the subject power, the type of the power plant, and the voltage level of connection. In other words, the possibility of connecting the subject solar power plant to the desired connection point has been convincingly demonstrated from the aspect of power flows and voltage conditions, ensuring the delivery of generated power and energy without negatively affecting the power system. The integration of the PVPP represents a positive step towards increasing the utilization of renewable energy sources and reducing harmful gas emissions.

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BIOGRAPHY

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