

PROFILE OPTIMISATION IN REAL DISTRIBUTION NETWORKS (CASE STUDY LONG MV FEEDER)

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Abstract: In the dynamic field of power systems, integrating distributed generation (DG) sources like solar photovoltaic (PV) plants is crucial for enhancing reliability and fostering sustainability. However, this integration poses voltage profile management challenges in electrical grids. This study investigates voltage profile optimization in Bosnia and Herzegovina's Gračanica network, focusing on a medium voltage feeder with 68 buses. Using DlgSILENT PowerFactory software, six scenarios with different configurations of solar plants are analyzed for their impact on voltage profiles and power losses. Results show that while DG integration offers benefits, incorrect sizing or placement can increase power losses. Optimal DG benefits are linked to specific sizes and locations. This research emphasizes the need for balancing PV generation with load demands and provides insights for optimal PV plant size and output to minimize negative impacts. These findings aid energy planners and policymakers in implementing distributed solar PV in medium voltage networks.

Keywords: Voltage Profile Optimization, DlgSILENT PowerFactory, Medium Voltage Distribution Network, Photovoltaic Plant

INTRODUCTION

The global energy landscape is experiencing a profound transformation driven by environmental consciousness, regulatory mandates, and an unprecedented emphasis on reducing carbon emissions and enhancing energy efficiency. At the forefront of this change is the growth of renewable energy sources, which are currently perceived as the most cost-effective means of delivering clean energy, diminishing greenhouse gas emissions, and mitigating the effects of climate change.

As the world anticipates an acceleration in the growth of renewables, particularly wind and solar, the complexity associated with their integration into the conventional power system escalates. Traditional power systems operate on a radial basis where power flows unidirectionally from the generation source to the end-user. Network voltage levels are maintained by regulating generation dispatch and utilizing network equipment such as tap-changing transformers. However, the integration of renewable generation disrupts this status quo, introducing variable and possibly bidirectional power flows, thus transforming the network into an active system with its distinct challenges.

One notable consequence of the increased penetration of distributed renewable generation is the potential occurrence of issues like voltage rise, over-voltage, and reverse power flow, especially in extensive feeders such

as those in rural areas. These challenges have intensified the focus on voltage profile optimization – the process of fine-tuning voltage levels within an electric power system to enhance its efficiency, stability, and reliability while minimizing power losses. [1] Various techniques, including mathematical optimization and artificial intelligence, are employed to achieve this aim.

In this context, the present study undertakes an investigation into how the different allocation and sizing of distributed generation, focusing on solar PV plants, impact the voltage profile in the distribution network. The specific area of interest is a part of the Gračanica network in Bosnia and Herzegovina, involving one real medium voltage distribution feeder comprising 98 buses. Through the examination of six alternative scenarios, each reflecting different configurations of distributed solar plants, this paper leverages the software DlgSILENT PowerFactory to model the network and rigorously test the possibilities. The assessments are conducted in line with the EN 50160 European standard for voltage quality, providing a comprehensive view of the complex interplay between distributed renewable generation and voltage profile optimization.

Following the introductory part of this chapter that sets the context and outlines the objectives of the study, the second part offers a comprehensive literature review. This section synthesizes previous studies on voltage profile analysis, distributed generation, and their interplay,

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thereby creating a robust theoretical framework for the research.

Literature review

The task of optimizing the size and location of distributed generation (DG) sources within electrical networks has been the focus of numerous research efforts. These endeavours strive to minimize system losses and subsequently enhance the voltage profile, recognizing that losses and voltage are inherently interconnected within the power network. Below, we review some of the pertinent literature that has contributed to the understanding and advancement of this field.

In [1], the authors address the influence of DG on distribution network losses and voltage profiles. Their work utilizes both the IEEE 34-node test feeder and the Nagarkot feeder of the Bhaktapur distribution system for simulations in DlgSILENT PowerFactory. They explore various penetration levels and locations for DG, particularly wind turbines, and their consequential impacts on power losses and voltage profiles. Their findings underscored the vital impact of both the location and size of the distributed generation unit on the system.

Mohamed Abdul Rasheed and Renuga Verayiah in [2] contribute to the discourse on optimal placement of photovoltaic distributed generation (PV-DG) to minimize system losses and enhance voltage stability. They utilize Genetic Algorithms and analytical processes to find optimal sizes and locations for DG while considering non-unity power factors. Their methodologies were tested on both IEEE 33-bus and IEEE 14-bus networks, showing that optimized DG placement and power factor adjustments led to improvements in voltage profiles and reduced losses.

In [3] Ayodeji Stephen Akinyemi et al. address the issue of voltage rise phenomena in networks with a high concentration of Renewable Distributed Generations (RDG). The study suggests an advanced control algorithm to mitigate voltage rise effects and to maintain voltage stability at the Point of Common Coupling. While this paper does focus on voltage, it is more an exploration of the effects of high RDG penetration rather than an optimization strategy per se.

Gianni Celli and colleagues in [4] propose a two-step approach to optimize the voltage profile in active distribution networks. The authors employ a genetic algorithm coupled with a linearly constrained optimization method. The method identifies suitable configurations for DG placement and sizes, followed by an optimization to find the operating point for all DGs that optimizes the voltage profile. This work is another cornerstone for understanding how DG can be effectively used to optimize voltage profiles.

The paper in [5] focuses on maintaining an optimal voltage profile using a coordinated network controller. The operations of DGs, on-load tap-changing transformers, and reactive power sources are considered in this model, making it relevant but not limited to voltage profile optimization. Bawa Abubakar et al. in [6] focus on optimizing DG placement in a Nigerian distribution network using Genetic Algorithms, achieving a 0.4% improvement in bus voltage. In [7], Ibrahim A. Nassar et al. employ Genetic Algorithms to determine optimal locations for reactive power compensators, aiming to improve both voltage profiles and power losses. In [8], Muqthiar Ali Shaik and his team introduce the Equilibrium Optimizer for DG placement and network reconfiguration, aiming for both voltage improvement and loss reduction.

Lzaro Alvarado-Barrios et al. propose a two-tiered optimization strategy for unbalanced Active Distribution Systems in [9]. Their model minimizes active power losses and adjusts transformer tap positions to meet technical constraints. The strategy incorporates photovoltaic and wind power, supported by battery storage, and is validated on the IEEE 34-Node Test Feeder for effective system performance. In [10] Brayan Enrique Aguirre-Angulo et al. adopt a mixed-integer nonlinear programming model to optimize the placement and sizing of dispersed generators in medium-voltage distribution networks. Their findings suggest that optimal placement of dispersed generators can lead to substantial improvements in voltage stability. In [11], authors provide an in-depth analysis on the impact of varying levels of distributed generation (DG) on voltage stability in low-voltage secondary distribution networks. Through extensive time-domain simulations and probabilistic allocation of DGs, the study identifies the upper limits of DG penetration that these networks can tolerate without experiencing voltage issues, offering critical insights for network planning engineers. The authors in [12] introduce an innovative methodology for optimally integrating battery energy storage systems (BESSs) and renewable distributed generators within medium-low voltage distribution grids. Employing a mixed-integer nonlinear programming model, the methodology's efficacy is validated through various test systems, demonstrating significant potential in enhancing grid efficiency and robustness.

The research in [13] delves into methodologies for optimal integration and operation of Distributed Generators and Energy Storage Systems within electrical networks, specifically within microgrids. The comprehensive review identifies prevailing objective functions, constraints, integration techniques, and reveals the current gaps, aiming to pave the way for advanced mathematical formulations for improved financial and operational benefits.

In [14] Ahmed et al. introduce a cutting-edge framework for the optimized allocation of diverse Distributed

Generation units in Distribution Systems, emphasizing the advantages of simultaneous versus individual integration. Utilizing a hybrid Salp Swarm Algorithm and Particle Swarm Optimization method, the study validates superior performance through benchmark tests and a 69-bus system, highlighting reduced multi-objective indexes and outperforming other meta-heuristic strategies.

Finally, the user manual for DigSILENT PowerFactory Version 15.1 in [15] served as a critical resource for understanding the software and its toolbox functionalities. This guide offered essential insights into the various reporting tools and optimization strategies, thus enabling a comprehensive evaluation of voltage profiles within the electrical network.

Together, these studies form a comprehensive understanding of the multifaceted relationship between distributed generation's location, size, and type, and the resulting effects on the voltage profile and system losses. They not only reveal the complexity of managing these parameters in the context of a global shift toward renewable energy but also highlight the innovative methodologies, mathematical models, simulations, and tools like DigSILENT PowerFactory that are increasingly used to optimize distributed generation integration. The growing body of literature in this field sets the stage for continuous exploration and innovation, as researchers and practitioners alike seek to harmonize the promises of renewable energy with the technical demands of modern power system architecture.

In contrast to existing literature, which primarily outlines the theoretical aspects and general implications of integrating DG, this research provides an in-depth, scenario-based exploration, specifically focusing on varied sizes and connection points of PV plants in a real distributed network. This study is distinctive due to its detailed investigation into the voltage profiles of the Gračanica network, utilizing DigSILENT PowerFactory software for optimization and analysing the resultant voltage profiles under multiple scenarios. While many previous studies have illustrated the potential challenges and benefits of DG, the level of detail and subtlety of analysis provided in this research, especially the emphasis on optimizing voltage profiles through strategic PV plant integration and the consideration of actual network consumption levels, offers refined insights. These insights are particularly crucial for network planning engineers and energy planners, providing a detailed reference point to understand the implications of PV plant integrations and to facilitate more informed and optimal decision-making in real-world distributed networks, thereby contributing substantively to the field of power systems and network optimization.

After the introductory chapter with the literature review, the first chapter articulates the methodology employed in

the research, featuring an overview of the software and toolbox used for data analysis. This chapter also delves into the modelling aspects of the distributed network under study, detailing the parameters and assumptions involved. Chapter 2 is dedicated to the presentation of simulation results and their interpretations. Here, the baseline scenario is first examined, followed by an analysis of six individual scenarios for distributed generation integration. Comparative studies between these scenarios are presented, offering insights into variations in bus voltages, as well as active and reactive power losses across different configurations. This multi-scenario analysis serves to underscore the paper's central thesis about the role of voltage profile analysis in optimizing the integration of distributed generation sources.

1. METHODOLOGY

Voltage optimization in distribution networks is the process of adjusting the voltage levels at various locations within a distribution system in order to improve the overall performance and efficiency of the system. This can involve modifying the settings of voltage regulators, transformers, and other equipment, as well as managing power flow in the system. The underlying objective is to ensure that voltage levels are maintained within permissible ranges, thus minimizing power losses and boosting the system's stability and reliability. The importance of voltage optimization is magnified with the integration of variable renewable energy sources, such as solar PV systems, which can lead to voltage fluctuations, and even instances of overvoltage.

Overvoltage can occur when solar panels inject more power than the load requires, potentially causing equipment damage and system reliability issues. Conversely, low solar generation may result in voltage drops below acceptable limits. To mitigate these challenges, various voltage control methods such as active and reactive power control, tap changer operation, and dynamic voltage restorers are implemented. Advanced monitoring and control technologies further aid in predicting and managing the solar PV's impact on the voltage profile.

1.1. Implementation Using DigSILENT PowerFactory

DigSILENT is a software tool that can be used for a wide range of power system analysis and planning tasks, including voltage profile optimization. One of the key features of DigSILENT is its ability to model and simulate the behaviour of power systems under various operating conditions, including different levels of solar PV generation. This enables users to examine the effect of solar PV on the voltage profile and identify places where system adjustments are required to optimize performance.

The Voltage Profile Optimization Toolbox used in our research employs a strategic and iterative methodology to optimize transformer tap settings, aiming to maintain stable voltage profiles within a power system. It starts by adhering to user-specified transformer tap ranges, carefully controlling voltage variations in different scenarios. The software calculates suitable upper and lower tap limits to keep the grid voltages within predetermined boundaries, typically between 0.9 p.u. and 1.1 p.u. In its optimization efforts, the software initially focuses on minimizing voltage rise by choosing the lowest feasible tap position. The software's iterative algorithms dynamically adjust these tap positions, responding to voltage deviations at various nodes. For instance, if a node's voltage falls outside acceptable limits, the algorithm may modify the tap setting of a nearby regulating transformer to correct the voltage level. This iterative process persists until the solution stabilizes, meaning further adjustments to tap positions don't substantially enhance the voltage profile, or until all node voltages align with their specified limits. The calculation considers two scenarios:

- "Consumption Case", or a maximum demand/minimum generation scenario: This scenario emphasizes modelling and analysing energy consumption, factoring in both customer load profiles and their impact on voltage levels. A generation scaling factor of 0% was utilized.
- "Production Case", or a minimum demand/maximum generation scenario: This scenario emphasizes the modelling and analysis of power generation from distributed sources, considering their output and impact on voltage levels. The load scaling factor here is set at 20%.

Given these two scenarios, our research assumes that if a voltage profile improvement strategy can effectively manage these two extremes, it inherently covers all possible intermediate voltage scenarios that can arise from load variations within these bounds. If the extreme cases of maximum and minimum voltages in the network are satisfied, then all cases of voltage values between these two extremes will also be satisfied.

Overall, DIgSILENT PowerFactory integrates automated efficiency with user-defined controls to effectively balance power delivery and voltage stability within a network. The optimization method seeks to find the optimal combination of parameters that achieves the desired voltage profile while also accommodating constraints such as network capacity, system stability, and equipment limitations.

1.2. Modelling of a real medium-voltage distribution network

For the examination conducted in this study, a specific segment of the "Gračanica" distribution network was chosen, specifically one MV distribution feeder. This feeder is connected to the external grid through a transformer

rated at 110/35/10 kV and 20 MVA. The simulated distribution network embodies 68 buses and 30 loads, which are interconnected via 30 transformers scattered along the primary feeder.

To fulfil the requirements of the Voltage Profile Optimization tool, all loads in this particular study were represented as medium voltage (MV) loads. This representation took into account both transformer and LV network parameters, all in accordance with the actual network parameters supplied. To govern the voltage fluctuation, tap limits on distribution transformers were defined, ranging between "-2" and "2" to confine the voltage rise and drop within 2.5% and -2.5%. For all the transformers involved in the model, a tap position of "1" was selected.

In the context of this project, two distinct locations were identified for the placement of solar PV plants, each to be modelled in three different sizes: 1 MW, 2 MW, and 3 MW. This resulted in a total of six different cases:

- 1) 1 MW PV plant connected at the end of the network,
- 2) 2 MW PV plant connected at the end of the network,
- 3) 3 MW PV plant connected at the end of the network,
- 4) 1 MW PV plant connected in the middle of the network,
- 5) 2 MW PV plant connected in the middle of the network,
- 6) 3 MW PV plant connected in the middle of the network.

The first location was proposed at the furthest bus in the network, while the second was positioned at the network's midpoint. Within the model, the PV plants were simulated as solely injecting active power into the system.

Figure 1, illustrating the final model of the analysed MV feeder in DIgSILENT PowerFactory, clearly depicts the two analysed positions for the proposed PV plants, symbolized by orange loads. The detailed modelling of this real distributed network provides an essential framework for the analysis of various scenarios related to the integration of solar PV plants and their impact on voltage optimization within the network.

2. SIMULATION AND RESULTS ANALYSIS

In the context of the "Gračanica" distribution network, specifically the analysed MV distribution feeder this section provides a comprehensive analysis of different PV plant integration scenarios. The study encompasses the examination of a baseline scenario without PV plants and further explores three distinct PV plant sizes connected at two suggested locations within the network. Utilizing advanced tools such as DIgSILENT PowerFactory, the investigation delves into aspects like voltage drops and rises, transformer tap positions, active and reactive losses, and the overall network behaviour.

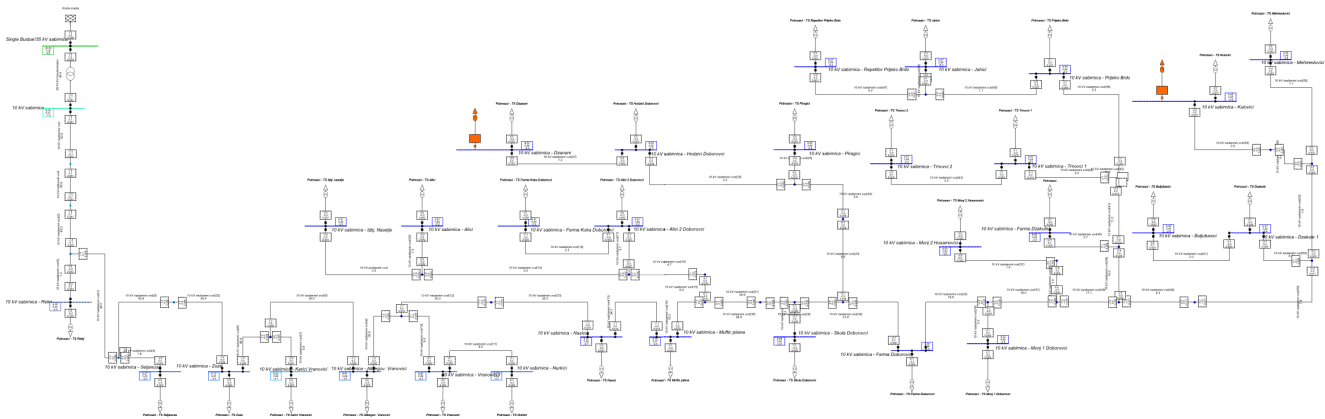


Figure 1: Model of MV Feeder 10 kV Doborovci in DlgSILENT PowerFactory

2.1. Baseline Scenario Analysis

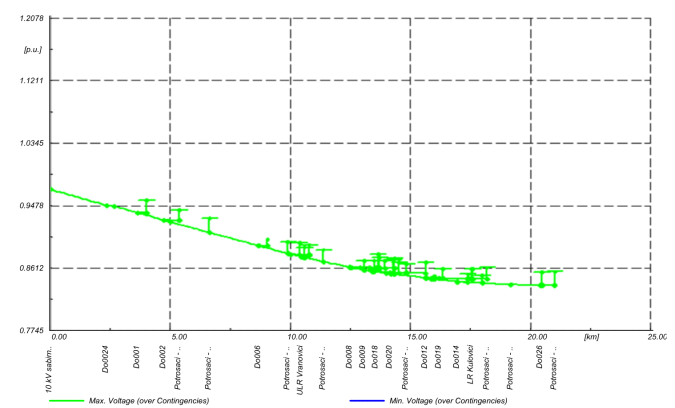
In order to be able to make an accurate comparison of the outcomes, a baseline scenario was initially studied in which there were no PV plants connected to the system. After executing the Load Flow analysis in DlgSILENT PowerFactory, the Complete System Report highlighted substantial voltage drops below the acceptable lower limit of 0.9 p.u. on the majority of loads connected to the network, alongside significant total active and reactive losses of 0.21 MW and 0.2 MVar, respectively. The medium voltage network of Gračanica, characterized by its numerous loads, frequently experiences voltage levels that fall below 0.9 per unit (p.u.), making low voltage a recurring issue in this system.

The outcome of optimizing the voltage profile typically produces comprehensive reports, available in table or ASCII formats, that give specific recommendations on adjusting transformer tap settings. These reports also shed light on medium voltage (MV) loads that are susceptible to either significant voltage drops or spikes. When the Voltage Profile Optimization tool is used, three types of reports are generated for each given scenario:

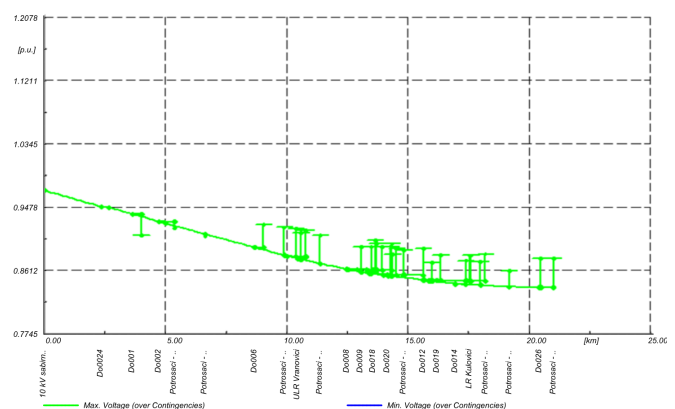
- 1) *Optimal Tap Position Report*: This first tabular report showed the optimal tap positions for each MV to LV transformer connected with an MV Load object. In this scenario, most transformers had the optimal tap position calculated to be 2, indicating the necessity to elevate the voltage at these points.
- 2) *Critical Voltage Drop Report*: The second tabular report focused on any MV Loads that experienced a critical drop, defined as a drop below 0.9 p.u. Here, 21 loads showed a critical voltage drop.
- 3) *Critical Voltage Rise Report*: This final report identified any critical voltage rises, defined as rises above 1.1 p.u. However, no such loads were found in this scenario.

A voltage profile plot was also created, displaying the voltage in p.u. against the feeder's progression in kilometres. This plot revealed multiple voltage reductions

in the consumption case prior to optimization, visibly dropping below the lower limit of 0.9 p.u. Even after optimizing, some voltage drops, which were linked to the constraints of the tap changer settings, persisted. As one moves farther down the feeder, voltage decline was observed due to line losses, but post-optimization, the tap changers were adjusted to higher settings, resulting in a slight voltage improvement.



a)



b)

Figure 2: Voltage profile plot for baseline scenario: a) before optimization, b) after optimization

2.2. First Scenario – 1 MW Solar PV Plant at the Network's End

In this scenario, a 1 MW PV plant was connected at the network's end. The load flow analysis revealed slight permissible voltage decreases and a reduction in total active and reactive losses to 0.06 MW and 0.10 MVar. Following voltage profile optimization, repeated voltage drops below 0.9 p.u. were observed before optimization.

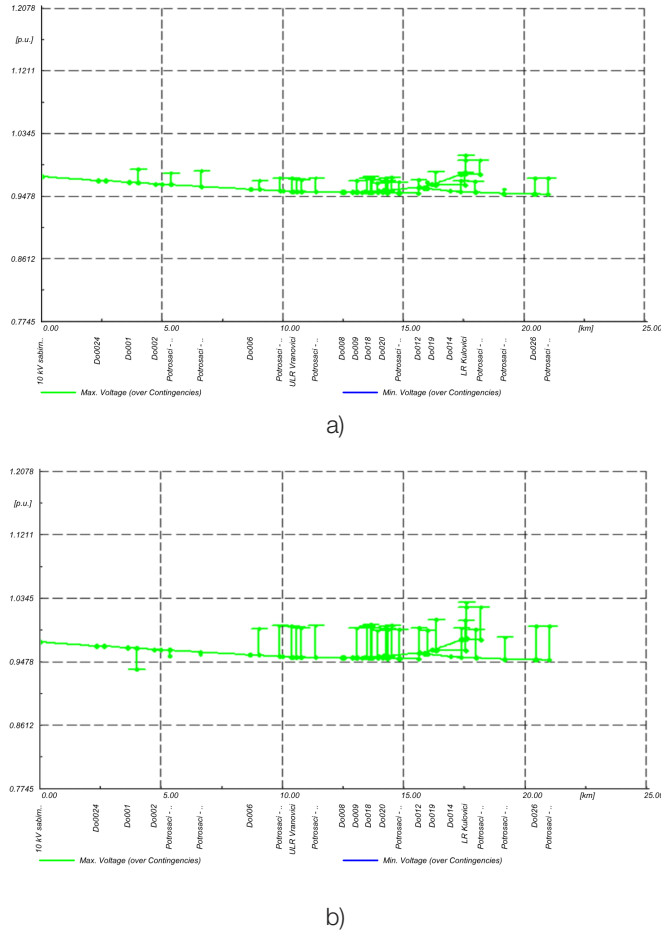


Figure 3: Voltage profile plot for first scenario: a) before optimization, b) after optimization

A slight voltage increase was noticed at the PV plant connection point, with voltages falling within the set limits after optimization. Compared to the baseline scenario, the voltage levels were higher, especially towards the network's end where the PV plant was linked, and all voltages remained within acceptable boundaries.

2.3. Second Scenario – 2 MW Solar PV Plant on the Network's End

This scenario evaluated a 2 MW PV plant connected at the end of the network. The results showed modest voltage increases within authorized limits, with total active and reactive losses of 0.15 MW and 0.16 MVar. Prior to optimization, there were repeated voltage reductions

towards the end of the feeder that were less than the allowed limit of 0.9 p.u. in the consumption case. At the point where the PV plant is connected to the grid, there is a slight rise in voltage that may be detected. Optimization calculations helped to find the best combination of tap positions to eliminate critical voltage drops, with all voltages within specified limits after optimization. Importantly, the voltages were considerably increased compared to the baseline scenario, particularly at the site where the PV plant was connected. The larger capacity of the 2 MW plant contributed to this voltage increase, reducing the reliance on distant sources and thereby reducing line losses.

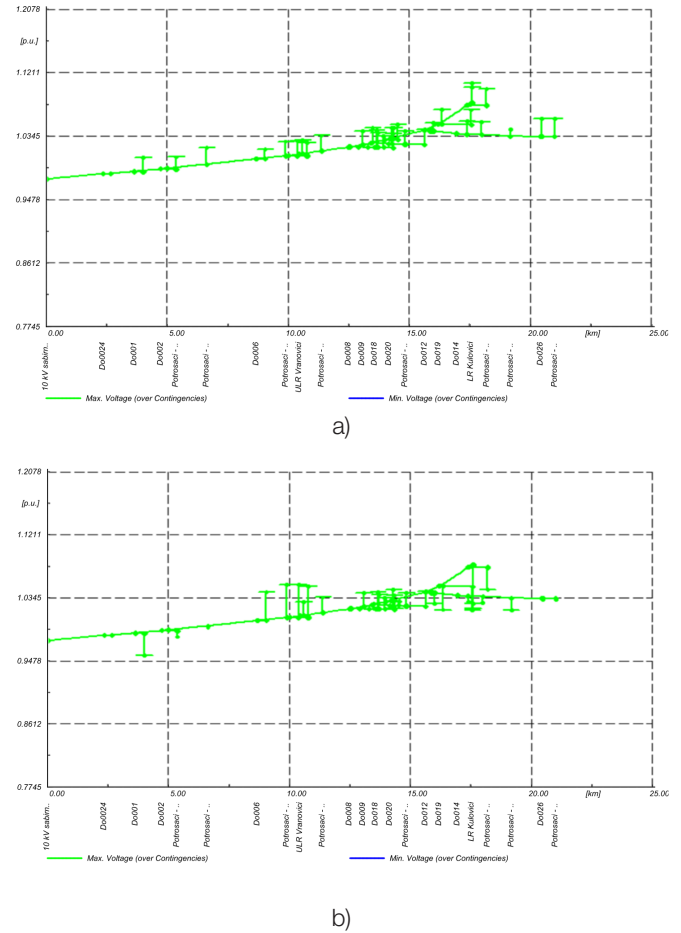


Figure 4: Voltage profile plot for second scenario: a) before optimization, b) after optimization

2.4. Third Scenario – 3 MW Solar PV Plant on the Network's End

This scenario involved a 3 MW PV plant at the network's end. When contrasted with the baseline scenario, which exhibited multiple voltage drops and generally low voltage levels, this arrangement presented a significant shift. The load flow study identified numerous voltage rises, some surpassing the 1.1 p.u. limit, with active and reactive losses of 0.39 MW and 0.32 MVar, respectively. Voltage Profile Optimization revealed that there were several critical voltage drops in the analysed consumption case and a few

instances of critical voltage rises in the production case. A significant increase in voltage level can be noticed at the point where PV plant is connected to the grid. However, despite optimization efforts, some lines remained overloaded. The notable surge in voltage at the PV plant's connection is a direct outcome of its vast 3 MW output, which significantly overshadows the network's consumption. This imbalance results in excessive production, leading to the heightened voltage levels observed. Optimization revealed that there were several critical voltage drops in the analysed consumption case and a few instances of critical voltage rises in the production case. A significant increase in voltage level can be noticed at the point where PV plant is connected to the grid. However, despite optimization efforts, some lines remained overloaded. The notable surge in voltage at the PV plant's connection is a direct outcome of its vast 3 MW output, which significantly overshadows the network's consumption. This imbalance results in excessive production, leading to the heightened voltage levels observed.

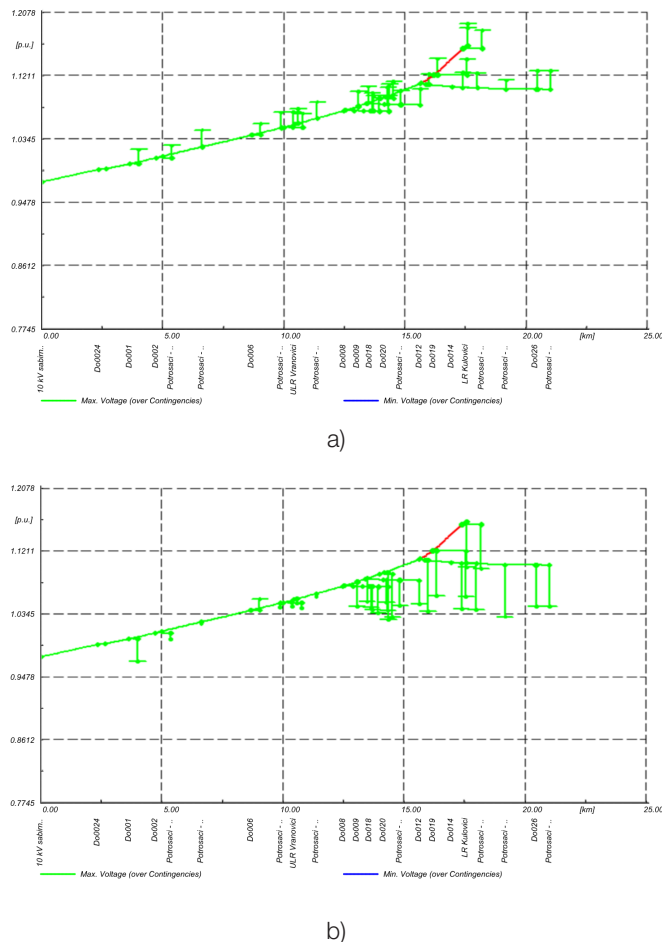


Figure 5: Voltage profile plot for third scenario: a) before optimization, b) after optimization

2.5. Fourth Scenario – 1 MW Solar PV Plant at the Network's Midpoint

In the fourth scenario, a 1 MW PV plant is integrated at the network's midpoint. Compared to the baseline scenario,

which had pronounced voltage drops, this arrangement results in slightly elevated voltage levels, a consequence of positioning the PV plant centrally in the network. Despite minor voltage drops, the system remains largely within the permissible limits. The recorded active and reactive losses, at 0.07 MW and 0.10 MVar respectively, are comparable to those observed in the first scenario, where the PV plant was sited at the network's end. After Voltage Profile Optimization, a few minor critical drops are identified with no significant rises, and most transformer tap settings are optimized to the "2" position. Following optimization, the voltage profile consistently remains within the acceptable range.

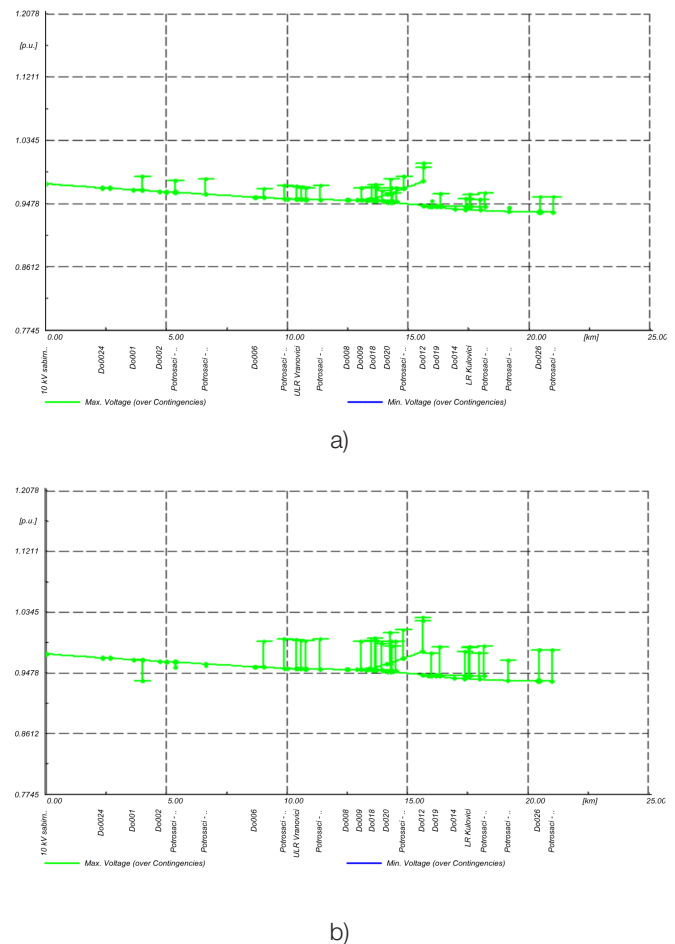
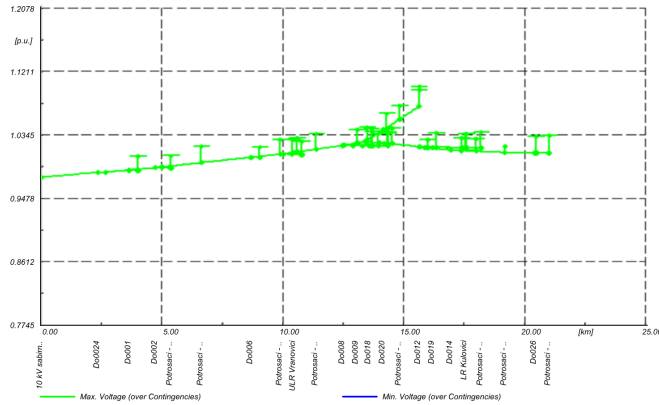


Figure 6: Voltage profile plot for fourth scenario: a) before optimization, b) after optimization

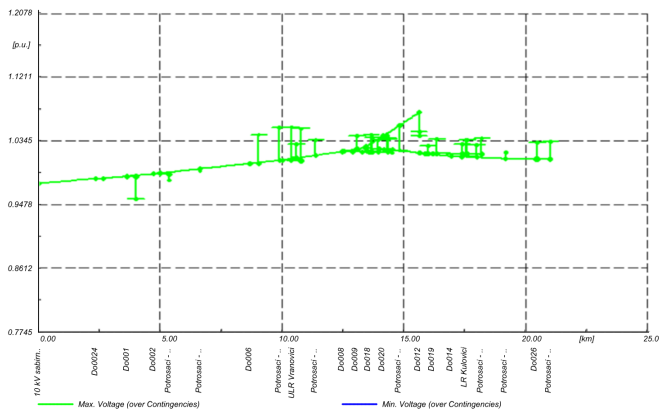
2.6. Fifth Scenario – 2 MW Solar PV Plant at the Network's Midpoint

In the fifth scenario, which centres on the integration of a 2 MW PV plant midway through the network, there's a noticeable yet permissible increase in voltage levels compared to the baseline scenario. While the active and reactive losses, amounting to 0.15 MW and 0.16 MVar respectively, are marginally higher than those in the first and fourth scenarios, they align closely with the results from the second scenario, where the 2 MW PV plant was connected at the network's end. Voltage Profile

Optimization identifies certain critical voltage drops, yet no instances of voltage rises. By adjusting the transformer tap positions optimally, these drops are effectively mitigated. Post-optimization, the voltage profile plot confirms that all voltage levels remain consistently within the accepted bounds.



a)



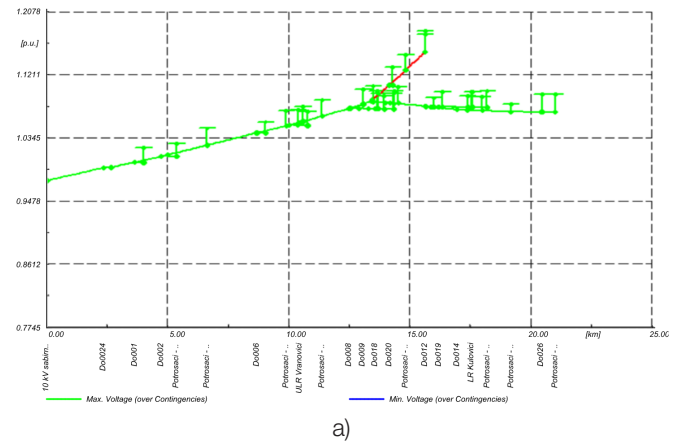
b)

Figure 7: Voltage profile plot for fifth scenario: a) before optimization, b) after optimization

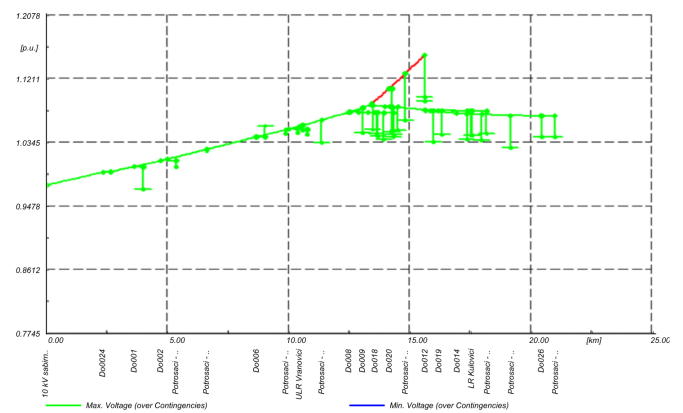
2.7. Sixth Scenario – 3 MW Solar PV Plant on the Network's Midpoint

In the sixth scenario, which evaluates the impact of a 3 MW PV plant connection, there's a pronounced increase in voltage levels, with some even crossing the 1.1 p.u. threshold, especially when compared to the baseline scenario. This marked rise in voltage levels is attributed to the substantial mismatch between the production, which is at 3 MW, and the network's consumption, roughly around 1.2 MW. Such a discrepancy leads to more pronounced voltage elevations than those observed in the third scenario, where the same 3 MW PV plant was connected at the network's end. The scenario results in active and reactive losses of 0.38 MW and 0.30 MVar, respectively, higher than in previous scenarios. Through Voltage Profile Optimization, both critical voltage drops and spikes are identified. Despite the optimization adjustments, including modifying transformer tap positions, the voltage profile

plot continues to display certain voltage increases and line overloads.



a)



b)

Figure 8: Voltage profile plot for sixth scenario: a) before optimization, b) after optimization

2.8. Results Comparison

An examination of the graphs representing the bus voltage in per unit (p.u.), shown in Figure 9. and Figure 10., unveils some critical observations:

- 1) *Baseline Scenario*: The scenario with no PV connection yielded the lowest voltage levels, serving as a reference for further analysis.
- 2) *3 MW Connection*: Conversely, the scenarios with the 3 MW PV power plant connected to the grid exhibited the highest voltage levels, a direct result of the imbalance between generation and load.
- 3) *Impact of Excess Generation*: The scenarios with higher PV injections logically led to increased voltage levels. This phenomenon emerges primarily due to excess power generated that the connected loads cannot consume. Such surplus power fed back into the grid elevates the voltage levels, notably near the connection points, as evidenced in the corresponding graphs.
- 4) *Potential Mitigation*: A partial remedy for this problem might be found in tasking the PV system with injecting reactive power alongside active power, thereby harmonizing the voltage profile.

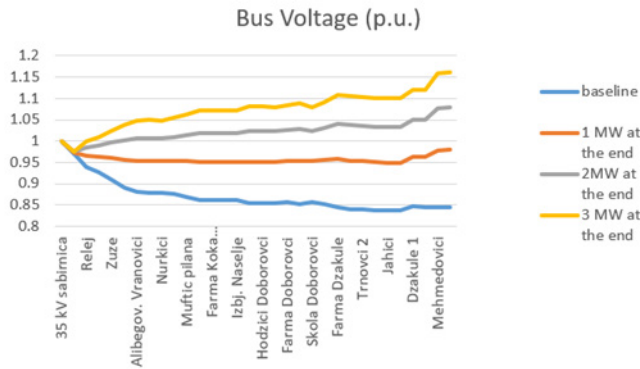


Figure 9: Power flow analysis: Bus voltage, scenarios with PV plants connected at the end of the feeder

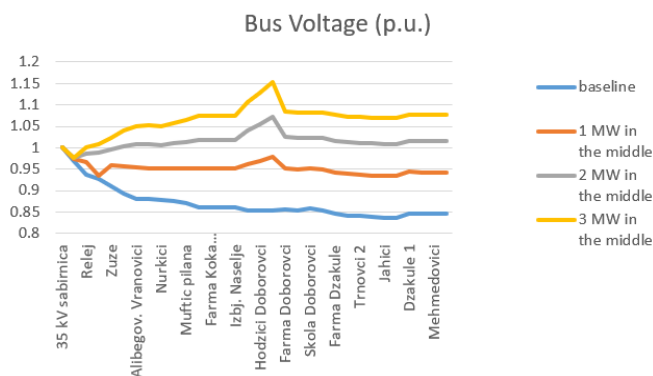


Figure 10: Power flow analysis: Bus voltage, scenarios with PV plants connected at the midpoint of the feeder

Our study of the graphs depicting the total active (shown in Figure 11.) and reactive losses (shown in Figure 12.) in the network allows for the following inferences:

- 1) *Location Invariance*: The position of the PV plant, whether in the middle or at the end of the network, displayed no significant variance in losses.
- 2) *1 MW PV Plant Efficiency*: The connection of a 1 MW PV plant marked the point of minimum total active and reactive losses. It is deducible that the reduced load, attributed to the generated power from the PV plant, led to this efficiency. Given that the overall load of the network was close to 1.2 MW, a photovoltaic (PV) generation capacity of 1 MW was nearly in balance with this load. This near-equilibrium condition contributed to a reduction in power losses within the system.
- 3) *3 MW Connection Challenges*: Conversely, the 3 MW connection demonstrated a potential increase in both active and reactive losses, a consequence of the mismatch between supply and demand. This scenario underscores the challenges in managing large-scale PV connections.

Looking forward, the scope of this research can be significantly broadened by extending our analysis from mere power losses to a more comprehensive study of energy losses. This approach would entail detailed examinations

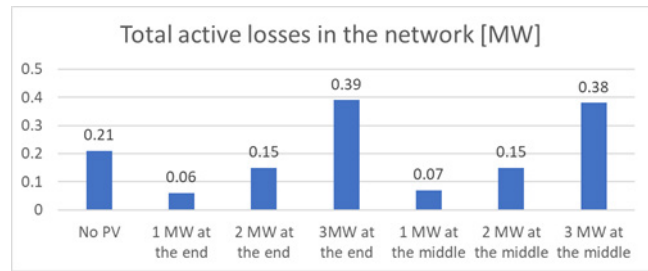


Figure 11: Power flow analysis: Total active losses in the network [MW]

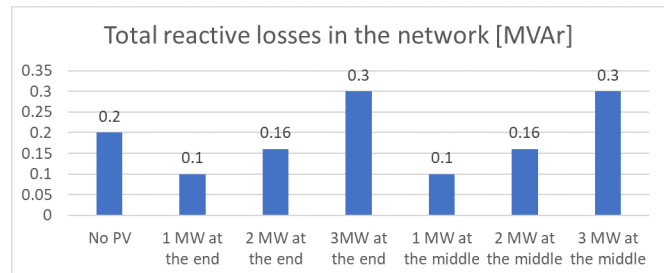


Figure 12: Power flow analysis: Total reactive losses in the network [MVar]

of energy flow within the grid at finer intervals, such as every 15 minutes or hourly. While this granularity promises a deeper understanding of the grid's efficiency, especially in the face of fluctuating demand and renewable energy integration, it also brings forth the challenge of managing an immense volume of data generated from simulations — potentially 24 for each hour in a day. Automating these extensive calculations would require the utilization of advanced programming tools adding layers of both complexity and precision to our work. This expansion, though ambitious and outside the current project's scope, opens a pathway to unprecedented insights into the energy grid's operational dynamics, potentially leading to more robust and economically efficient grid management strategies in the future.

3. DISCUSSION AND CONCLUSIONS

The transition towards a sustainable and resilient energy framework necessitates an intricate understanding of distributed generation and its effect on the existing distribution network. This study embarked on an extensive examination of these effects, with a special focus on voltage profile optimization, utilizing the DlgSILENT PowerFactory toolkit.

Our exploration revealed multifaceted insights into the integration of distributed renewable energy, specifically photovoltaic (PV) plants. The findings can be summarized as follows:

- 1) *Positive and Negative Effects*: PV integration can bring about both enhancements and challenges to the network, making the decision on placement and size vital in minimizing power losses and refining the voltage profile.

- 2) *Limits on Loss Reduction*: The results of this study indicated that the expected reduction in power losses through distributed generation doesn't occur invariably. It was noted that achieving substantial loss reduction is contingent on the specific rating and location of the units. Minimal losses are attained when the generated power is roughly equal to the load. Additionally, key insight revealed that power loss reduction can only be realized up to certain thresholds in rating and placement of the distributed generation unit. Beyond these, there may even be detrimental effects leading to heightened power losses.
- 3) *Balance of Supply and Demand*: Striking an optimal balance between energy supplied by PV generation and that demanded by the loads emerged as a cardinal principle. This balance is instrumental in mitigating the negative impacts of PV plants.
- 4) *Dependence on Rating, Location and Power Factor*: The strategy for implementing distributed generation needs careful consideration of these factors to maintain stability and efficiency in the network.
- 5) *Future research direction*: An intriguing avenue for further research will be to explore dispersed distributed generation. This innovative approach may lead to lower line losses and reduced transmission distances, consequently lowering overall system losses.

In conclusion, this research provides a deeper understanding of how distributed generation interacts with existing networks. It emphasizes the fact that while integrating PV plants can offer significant advantages, it is a process that requires careful planning, thorough understanding of system dynamics, and a targeted approach.

As the world continues its shift towards renewable energy sources, the insights from this study can guide effective strategies for integrating renewable energy, ensuring resilient and efficient networks aligned with future energy demands. Future research in this direction may extend into exploring more advanced control strategies, smart grid integrations, and developing comprehensive models that simulate real-world complexities.

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