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OPTIMAL CAPACITOR PLACEMENT IN REAL DISTRIBUTION NETWORK WITH REACTIVE POWER SUPPORT OF DISTRIBUTED GENERATION

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Abstract: This paper investigates the strategic placement of capacitor banks in the distribution network of Gračanica, with a specific focus on the medium-voltage feeder Grades. The primary objective is to optimize voltage profiles, minimize power losses, and enhance the overall performance of the distribution network. The significance of this research lies in its thorough examination of optimal capacitor placement within the medium-voltage (MV) branch of distribution networks, specifically considering the intricate interplay between capacitor banks and MV branch components, underlining the necessity for informed decisions in the context of distributed generators (DG) integration to enhance overall network performance. The study further investigates the impact of integrating DGs on these objectives on capacitor placement in the MV feeder. Employing the DIgSILENT PowerFactory software tool for modelling the MV feeder and utilizing a genetic algorithm for capacitor placement optimization, the study underscores the robustness of this approach in handling various conditions and seeking optimal solutions. Simulation results demonstrate that strategically placing capacitor banks and integrating DGs can significantly improve the voltage profile and reduce power losses within the distribution system. The findings of this research support 2MVA of concentrated DGs at the middle of the line as the most efficient and most economically beneficial situation on the medium-voltage feeder Grades study case and contribute valuable insights, serving as a reference for future studies on optimal capacitor placement.

Keywords: capacitor banks, distributed generators, power losses, optimization, voltage profiles

INTRODUCTION

The installation of capacitor banks and the integration of distributed generators (DG) into distribution networks have become a key aspect of modern power systems. With the growing demand for electrical energy and the increasing use of renewable energy sources such as PV and wind power, it is essential to analyze and understand the impact of capacitor banks and DG on voltage and power profiles in distribution networks. The placement of capacitor banks plays a crucial role in improving the overall performance and efficiency of distribution networks. This study is focused on the impact of DG integration on voltage and power profiles, as well as its influence on the placement of capacitor banks within the distribution network.

In this paper optimal capacitor placement in the distribution network was investigated, with an emphasis on medium-voltage (MV) branches. The goal was to improve the voltage profile, minimize power losses, and optimize the costs of installed capacitors. Through a comprehensive analysis of optimization techniques, the authors demonstrated the effectiveness of their proposed approach by conducting a case study on a real MV branch. The results of this previous work provide a solid foundation for further research on DG integration in distribution networks and its implications for capacitor bank placement.

The MV branch, as a key component of the distribution network, requires precise modelling to gain insights into its behaviour and enable informed decision-making regarding design and operation. In this study, our focus remains on the MV branch but with a broader perspective that encompasses DG integration. The main objective of this research is to determine optimal locations for installing capacitor banks within the MV branch, considering various parameters such as load, system losses, voltage profiles, and technical specifications of branch components.

To address the challenge of optimal capacitor placement, this study formulates it as a mathematical optimization problem. By applying this technique, the proposed approach aims to provide efficient solutions and enhance understanding of the impact of capacitor placement on the performance of the MV branch under the influence of DG integration. The results obtained from the case study

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illustrate the effectiveness of the proposed optimization approach and offer valuable insights into the consequences of capacitor placement on the performance of the MV branch. These findings have significant implications for electrical engineers and researchers in the field of power systems, demonstrating the practical application of advanced optimization techniques to real-world problems.

This study emphasizes the importance of considering interactions between capacitor banks and MV branch components, as well as the impact of different operating conditions on optimal capacitor placement. Understanding these factors allows designers and operators of distribution networks to make informed decisions regarding DG integration and capacitor bank placement. Additionally, the results of this research provide a foundation for further studies in this area, highlighting the need for more comprehensive investigations into the impact of DG integration on the performance of distribution networks. This paper is written based on the published CIGRE National Committee of Bosnia and Herzegovina (BH K CIGRE) paper. [1]

After the introduction, Section 1 is used to have a view of the literature. The second section gives information about methodology which is divided into several subsections MV branch model, Modeling active and reactive loads in electrical power systems, Transformer tap changing modelling, Power flow analysis in DIgSILENT PowerFactory, Modeling capacitor banks in power systems, DG integration, Integration of concentrated DGs into the system. The DG integration subsection contains 4 case studies involving 1, 2, 3, and 5 MVAr DGs integration, while the subsection Integration of concentrated DGs contains 3 case studies involving integration beginning, middle, and end. Section 3 explains the results and involves discussion. In fourth section gives a conclusion about the whole process and results. The paper ends with references and the author's biography.

1. LITERATURE REVIEW

Optimal capacitor placement in real distribution networks with reactive power support of distributed generation is a critical aspect of enhancing system performance and efficiency. Several studies have contributed valuable insights to this area, shedding light on methodologies, techniques, and considerations for achieving optimal capacitor configurations.

The research about the optimal placement of capacitor banks in the real distribution network of Gračanica. Focusing on the medium-voltage supplier KO Grades and considering the impact of distributed generators, the study emphasizes improving voltage profiles, minimizing power losses, and enhancing overall network performance. Utilizing DIgSILENT PowerFactory and a genetic algorithm for optimization, the research provides a comprehensive analysis of the interaction between distributed generators and capacitor placement. [1]

Optimal capacitor placement in Power System Analysis offers insights into power system fundamentals. Its importance lies in providing a fundamental understanding of power system analysis, a crucial background for capacitor placement studies. It contributes to power systems engineering, offering additional foundational knowledge for understanding the broader context of power system dynamics and operations. [2][3]

Electric Power Distribution Handbook, offers insights into electric power distribution, which can be valuable for understanding the intricacies of distribution systems and the placement of reactive power support elements like capacitors. It also presents the Power Electronics Handbook, which may provide insights into power electronics aspects relevant to distributed generation integration and its impact on capacitor placement. [4][5]

Power System Analysis and Design contribute to understanding power system analysis, providing a theoretical foundation for optimal capacitor placement studies. It also specifically addresses optimal capacitor placement in distribution systems using genetic algorithms. The paper emphasizes loss reduction and voltage profile improvement, demonstrating the effectiveness of the proposed approach through an IEEE 33-bus distribution test feeder. [6][7]

Novel optimal capacitor planning (OCP) procedure for large-scale utility power distribution systems considers the minimization of total system active power losses, standard deviation of node voltages, and investment in total capacitor power rating. This study offers insights into the application of optimization methods for optimal capacitor placement in real large-scale utility circuits. [8]

The load profile's effect on shunt capacitor placement in radial distribution feeders highlights the importance of considering load variability in reducing power losses through reactive power compensation, acknowledging the computational challenges associated with such considerations. [9] While addressing optimal capacitor placement for loss reduction in a real power network, emphasizing economic minimization of loss and voltage enhancement. The optimization problem is solved using MATLAB and DIgSILENT PowerFactory in conjunction with Genetic Algorithm. [10]

Regarding this topic, Rauch's and Bruckl's paper has analyzed the role of industrial compensation systems to attain optimum reactive power compensation in distribution networks. Their work provides the real implementation approaches for the purpose of improving the grid's functionality. [12] In the same

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vein, Lin's et al. paper have made an assessment on a reactive power compensation approach of electric vehicles connected to distribution networks that could result in voltage constraints at extreme operating state. These researchers are finding out about the supportive role that electric vehicles assume on power grids and the related possibility of reactive power increase and preventing it. [13]

Guo's and Xu's paper addressed the field by introducing a couple of ways to enhance the grid-connected inverters photovoltaic multifunction miscellaneously for harmonic suppression and reactive power compensation. This study is focused on the close integration of renewable energy sources into the distribution systems and hence the innovation of easy reactive power management methodology. [14] To take advantage of renewable energy sources like wind farms in the balanced voltage-controlled system building, Liu's et al. paper proposed a cooperative control concept of the voltage to stabilize the power generation system depending on the reactive power reserves from the wind farms. Their actions indeed point to the necessity of considering coupling renewable energy sources together with grid management as a way of securing system reliability and strength. [15]

Blasco's et al. paper came up with an algorithm for the compensation with reactance of passive power in a three-phase four-wire system with unbalance using capacitors, which was aimed for line loss minimisation. This study will consequently facilitate the optimal design of power compensating techniques, especially in systems that exhibit frequency or voltage fluctuations, when the system conditions are in a balanced state. [16] Dirik's, and Gezegin's paper took up a task of hybrid compensator combining synchronous motor and switched capacitors that can offer reactive power compensation. This study, in turn, contributes with a new method to handle reactive power requirements required in transmission systems having the positive effect of increasing system efficiency and stability. [17]

The latest developments in the reactive power compensation domain portray the depth of the research goings-on. This characterization comes from the fact that many methods and technologies are present in the process and they all move towards achieving a high-quality grid, which is reliable, efficient, and can withstand any challenge, including changing operational conditions and rapid renewable energy integration. [12] [14] Improving the voltage profile and active power loss in electrical power distribution systems through optimal capacitor placement is done using genetic algorithms. The study employs loss sensitivity analysis and GA, demonstrating a multi-purpose goal function for the simultaneous reduction of losses and improvement of the voltage profile. [11]

2. METHODOLOGY

2.1. MV branch model

The electrical distribution system is a complex system that requires a thorough understanding of its components and their interactions to ensure reliability and efficiency. One of the key components in the electrical distribution system is the MV branch, responsible for transmitting electrical energy from the MV substation to end-users. To analyze and optimize the performance of the MV branch, it is necessary to develop a mathematical model that represents its behaviour. [4] The MV branch model should include all components involved in the transmission of electrical energy, including the substation, branch cables, transformers, and users. The model should also take into account the electrical characteristics of components, such as the resistance, inductance, and capacitance of branch cables and transformers. The most commonly used method for modeling the MV branch is the lumped parameter model. In this model, the branch is divided into several segments, with each segment treated as a lumped parameter representing the electrical characteristics of that segment. Lumped parameters are then used to represent the resistance, inductance, and capacitance of branch cables and transformers. [5] Another important aspect of the MV branch model is representing the electrical load on the branch. Electrical load is represented by the demand for electrical energy from end-users, which can vary throughout the day. The load profile can be estimated based on historical data or measured in real time using smart meters or other monitoring devices. Once the mathematical model of the MV branch is developed, it can be used to analyze the branch's performance under different conditions. One of the key advantages of using a mathematical model for MV branch analysis is that it allows the evaluation of various scenarios and operational situations. [3] Based on the defined tasks, the first step is to model the part of the Gračanica network powered by the Grades branch shown in Figure 1 in the DIgSILENT PowerFactory application solution. All necessary data is provided by Public Enterprise Electric Utility of Bosnia and Herzegovina d.d. - Sarajevo and bus data is used to create buses with their nominal, minimum, and maximum voltages, bus types, and parameter names.

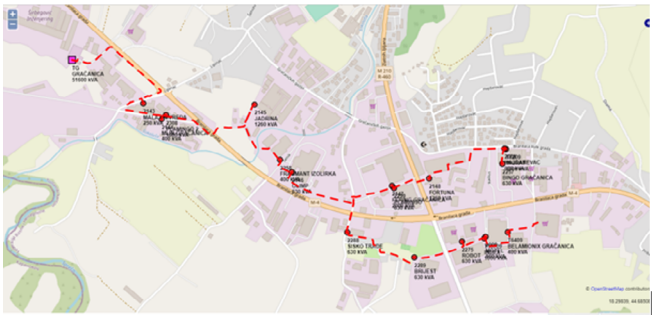


Figure 1: Part of the network for modelling

2.2. Modeling active and reactive loads in electrical power systems

Active and reactive loads play a crucial role in determining system performance. A complete understanding of the behaviour of active and reactive loads is essential for optimizing the performance of electrical power systems. Real data on active and reactive loads provided by JP Elektroprivreda BiH d.d. – Sarajevo were used for analysis. Power flow analysis is a tool for modelling the behaviour of active and reactive loads in electrical power systems. This method involves using mathematical models to represent system behaviour under different load conditions and analyzing the impact of changes in consumption profiles, the addition of new loads, and other factors on system performance. [1] In power flow analysis, active and reactive loads are modelled as combinations of resistive, inductive, and capacitive elements. The resistive component of the load represents the active power consumed by the load, while the inductive and capacitive components represent the reactive power consumed by the load. The impedance of each load is modelled as a complex quantity that includes both resistance and reactance. [3] Load data is used to create loads in the network configuration with names, nominal voltage, active and reactive power, and current. After completing the modelling, the network model of the Gračanica system part that will be analyzed in the following is obtained.

2.3. Transformer tap changers modeling

In electrical power systems, accurately modeling tap changers for transformers is essential for understanding system behavior and performance. Tap changers, vital components of transformers, allow adjustment of output voltage in response to load changes. Various approaches, including mathematical and simulation methods, are employed for modeling. Mathematical models, using tools like differential equations, aid in analyzing performance and optimizing control parameters [3]. Simulation models, through computer simulations, offer real-time insights into behavior. Precise modeling requires understanding tap changer mechanics, their system interactions, and accounting for load variations [1]. Considering different control strategies is crucial, impacting voltage regulation and energy losses. Assessing performance under various conditions is necessary for optimal strategy selection [1]. Operating conditions, especially load variations, significantly influence tap changer behavior [4]. Modelling tap changers for each transformer is done based on transformer data indicating +2.5% additional voltage per tap. It was necessary to create -2 and +2 taps to meet project criteria, with 5 tap positions, and set the tap position to 1.

2.4. Power flow analysis in DIgSILENT PowerFactory

Power flow analysis is a vital tool in electrical engineering, examining system behavior and states under diverse operating conditions. Its purpose is to compute steady-state voltage and current values at each network node, along with power flow through branches. This data helps identify and address issues like voltage stability, overloads, and energy losses. DIgSILENT PowerFactory, a widely used software, excels in modeling intricate networks with multiple voltage levels and diverse components like transformers, generators, loads, and capacitor banks [1]. To conduct power flow analysis in DIgSILENT PowerFactory, engineers create a system model using data from utilities. This model includes electrical parameters for components, and numerical methods like Newton-Raphson are applied for analysis. Results aid in tasks such as determining voltage profiles, identifying critical nodes, assessing load or generator impact, and optimizing capacitor bank installations for enhanced voltage regulation and reduced energy losses [2]. The software provides engineers and technicians with a robust platform for analyzing, designing, and optimizing power systems. Observing the modelled system after analysis, it can be noted that end-users (farther from the source) have a voltage of 0.92 p.u. at their buses, barely within the range of 0.9 to 1.1 p.u. voltage in distribution networks. This phenomenon is caused by voltage drop from previous loads in the network. Voltage drop occurs in the power distribution system due to the flow of current through the impedance of the network lines and transformers. This results in a reduction in voltage along the distribution lines, affecting the operation of devices connected to it. This is particularly relevant for distribution systems located far from the substation with long feeder lines. Loads such as motors, lighting, and transformers can cause a significant voltage drop, reducing power quality and leading to equipment failures and malfunctions. To mitigate voltage drops and improve system performance, proper load management and the implementation of voltage regulation devices, such as capacitor banks, are crucial, as further discussed in the paper.

The overall system report shown in indicates that the load requires 3.42 MW of active power and 3.66 MVAr of reactive power. Additionally, the external grid supplies the network with 3.54 MW of active power and 4.19 MVAr of reactive power, with the network itself experiencing losses of 0.13 MW and 0.93 MVAr of active and reactive power as shown in Table I.

Table I: Load flow system report (supply, demand, and losses)

	Active power [MW]	Reactive power [MVAr]
Supply	3.54	4.19
Demand	3.42	3.66
Losses	0.13	0.93

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2.5. Modeling capacitor banks in power systems

Capacitor banks play a pivotal role in power systems, offering significant benefits in power quality and energy efficiency. Precise modeling of capacitor banks is essential for effective system design, operation, and control. The choice of an appropriate representation for capacitors is crucial during modeling, and various types exist, each serving specific purposes. Ideal capacitors are the simplest, suitable for basic power system analysis but lacking in accuracy. Constant voltage capacitors offer greater complexity, providing more accurate analyses of power systems. They represent capacitors as electro-thermodynamic components with predetermined voltage and current values. On the other hand, constant current capacitors, the most intricate type, are utilized for advanced power system analyses, presenting capacitors with predetermined current values and losses. This complexity allows for a detailed analysis of the performance and characteristics of capacitor banks [3][4].

DIgSILENT PowerFactory utilizes advanced modeling techniques for capacitor banks. The software employs electro-thermodynamic models with predetermined voltage and current values, similar to constant voltage capacitors, ensuring a more accurate representation of the physical behavior of capacitor banks. This advanced modeling capability enhances the software's effectiveness in conducting detailed analyses of power systems involving capacitor banks. It contributes to its reputation as a comprehensive tool for power system analysis and optimization.

Table II shows the proposed capacitor banks automatically assigned by the DIgSILENT PowerFactory algorithm installed at 10 kV bus numbers 5 and 16 in the network model. Both capacitors have an installed reactive power of 1 MVAr, covering part of the reactive power requirements.

Table II: Arrangement of capacitor banks for the case without DG

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	10	5	1
2	10	16	1
		ΣC	2

From the power flow analysis (Figure 2), it can be concluded that end-users who previously had a voltage of 0.92 p.u. now have a voltage of 0.94 p.u. at their buses after optimization. All other buses along the lines have higher voltage values, which is a more favourable condition compared to the previous state. The overall system report indicates that power losses before optimization amounted to 135,918.26 BAM. After optimization, they are 113,993.81 BAM annually, assuming an average price of 0.1225 BAM/kWh, representing the average price of electricity for losses according to the Operator of distribution systems unless otherwise defined by a contract with the supplier. Based on the difference of 21,924.45 BAM annually, it can be concluded that by installing capacitor banks in the model network, we have improved the quality and efficiency of the system, reduced losses, and thus achieved a financial benefit.

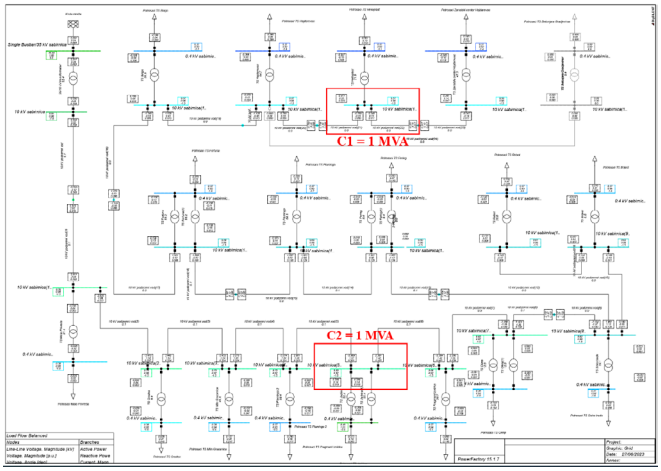


Figure 2: Capacitor bank arrangement in the studied network

2.6. DG integration

The integration of dispersed DG into the power system represents a transformative shift in the way electrical energy is generated and consumed. The concept of dispersed DG refers to a decentralized approach where numerous small-scale production units, such as rooftop PV panels, small wind turbines, or microgrids, are interconnected throughout the distribution network. This approach brings numerous advantages and considerations for the efficient and reliable operation of the system. One key advantage of integrating dispersed DG is the potential for improved flexibility and system adaptability. By dispersing production resources throughout the network, the system becomes more resilient to disturbances and capable of withstanding unforeseen events. If a specific DG unit or part of the network experiences a disruption, other units can continue supplying electrical energy, reducing the impact on consumers, and enhancing system reliability. [3] Additionally, the integration of dispersed DG can contribute to load balancing and voltage regulation within the distribution system. Production units located near the served loads can help mitigate voltage fluctuations and minimize losses that occur during transmission over long distances. This localized production reduces the need for expensive infrastructure upgrades and promotes the efficient use of network resources. [4] The integration of dispersed DG plays a crucial role in supporting the integration of renewable energy sources into the grid. Energy production from renewable sources, such as PV and wind, is often variable and intermittent. The dispersal of DG units throughout the system can smooth

out fluctuations in renewable production, enabling better integration of these variable resources into the overall energy mix. This helps reduce dependence on conventional fossil fuel-based production and promotes a cleaner and more sustainable energy system. The integration of dispersed DG can lead to increased engagement and participation of consumers in the energy system. The ability to generate their electricity makes consumers active participants rather than passive energy recipients. [4] This empowerment promotes energy efficiency, energy savings, and the adoption of smart grid technologies. Consumers can monitor and manage their energy consumption, optimize the operation of their DG units, and even participate in demand response programs, contributing to a more dynamic and interactive energy ecosystem. The integration of dispersed DG into the system also poses certain challenges that need to be addressed. The intermittency of renewable energy sources requires advanced forecasting and control mechanisms to ensure system stability and reliability. The coordination and management of different DG units throughout the system require sophisticated communication and control systems to optimize their operation and maintain network integrity. [5]

2.6.1. Case Study 1: 1 MVA DG Power and Optimal Capacitor Placement

The first case study in this research paper pertains to integrating 1 MVA dispersed DG into the system. The system includes 5 PV systems and 4 wind generators (synchronous machines) with a total power of 1 MVA and a power factor - cosφ = 0.95.

The optimal capacitor placement algorithm suggests integrating 7 capacitor banks with different capacities at different locations: C1=0.5 MVAr, C2=0.5 MVAr, C5=0.5 MVAr, C3, C4, C6, C7=0.1 MVAr, total ΣC=1.9 MVAr, as shown in Figure 3 and Table III. Before optimal capacitor placement, the system had losses of 98 055,21 BAM annually. After placement, the losses were reduced to 83,141.66 BAM, indicating that integrating capacitor banks at the proposed locations could result in an annual savings of 14,913.55 BAM in electricity costs, according to the overall system report.

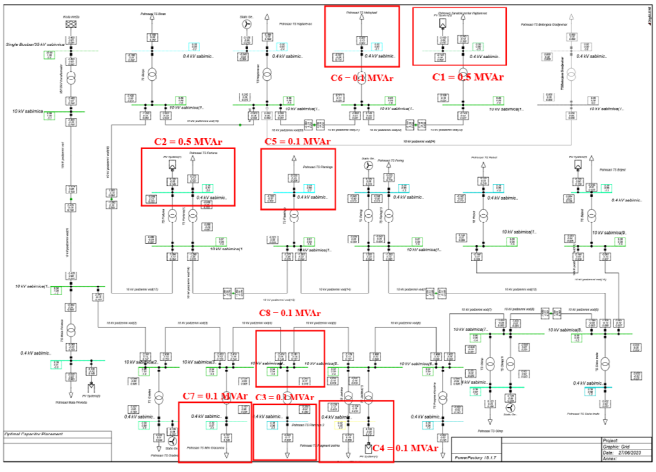


Figure 3: Arrangement of Capacitor Banks on the Target Network after Integrating 1 MVA DG

Table III: Arrangement of Capacitor Banks after Integrating 1 MVA DG

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	17	0.5
2	0.4	10	0.5
3	0.4	3	0.1
4	0.4	12	0.1
5	0.4	4	0.5
6	0.4	14	0.1
7	0.4	2	0.1
		ΣC	1.9

2.6.2. Case Study 2: 2 MVA DG Power and Optimal Capacitor Placement

The second case study in this research paper focuses on integrating 2 MVA dispersed DG into the system. The system includes 5 PV systems and 4 wind generators (synchronous machines) with a total power of 2 MVA and a power factor - cosφ = 0.95.

Table IV: Arrangement of Capacitor Banks after Integrating 2 MVA DG

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	17	0.5
2	0.4	10	0.5
3	0.4	3	0.1
4	0.4	2	0.1
5	0.4	12	0.1
6	0.4	14	0.1
7	0.4	4	0.1
8	10	5	0.1
		ΣC	1.9

The optimal capacitor placement algorithm suggests integrating 8 capacitor banks with different capacities at different locations: C1=0.5 MVAr, C2=0.5 MVAr, C3, C4, C5, C6, C7=0.1 MVAr, total ΣC=1.6 MVAr, as shown in Figure 4 and Table IV. Before optimal capacitor placement, the system had losses of 74,583.65 BAM. After placement, the losses were reduced to 63,741.10 BAM, indicating that integrating capacitor banks at the proposed locations could result in an annual savings of 10,844.55 BAM in electricity costs, according to the overall system report.

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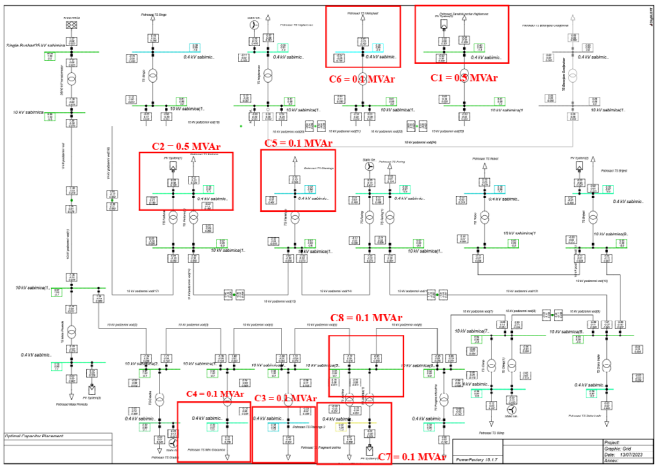


Figure 4: Arrangement of Capacitor Banks on the Target Network after Integrating 2 MVA DG

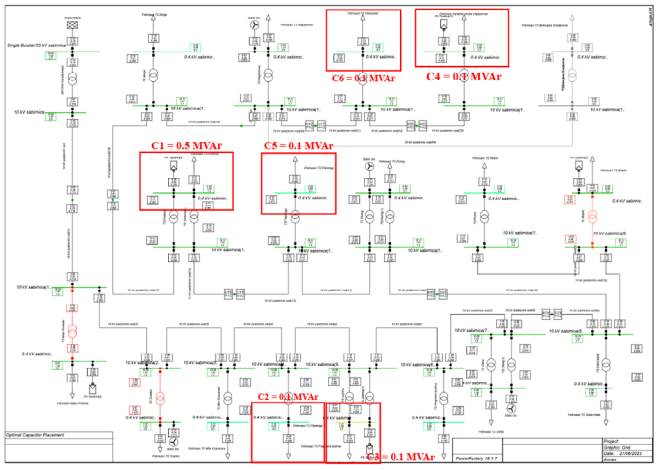


Figure 5: Capacitor Bank Allocation on the Targeted Grid after Integrating 3 MVA DG

2.6.3. Case Study 3: 3 MVA DG Power and Optimal Capacitor Placement

The third case study in this research focuses on integrating 3 MVA dispersed DG into the system. The system includes 5 PV systems and 4 wind generators (synchronous machines) with a total power of 3 MVA and a power factor - cosφ = 0.95. After the distributed generation is integrated into the grid, the next step is to calculate the load distribution to observe how distributed generation affects the system.

Table V: Capacitor Bank Allocation after Integrating 3 MVA DG

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	17	0.5
2	0.4	10	0.5
3	0.4	4	0.1
4	0.4	3	0.1
5	0.4	12	0.1
6	0.4	14	0.1
		ΣC	1.4

The optimal capacitor placement algorithm suggests integrating 6 capacitor banks of different capacities at various locations: C1=0.5 MVAr, C2=0.5 MVAr, C3, C4, C5, C6=0.1 MVAr, totalling ΣC=1.4 MVAr, as shown in Figure 5 and Table V. Before optimal capacitor placement, the system had losses of 68 079,59 BAM. After placement, the losses were reduced to 60 819,98 BAM, indicating that integrating capacitor banks at proposed locations could result in an annual saving of 7 259,61 BAM worth of electrical energy according to the overall system report.

2.6.4. Case Study 4: 5 MVA DG Power and Optimal Capacitor Placement

The fourth case study in this research involves integrating 5 MVA dispersed DG into the system. The system includes 5 PV systems and 4 wind generators (synchronous machines) with a total power of 5 MVA and a power factor - cosφ = 0.95. After integrating the distributed generation into the grid, the next step was to calculate the load distribution to observe how distributed generation affects the system.

Table VI: Capacitor bank allocation after integrating 5 MVA DG

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	10	0.5
2	0.4	3	0.1
3	0.4	4	0.1
4	0.4	17	0.1
5	0.4	14	0.1
6	0.4	12	0.1
		ΣC	1

The optimal capacitor placement algorithm suggests integrating 6 capacitor banks of different capacities at various locations: C1=0.5 MVAr, C2=0.5 MVAr, C3, C4, C5, C6=0.1 MVAr, totalling ΣC=1 MVAr, as shown in Figure 6 and Table VI. Before optimal capacitor placement, the system had losses of 105,771.31 BAM. After placement, the losses were reduced to 99,898.65 BAM, indicating that integrating capacitor banks at proposed locations could result in an annual saving of 5,872.66 BAM worth of electrical energy according to the overall system report.

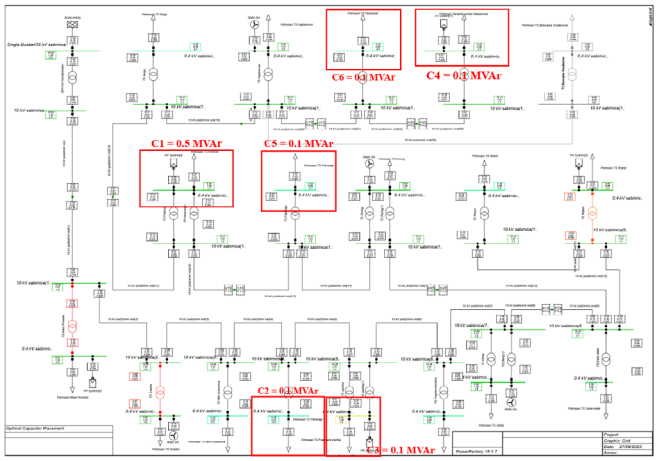


Figure 6: Capacitor Bank Allocation on the Targeted Grid after Integrating 5 MVA DG

2.7. Integration of concentrated DGs into the system

The integration of concentrated DG into the power system represents an alternative approach to traditional centralized electricity production. Concentrated DG involves deploying larger-scale production units, such as shared PV farms, small wind farms, or remote heating systems, strategically located in specific areas of the distribution network. This approach brings its advantages and considerations for the efficient and reliable operation of the system. [5] One of the fundamental advantages of integrating concentrated DG is the potential for economies of scale and optimization of resource utilization. By consolidating production resources at specific locations, the system can leverage the benefits of larger installations, such as increased efficiency, reduced costs per unit, and optimized operation and maintenance. This approach enables the efficient use of available land and resources, making it particularly suitable for areas with limited space or specific geographical advantages. The integration of concentrated DG can provide improved network support and system services. Larger-scale production units can be designed to provide ancillary services such as voltage regulation, reactive power support, or frequency control, crucial for maintaining system stability and reliability. [1] Integrating concentrated DG into the system requires addressing certain challenges. The transmission infrastructure may require reinforcement to accommodate the higher capacity of these larger-scale production units and ensure reliable energy delivery to the distribution network. Additionally, updating connection requirements, regulatory frameworks, and network codes is necessary to adapt to the unique characteristics and capabilities of concentrated DG installations. This ensures compliance with technical standards, effective grid connection, and fair compensation for injecting energy into the system. [6]

When integrating DG into the system, it is necessary to consider the Allowable Power Change Criterion (Rapid Voltage Change), which is one of the criteria that need to be analyzed. The selection of this criterion was made because it is often the eliminating factor until this analysis does not prejudge the need for a complete analysis when connecting DG. In our case, it is defined by the Technical Recommendation for the Connection and Operation of DG (TP-17), 4th edition, in the electricity distribution sector of the Public Enterprise Elektroprivreda BiH d.d. - Sarajevo. The allowed DG power, considering the rapid voltage change, ensures that during the connection/disconnection of DG, the voltage change at the connection point to the distribution network does not exceed:
Δu = 4% in the case of connection to the HV network
Δu = 5% in the case of connection to the MV network by the provision of the EN 50160 standard annex [L 15]:

Expressed about the DG power, verification of this condition is determined based on the following expression:

$$S_{nDG} \leq \Delta u \frac{S_{k3}}{k} \quad (1)$$

where:
S_{nDG} [MVA] - connected apparent power of DG or total connected apparent power of multiple generators if simultaneously connected to the network;
S_{k3} [MVA] - three-phase short-circuit power at the DG connection point to the distribution network;
Δu [%] - allowed rapid voltage change at the connection point during DG connection/disconnection and
$k = I_p/I_n$ - coefficient determined as the ratio of the connection current to the nominal generator current (k = 1 for synchronous generators and converters, k = 2 for asynchronous generators, and k = 8 in cases where I_p is unknown).

Referring to the equation, it was necessary to conduct a short-circuit analysis for 3 cases (DG at the beginning, in the middle, and at the end).

Table VII: Three-phase short-circuit power at the DG connection point to the distribution network

Connection point	Three-phase short-circuit power at the DG connection point [MVA]
Beginning ($Sk3_1$)	122.09
Middle ($Sk3_2$)	85.75
End ($Sk3_3$)	64.20

For the analysis, we use the same apparent power of DG at different locations, so we use the lowest value $Sk3_3$=64.20 MVA for application in Formula 2. DG with multiple synchronous generators must meet the following conditions:

$$\sum S_{nDG} \leq \Delta u \frac{S_{k3}}{k} \quad (2)$$

It can be concluded that the total connected apparent power $\Sigma S_{nDG} \leq$ 2.568 MVA, so we use the lower value ΣS_{nDG}=2 MVA for the connected apparent power of DG.

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2.7.1. Case Study 5: 2MVA DG Power at the Beginning of the Line and Optimal Capacitor Placement

After integrating 2MVA DG power at the beginning of the line, load analysis and optimal capacitor placement were performed.

Table VIII: Arrangement of Capacitor Banks after Integrating 2 MVA DG at the Beginning of the Line

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	17	0.5
2	0.4	10	0.5
3	0.4	14	0.1
4	0.4	12	0.1
5	0.4	3	0.1
6	0.4	4	0.1
7	**0.4**	**15**	**0.1**
8	**0.4**	**6**	**0.1**
9	**0.4**	**11**	**0.1**
		ΣC	1.7

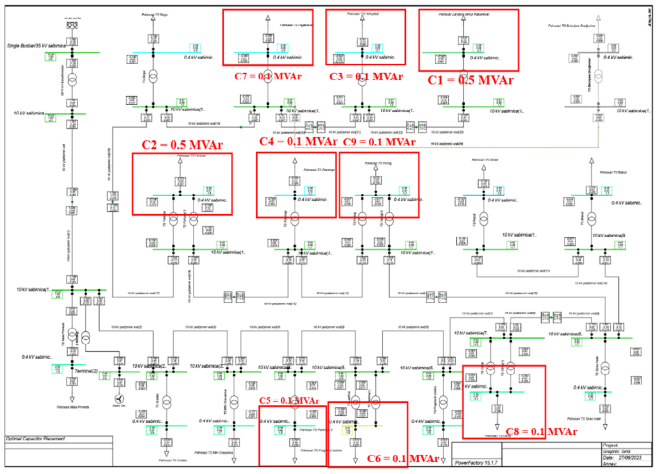


Figure 7: Arrangement of Capacitor Banks after Integrating 2 MVA DG at the Beginning of the Line

Optimal capacitor placement shows that it is necessary to integrate 9 capacitor banks: C1=0.5 MVAr, C2=0.5 MVAr, C3, C4, C5, C6, C7, C8, and C9=0.1 MVAr, total ΣC=1.7 MVAr, as shown in Figure 7 and Table VIII. Before optimal capacitor placement, our system had losses of 111,111.53 BAM. After placement, the losses were reduced to 95,804.84 BAM, indicating that integrating capacitor banks at the proposed locations could result in an annual savings of 15,306.69 BAM in electricity costs, according to the overall system report.

2.7.2. Case Study 6: 2 MVA DG Power in the Middle of the Line and Optimal Capacitor Placement

After integrating 2 MVA DG power in the middle of the line, load analysis and optimal capacitor placement were performed.

Table IX: Arrangement of Capacitor Banks after Integrating 2 MVA DG in the Middle of the Line

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	0.4	17	0.5
2	0.4	3	0.1
3	0.4	4	0.1
4	0.4	10	0.1
5	0.4	12	0.1
6	0.4	14	0.1
7	**0.4**	**2**	**0.1**
		ΣC	1.1

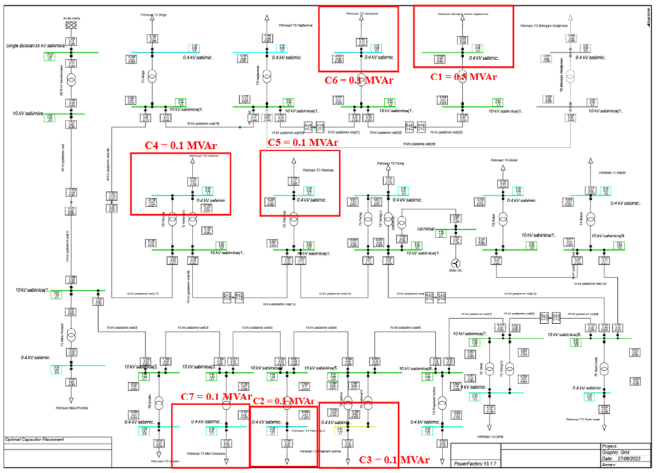


Figure 8: Arrangement of Capacitor Banks after Integrating 2 MVA DG in the Middle of the Line

Optimal capacitor placement shows that it is necessary to integrate 7 capacitor banks: C1=0.5 MVAr, C2, C3, C4, C5, C6, and C7=0.1 MVAr, total ΣC=1.1 MVAr, as shown in Figure 8 and Table IX. Before optimal capacitor placement, our system had losses of 67,787.54 BAM. After placement, the losses were reduced to 63,938.75 BAM, indicating that integrating capacitor banks at the proposed locations could result in an annual savings of 3,848.79 BAM in electricity costs, according to the overall system report.

2.7.3. Case Study 7: 2MVA DG Power at the End of the Line and Optimal Capacitor Placement

After integrating 2 MVA DG power at the end of the line, load analysis and optimal capacitor placement were performed. The results of the load analysis shown in Figure 9 indicate that the integration of concentrated DG into the system has a significant impact on the busbar and consumers where it is connected in terms of power and voltage profile. It also has a significant impact on the voltage and power profile on other 10 kV and 0.4 kV busbars in the system.

Optimal capacitor placement shows that it is necessary to integrate 3 capacitor banks: C1, C2, and C3=0.1 MVAr, total ΣC=0.3 MVAr, as shown in Figure 9 and Table X. Before optimal capacitor placement, our system had losses of 163,858.17 BAM. After placement, the losses were reduced to 163,128.71 BAM, indicating that integrating capacitor banks at the proposed locations could result in an annual savings of 729.46 BAM in electricity costs, according to the overall system report.

Table X: Arrangement of Capacitor Banks after Integrating 2 MVA DG at the End of the Line

Serial No.	Voltage Level [kV]	Busbar No.	Installed Power [MVAr]
1	10	GrSp1	0.1
2	0.4	3	0.1
3	0.4	4	0.1
		ΣC	0.3

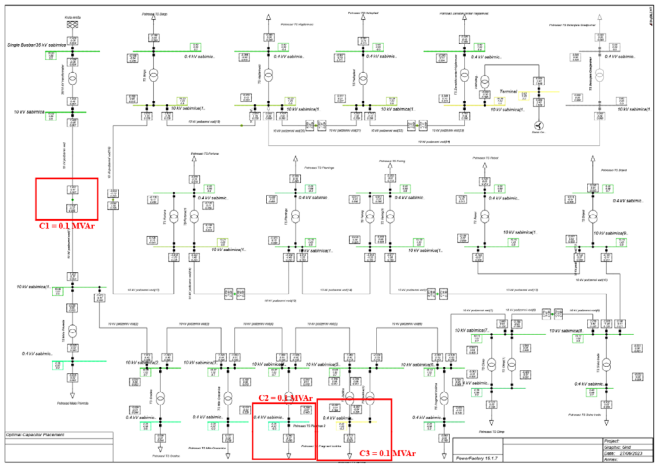


Figure 9: Arrangement of Capacitor Banks after Integrating 2 MVA DG at the End of the Line

3. RESULTS AND DISCUSSION

From case studies 1-4, it can be concluded that as the capacity of DG increases within the electrical distribution network, the need for reactive power compensation through capacitor banks noticeably decreases. This phenomenon can be attributed to the inherent characteristics of DG sources, especially those based on renewable energy sources such as PV panels and wind turbines. When DG units are connected to the distribution network, they exhibit favourable reactive power capabilities and act as local voltage regulators. As the capacity of DG increases, the reactive power supplied by these units becomes more significant, effectively compensating for reactive power requirements and reducing the load on capacitor banks. Consequently, the need for reactive power support from capacitor banks decreases, leading to a reduction in the level of required compensation. With the increase in DG power contribution, the demand for reactive power in the distribution network records a significant drop from 1.9 MVAr to 1.1 MVAr.

By comparing the case study involving 3 MVA integrated DG which demonstrates the lowest power losses within the distribution system with 5 MVA integrated DG it can be seen that before optimal capacitor placement, the system incurred losses of 68,079.59 BAM. However, after installing the proposed capacitor banks, losses were reduced to 60,819.98 BAM, resulting in annual savings of 7,259.61 BAM. In the last case, the system had higher losses of 105,771.31 BAM before optimal capacitor placement. After integrating capacitor banks at the proposed locations, losses decreased to 99,898.65 BAM, leading to annual savings of 5,872.66 BAM.

From case studies 5-7, it can be concluded that integrating 2 MVA DG in the middle of the distribution line shows the most efficient configuration in terms of minimizing power losses. Before optimal capacitor placement, the system incurred losses of 67,787.54 BAM. However, after integrating capacitor banks at the proposed locations, losses were reduced to 63,938.75 BAM, resulting in annual savings of 3,848.79 BAM. In comparison, integrating 2 MVA DG at the beginning of the line resulted in higher losses. Before optimal capacitor placement, the system recorded losses of 111,111.53 BAM, significantly higher than the case of placing DG in the middle of the line. After integrating capacitor banks at the proposed locations, losses were reduced to 95,804.84 BAM, resulting in annual savings of 15,306.69 BAM. The higher losses in this case can be attributed to the greater distance between the DG source and electricity demand, resulting in increased energy losses as energy travels through the distribution line with minimal demand. Similarly, integrating 2 MVA DG at the end of the line also resulted in higher losses. Before optimal capacitor placement, the system incurred losses of 163,858.17 BAM, and despite implementing capacitor banks at the proposed locations, losses remained relatively high at 163,128.71 BAM, resulting in savings of only 729.46 BAM annually. This configuration further emphasizes the importance of strategically placing DG sources closer to demand to minimize energy losses

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and enhance overall system efficiency. This reduction can be attributed to the dynamic nature of DG sources, such as their ability to inject/absorb reactive power instantly based on fluctuations in electricity production or demand. With increased production, DGs inject reactive power into the network, mitigating voltage variations and improving power factor.

The final observation is that when DG is integrated at the end of the line, it requires the least reactive power, for which only 3 capacitor banks with a total compensation of 0.3 MVAr are sufficient. In contrast, integrating DG at the beginning of the line requires a higher level of reactive power compensation, with the need for 1.7 MVAr power from capacitor banks. The most efficient configuration is when DGs are integrated into the middle of the line, requiring the least reactive power support from capacitor banks, with only 1.1 MVAr needed. This highlights the importance of reactive power support for optimal system performance and power loss reduction. Comparing the results of optimal capacitor placement for case study 2, which involves 2MVA distributed DGs, the algorithm suggests integrating eight capacitor banks, namely C1, C2 = 0.5 MVAr, C3-C7 = 0.1 MVAr, resulting in a total compensation of ΣC = 1.6 MVAr. Before optimal capacitor placement, the system had losses of 74,583.65 BAM. However, after integrating capacitor banks at the proposed locations, losses were reduced to 63 741,10 BAM, resulting in annual savings of 10,844.55 BAM. On the other hand, in case study 6, involving 2 MVA concentrated DGs, optimal capacitor placement requires integrating seven banks. These capacitor banks have power ratings of C1 = 0.5 MVAr, and C2-C7 = 0.1 MVAr, resulting in a total compensation of ΣC = 1.1 MVAr. Before optimal capacitor placement, the system incurred losses of 67,787.54 BAM. However, after integrating capacitor banks at the proposed locations, losses were reduced to 63,938.75 BAM, resulting in annual savings of 3,848.79 BAM.

Considering all study cases for comparison optimal cases from both dispersed and concentrated DG implementation can be drawn. The optimal cases for comparison would be 2 MVA DG integration dispersed and 2 MVA integration in the middle of the line. By comparing these two cases it can be concluded that implementing 2 MVA of DGs is more beneficial to the system as it requires less reactive support from capacitor banks which are implemented later on. These findings are important because they boost the performance of the MV feeder, including a reduction in system losses, improvement in voltage profile, and increased efficiency of the distribution network which leads to a more economically beneficent situation than another solution. This conclusion is important for studies that will be taken later on for implementation in real-life situations.

4. CONCLUSION

In this study, we presented a comprehensive investigation into the optimal installation of capacitor banks in a real distribution network, with a focus on the MV feeder. The primary research objective was to determine optimal locations for installing capacitor banks in the MV feeder, considering various parameters such as load, system losses, voltage profile, and technical specifications of feeder components. The case study results demonstrated the effectiveness of the proposed approach and provided a better understanding of the impact of capacitor bank installations on the performance of the MV feeder.

The study results indicated that the optimal placement of capacitor banks can significantly influence the performance of the MV feeder, including a reduction in system losses, improvement in voltage profile, and increased efficiency of the distribution network. Furthermore, the study results showed that the proposed approach could provide a better distribution of reactive power among different sections of the MV feeder, leading to a more balanced and reliable system.

One of the key advantages of the proposed approach is its ability to consider a range of parameters relevant to the design and operation of distribution networks, such as load, power factor, and voltage profiles. This allows for a balance between different performance metrics and the identification of the most economical solutions. This research highlights the importance of considering interactions between capacitor banks and MV feeder components, as well as the impact of different operating conditions on the optimal placement of capacitor banks.

The results of this research can be utilized to support further studies in this area and inform the design and operation of distribution networks, ultimately aiming to enhance the reliability and efficiency of these systems. Overall, this research makes a significant contribution to the field of power systems by demonstrating the feasibility and effectiveness of using advanced optimization techniques to address real-world challenges related to the placement of capacitor banks in distribution networks.

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