Scientific Research Publishing

Open Journal of Applied Sciences, 2025, 15(2), 501-516
https://www.scirp.org/journal/ojapps
ISSN Online: 2165-3925
ISSN Print: 2165-3917

Reconfiguration and Optimal Positioning of Multiple-Point Capacitors in a High-Voltage Distribution Network Using the NSGAII

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Abstract

The distribution networks sometimes suffer from excessive losses and voltage violations in densely populated areas. The aim of the present study is to improve the performance of a distribution network by successively applying mono-capacitor positioning, multiple positioning and reconfiguration processes using GA-based algorithms implemented in a Matlab environment. From the diagnostic study of this network, it was observed that a minimum voltage of 0.90 pu induces a voltage deviation of 5.26%, followed by active and reactive losses of 425.08 kW and 435.09 kVAR, respectively. Single placement with the NSGAII resulted in the placement of a 3000 kVAR capacitor at node 128, which proved to be the invariably neuralgic point. Multiple placements resulted in a 21.55% reduction in losses and a 0.74% regression in voltage profile performance. After topology optimization, the loss profile improved by 65.08% and the voltage profile improved by 1.05%. Genetic algorithms are efficient and effective tools for improving the performance of distribution networks, whose degradation is often dynamic due to the natural variability of loads.

Keywords

Reconfiguration, Capacitor Bank, NSGA II, Dynamic Network Degradation, Distribution Network Reliability

How to cite this paper: Oloulade, A., Agbokpanzo, R.G., Aza-Gnandji, M.R., Ibrahim, H.O., Gonda, M., Tokoudagba, E., Sétondji, J., Fifatin, F.-X. and Imano, A.M. (2025) Reconfiguration and Optimal Positioning of Multiple-Point Capacitors in a High-Voltage Distribution Network Using the NSGAII. *Open Journal of Applied Sciences*, **15**, 501-516.
https://doi.org/10.4236/ojapps.2025.152032

Received: November 12, 2024
Accepted: February 23, 2025
Published: February 26, 2025

1. Introduction

The optimization of electrical network topology represents a highly cost-effective solution, whether conducted manually or automatically by the network operator. It serves to enhance voltage quality at the busbars and curtail technical losses. In developing countries, where there is minimal automation of distribution networks, this operation is typically performed manually, with a number of consequences. These include overloads that exceed the rated capacity of the interconnecting cables and cascading faults that can potentially lead to a significant number of network failures. As cable cross-sections are typically not uniform due to the absence of standardization, reconfiguring the topology in this context can result in overloads on specific sections or overvoltages on underground lines that are both capacitive and long-distance, due to the low loads on certain sections. This phenomenon is known as the small Feranti effect.

In some areas, for example, several of Benin's national distributor networks have a radial structure, which means they cannot be operated flexibly when customers need to be re-supplied in the event of a disruption [1]. With the relentless growth in consumption and the very ambitious targets set by governments, utilities are constantly looking for effective and efficient tools to optimize their distribution networks and move towards zero outage targets for their customers. In most cases, operators therefore generally consider placing compensators in HV/HV source substations or in HV/HV distribution substations. Today, however, this approach is proving to be highly ineffective in coping with growing and variable network loads [1] [2]. In fact, the response time of the compensators installed in these source or distribution substations, as designed, does not respond effectively to the rapid variations in loads due to the use of more dynamic, non-linear and other types of ultra-linear loads. What's more, from the point of view of the specific reactive power flow to be compensated, the dispersion of the distribution networks is a limiting factor for their efficiency [2]. It has been observed that this positioning, which is not based on an analysis of the load dynamics, the load characteristics and the specific reactive flow to be compensated, can lead to unpleasant phenomena for the customers, such as overvoltages due to resonances, voltage dips that cannot be effectively corrected, and also the lack of an active and fast response of this dearly acquired equipment to manage the voltage deviations inherent in any network operation serving the subscribers [2] [3], Since time immemorial, scientists have been working to improve the performance of power systems and to eliminate avalanches of faults that are catastrophic and detrimental to maintaining a minimum level of reliability in a distribution system. The literature cites several authors who have proposed a variety of solutions that vary from one concept to another and from one operational experience to another, ranging from reconfiguration and compensation means such as capacitors, which are the most popular, to FACTS (DVR, DSTATCOM, SVC…).

In general, the process of reconfiguring a medium-voltage electrical network is associated with the search for a radial topology that allows the energy to be distributed in the most efficient and technically feasible way. Within this framework, in [4], Oloulade *et al*. [5] developed a Modified Ant Colony Algorithm (MACA) that combines ant colony and fuzzy logic to optimize the reconfiguration process. The results of this work were used to propose improvements to the network quality indicators of the national operator of Benin. In [6], Wishart, Michael, Ledwich, *et al*. have developed an algorithm to reconfigure rural feeders with satisfactory results.

In [7], Micheal *et al*. optimized the line cross-section and voltage profile of a long single-phase network with ground return using the genetic algorithm, with relevant results. In [8], a fast and efficient method for power flow analysis of radial distribution networks was developed. This method was tested and validated on 34-node and 69-node distribution networks. Based on the results obtained, it was concluded that the author had developed a tool for efficient optimization of distribution networks. In [9], the objective was to optimize the reconfiguration of a distribution network in the presence of distributed generation using intelligent techniques. In this work, the Fast Genetic Algorithm (FGA) is first used to determine the best network configuration, and then the implementation of the Differential Evolution Algorithm (DEA) ensures the selection of the optimal size of distributed generation. The main objectives are to minimize line losses, minimize voltage deviation, minimize violation of branch current limits, and minimize current imbalance. This compensation can be achieved using fixed-value capacitors or stepped capacitor banks with regulators (or automatic banks). The choice of compensation type depends on the size (power) of the capacitor. If the capacitor rating is less than 15% of the transformer rating, a fixed-value capacitor bank is selected. Otherwise, stepped capacitor banks are used.

In his thesis defended on 10, December 2019 [10], Olouladé proposed efficient distribution network performance tools. These tools were combined with compensators such as DSTATCOM, and were used to efficiently reconfigure a real 41-node distribution network. In this work, the optimization is performed using the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The first step will be to optimize the reconfiguration of the distribution network, taking into account the minimization of line power losses. Second, we will optimize the insertion of capacitor banks in the reconfigured network.

2. Overview of the Current Status of the Actual Distribution Network

The network studied here is that of an HTA feeder belonging to the aforementioned operator SBEE. It is a feeder from the Maria-Gléta source substation in Benin to a 161 kV/15kV transformer. The feeder is supplied at a voltage of 15 kV and comprises sixty-seven (67) MV/LV substations. The installed capacity on this feeder is 15.56 MVA or 14 MW, while the peak load on this feeder stabilises at around 6.2 MW, with an average load factor of 44.29%. It can therefore be concluded that it is theoretically underloaded. Conversely, there are 37 lightning arresters and 9 spark gaps. In the event of an atmospheric overvoltage, the surge arresters are liable to be the source of micro-interruptions due to the flow of discharge currents to earth. This is because these flows generate follow-up currents that short-circuit the two poles of the arresters, creating a single-phase phase-to-earth fault. In light of the considerable number of spark gaps in circulation and in consideration of the recommendations set forth in the NFC 11-201 standard, which stipulates the installation of lightning arresters on overhead transformers to safeguard against atmospheric overvoltages, it is anticipated that distributors will integrate the replacement of this technically and functionally obsolete equipment into a comprehensive and strategically coherent project aimed at addressing the challenges associated with enhancing the quality of supply to customers. Before optimizing any distribution network, it is imperative to check its electrical status in order to identify its vulnerable nodes or branches, which may or may not be locations for compensators, depending on the means to be used to optimize it. Power flow must precede all planning and design work on an electrical system. To this end, several methods exist, and given that the network under study is a distribution network, we have used the Backward Forward Sweep (BFS) method. The variant used is current and voltage injection, using the BIBC (Bus Injection to Branch Current) and BCBV (Branch Current to Bus Voltage) matrices [9]. As far as the state of active and reactive power flow is concerned, it's only through power flow. To better assess the electrical state of this HTA network, we applied a calculation tool based on the BIBC/BCBV algorithm implemented in MATLAB.

3. The BIBC/BCBV Power Flow Calculation Algorithm

The algorithm is based on forward and backward scanning and is implemented in a digital MATLAB environment.

```
Algorithm 1 POWER SCALING BY BFS METHOD
Step 1: Reading the data
    Reading network data:
    The node information matrix
    The branch information matrix
    the tolerance $\epsilon$ ($\epsilon = 1e-8$)
    Reading the nominal network voltage
    Reading the nominal power of the network
Step 2: Initialisation
    Initialisation of iterations, $k = 1$
    Initialisation of voltages at all nodes, $V_i^1 = 1$.
Step 3: Calculation of nodal currents
    Calculation of current injections at the various nodes using formula 2.14
Step 4: Backward Sweep
```

Continued

Calculation of branch currents using formula 2.15

Step 5: Forward sweep

Calculation of the new nodal voltages $V^{(k+1)}$ using formula 2.16

Step 6: Evaluation of the stopping criterion

Calculate the maximum deviation between the nodal voltage values of two consecutive iterations: $\Delta P_{\max} = \max\left(V^{(k+1)} - V^{(k)}\right)$

Check whether the maximum deviation is less than the tolerance ($\Delta P_{\max} \le \epsilon$)

If yes, go to Step 7.

If no:

Go to the next iteration, $k = k + 1$.

Return to Step 3.

Step 7: Perform the power balance

Step 8: Display the power flow solutions

4. Application of the BFS to Calculate the Electrical State of the MV Network

Table 1 presents the results of the initial calculation of the study network. As can be observed from the presented table, the lowest recorded voltage is identified at node 128 of the high-voltage network, with a value of 0.9 p.u. This is well below the standards stipulating that nodal voltages must be within ±5% of the nominal value, *i.e.* 0.95 p.u. to 1.05 p.u. The deviation is therefore 5.26%, which is outside the voltage wave quality standard. This calculation also shows that the active power losses are estimated at 425.08 kW and the reactive losses at 435.09 kVAR.

Table 1. Results of the calculation of the initial state of the study network.

Parameters	Values obtained
Vulnerability rate (Unstable nodes/total number of nodes)	80%
Vmin/Node (p.u.)/units	0.9/128
Active losses	425.08
Reactive losses	435.09
Financial losses due to losses	706,560 dollars US

The resulting loss rates are thus 6.24% for active losses and 12.33% for reactive losses. These loss rates exceed the permissible limits for an MV distribution network, as the power losses in an electricity distribution network must fall between 3% and 5%. The financial impact of these losses can be quantified using the following formula:

$$C_p = \tau * T * P_{loss} * C_{unit} \tag{1}$$

$\tau = 85\%$;

$T = 8760\ \text{h}$, annual duration in hours;

$P_{loss}(\text{kW})$: total active network loss;

C_{unit} = 125 F CF A/kwh: average unit cost of energy in Benin.

The application of this formula indicates that the estimated monetary loss is 706,560 US dollars.

Should this severely degraded state of the network persist for a decade without any enhancements being implemented, the resulting monetary loss would be a minimum of 706,560 US dollars. The company may then, on the basis of a well-developed project aligned with its strategic development objectives, recover the financial resources required to improve the system's performance by applying the principle that it can finance itself from the cash flow generated by reducing its technical losses. Subsequent to the simulation of the aforementioned MV feeder, the resulting voltage profile is illustrated in **Figure 1**.

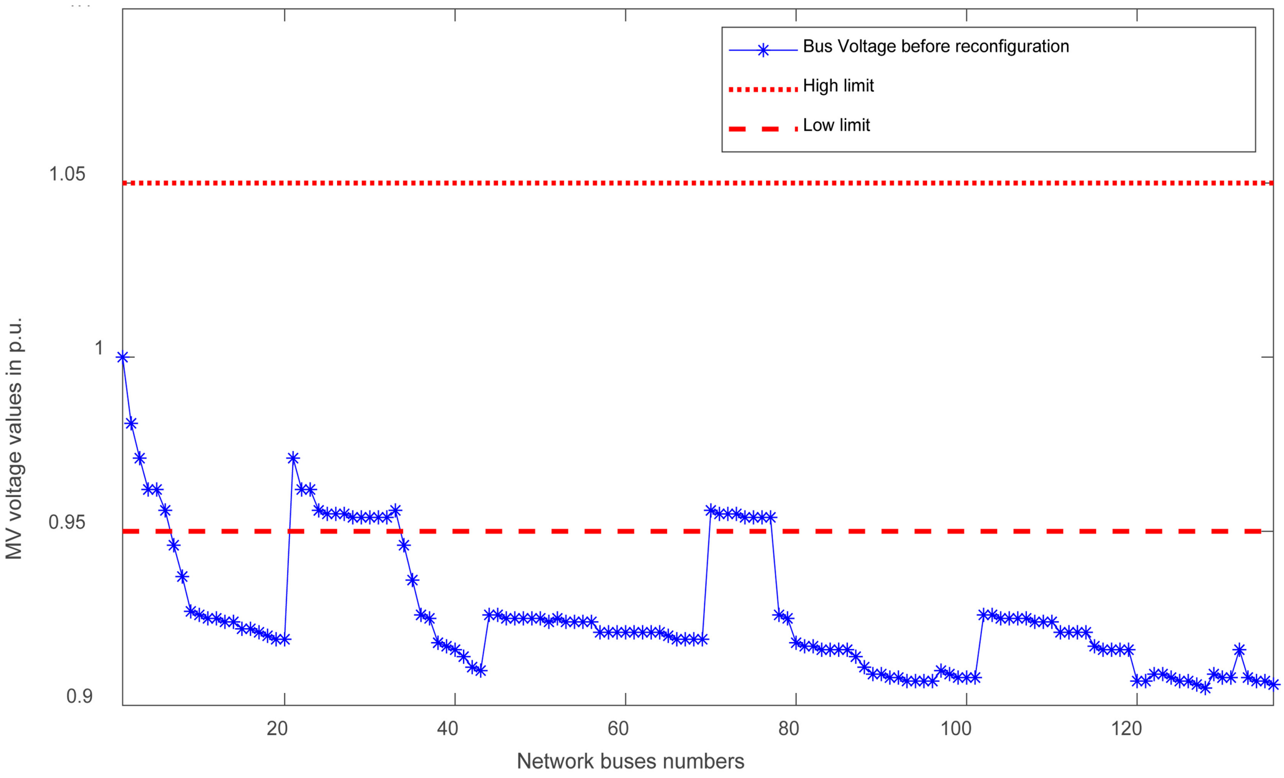

Figure 1. Voltage profile in the MV network before reconfiguration.

An examination of this figure reveals that the voltage profile is severely degraded, with a vulnerability rate of 80%, indicating that 125 nodes are in violation. The electrical state of this SBEE HTA feeder is severely compromised. The majority of the voltages have been exceeded, resulting in significant and excessive losses. The operation of this network gives rise to high operating costs, which must be reduced. It is imperative that this electrical condition be improved through the implementation of conventional or modern means.

5. Optimisation of Capacitor Positioning and Network Topology Using Genetic Algorithms

The optimization process entailed the definition of objective functions, their parameterization, and the simulation of these functions within a MATLAB environment utilizing the NSGA-II algorithm.

The objective of optimizing the topology is to identify an optimal network layout that reduces both active and reactive losses and minimizes voltage deviation. This represents a significant challenge in terms of obtaining an appropriate voltage at the terminals of customer receivers and ensuring compliance with the voltage quality metrics required by distribution networks. This reconfiguration is accompanied by the simultaneous optimal positioning of capacitors. The simultaneous optimization of the network diagram and positioning of capacitors within the same network represent an effective approach to optimizing the performance of a distribution network. The objective functions F1 and F2, subject to constraints, are solved using genetic algorithms implemented in MATLAB.

1) *Objective functions*

The objective is to identify the optimal topology for the distribution network and to ascertain the optimal size and location of the capacitor banks within the network. The objectives are both technical and economic in nature.

Technical objective: The objective is to minimise both active and reactive losses, while also reducing voltage instability on the network by minimising voltage deviation. The function is then defined as follows:

$$F_1 = x * X + y * Y + w * W \tag{2}$$

x, y and w are weighting coefficients such that "$x + y + w = 1$".

$$X = \frac{P_{loss}}{P_{loss}^0} \tag{3}$$

With $\begin{cases} P_{loss} : \text{total active loss, after reconfirguration} \\ P_{loss}^0 : \text{total active loss, befor reconfirguration} \end{cases}$

$$Y = \frac{Q_{loss}}{Q_{loss}^0} \tag{4}$$

With $\begin{cases} Q_{loss} : \text{total reactive loss, after reconfirguration} \\ Q_{loss}^0 : \text{total reactive loss, befor reconfirguration} \end{cases}$

$$w = \max\left(V_s - V_i\right) \tag{5}$$

With $\begin{cases} V_s : \text{the source substation voltage} \\ V_i : \text{bus voltage } i \text{ after reconfiguration} \end{cases}$

Economic standpoint: Here the objective is to reduce the expenditure incurred in the construction of new branches and the incorporation of capacitor banks. We may then express the objective as follows:

$$F_2 = C_{ligne} + C_{bat} \tag{6}$$

The optimal reconfiguration of the network necessitates the construction of new lines. It is essential to consider the financial implications of constructing these lines throughout the process. In the context of this work, the secondary branches under consideration have a cross-section of 75 mm^2.

The cost is a function of the length of the line, whereby the cost per unit length is a function of the cost per unit length of the preceding line. The total cost is given by the following equation:

$$C_{ligne} = \sum_i C_{unit} * L_i \tag{7}$$

With $\begin{cases} C_{unit} = 11000000 \text{ F CFA/km, the unit cost of construction} \\ L_i : \text{The length of the secondary branch } i \text{ to be added} \end{cases}$

The total cost of installing the three capacitor banks is as follows:

$$C_{bat} = \sum_1^3 C_{bat,i} \tag{8}$$

2) *Constraints*

Our optimisation problem was solved under certain constraints. The main ones are:

- Maintain the radial structure of the network: The aim here is to avoid the formation of meshes when the network is reconfigured. Whatever the topology, we must therefore use:

$$N = B + 1 \tag{9}$$

With $\begin{cases} N : \text{nodes number} \\ B : \text{branches number} \end{cases}$

- Maintaining tensions within the normative range: This is expressed by the relationship between:

$$0.95 \text{ p.u.} \le V_i \le 1.05 \text{ p.u} \tag{10}$$

- Limit the size of the capacitors: To ensure proper integration of capacitor banks, the total power injected must be less than the total reactive demand of the network, *i.e.*:

$$\sum_1^3 Q_{bat,i} < Q \tag{11}$$

3) *A critical examination of the outcomes of the capacitor positioning process*

In pursuit of sustainable solutions that are technically and economically viable, we investigated a number of scenarios. These included optimising the network with a single capacitor, three capacitors and optimising the topology without capacitors. The solutions obtained can be considered acceptable and viable, to varying degrees, in proportion to the impact of the technological contribution of the equipment inserted and/or the reconfiguration and the profitability obtained.

a) *Optimum insertion of a single capacitor bank*: In light of the potential issues associated with the conventional placement of capacitor banks in a practical network, namely overvoltage and inefficiency, we have implemented an automated positioning strategy that considers critical points, namely nodes with the potential for a significant decline in voltage. The outcomes are presented in **Table 2**.

It is observed that despite the positioning of a capacitor at node 97 of the HV network, the minimum voltage drop is 0.945 pu at node 128, which is the same

Table 2. Mono placement results.

Parameters	Initial state of the network	Mono placement
Capacitor position/size		97/3000 kVA
Vmin (p.u./node)	0.9/128	0.945/128
Rate of improvement		476%
Battery cost (dollars)		5100
Ploss (kW)	425.08	366
Rate of improvement		13.89%
Qloss (kVAR)	435.09	360
Rate of improvement		17.258%
Vulnerability rate (%)	80%	61.71
Comfortability rate		22.86%

identical node on which the most vulnerable node of the network was previously identified. The observed voltage drop at this node is 0.9 pu, which is a notable improvement. From this observation, it can be inferred that the node identified as the most vulnerable may function as a compensator receiver, thereby enhancing the performance of a high-voltage distribution network to a certain extent. It can be inferred that the placement of the capacitor at this node resulted in an improvement of the voltage profile by 4.76%. Additionally, it was noted that the algorithm did not direct the installation of the capacitor at node 128, which was identified as the most vulnerable node in the network. It can thus be inferred that the most critical node in a network is not necessarily the optimal candidate for compensator positioning, as commonly assumed by operators. This performance has a negligible impact on the quality of the supply. Conversely, losses increased by 13.89% in comparison to the network without compensation, where losses were 425.05 kW, in contrast to 366 kW in the case of compensation utilising a single capacitor. The improvement in reactive losses was 17.258% in comparison to the initial case. The vulnerability rate is found to be 61.71%, rather than the initially assumed 80%. The resulting level of comfort is 22.68%. This performance, which is no less negligible, is still a considerable distance from that required for an efficient network, given that there are still customers on this network who are not supplied at the required voltage standards. It can be concluded that a single capacitor is an insufficient means of achieving a qualitative improvement in the supply of electrical energy in an electrical network. It is recommended that the criticality of the network in terms of its quality metrics be taken into account when determining the optimum number of compensators. Given the variability in load profiles across different geographical regions and the diverse range of connected loads, it is prudent to implement capacitors with varmetric relays. This approach allows for the measurement of the number of steps that can be in service for each load segmentation, thereby facilitating optimal compensation for the network's reactive deficit.

b) *Optimal insertion of multiple capacitor banks with multiple nodes in the network*: For an extended period, operators have been attempting to ascertain whether a single placement of mega reactive power is sufficient to effectively compensate the high-voltage network. Indeed, as part of this research project, we investigated the impact of multiple capacitor placements to ascertain their efficacy in enhancing voltage quality to a greater extent than single placements. Subsequent to the simulation, the application proposed three discrete locations for the installation of three capacitors. **Table 3** presents the results obtained from the simulation. It can be observed that the 3000 kVA power is distributed across three locations, namely nodes 18, 80, and 98. The compensation power remains largely consistent with the single-location case, with a summed power of 3060 kVAR. However, the voltage profile has exhibited a slight decline of 0.74% compared with the single-placement case, and the network's hotspot persists at node 128. It should be noted, however, that this node does not receive a compensator. The reduction in losses is 21.55% in comparison to the single placement case, which shows a reduction of 13.89%. It can thus be concluded that the placement of multiple capacitors not only significantly reduces technical losses in the distribution network but also decreases the number of vulnerable nodes in the network. Furthermore, the acquisition cost remains essentially unchanged, as the power remains identical. In the context of reducing losses in a distribution network that requires repair, it is therefore recommended that multiple capacitors be placed at multiple geographically dispersed points in an automated and non-fixed manner that generates overvoltages.

Table 3. Multiple positioning results.

Parameters	Initial state of the network	Mono-placement	Multi-placement
Location (node)/Size (kVAR)/Cost (dollars)		97/3000/5100	18/1030/1750 80/1000/1700 98/1030/5200
Vmin (p.u.)/node	0.9/128	0.945/128	0.938/128
Rate of improvement		4.76%	−0.74%
Active loss (kW)	425.08	366	333
Reactive loss (kVAR)	435.09	360	338
Active improvement rate (%)		13.89	21.55
Rate of improvement reactive losses (%)		17.25%	23.13%

With regard to the voltage profile, a notable decline was observed, from 0.945 p.u. to 0.938 p.u., at the same node, 128. This node is identified as the most vulnerable point on the network, and it is likely to be the point at which voltage collapse can begin. It is therefore imperative that operators monitor this parameter.

Figure 2 provides a clear illustration of the voltage profile following the positioning of the batteries at nodes 18, 98, and 80.

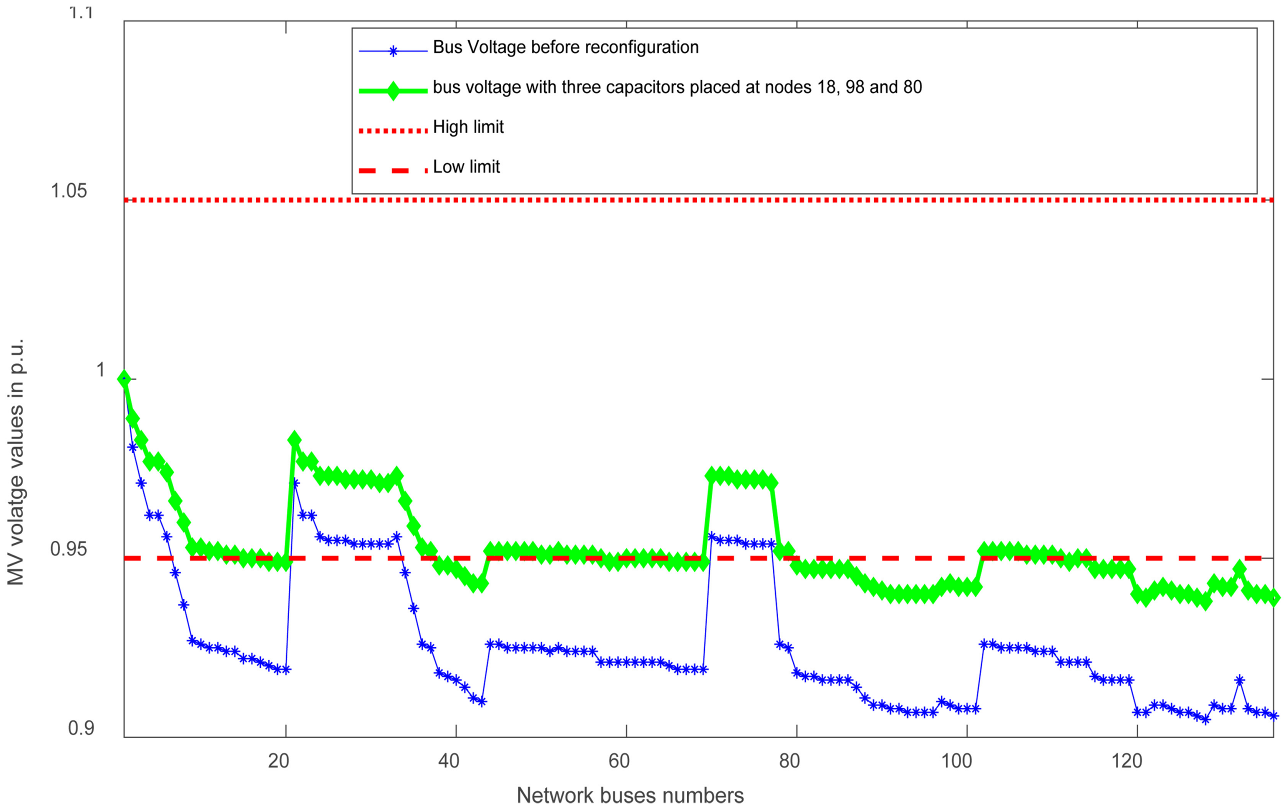

Figure 2. Voltage profile with three capacitors placed at nodes 18, 98 and 80.

A 0.74% decline was observed in the profile in comparison to the mono placement. These findings demonstrate that the impact of multiple investment on the tension profile is relatively minimal. However, it does contribute to an improvement in the loss profile.

It is important to note that, despite the positive effects observed following the positioning of multiple capacitors, this approach remains less effective for achieving a comprehensive improvement in the technical performance of the medium-voltage (MV) network. It can thus be concluded that multiple-capacitor compensation is less effective in ensuring that distribution networks perform in accordance with the standards set by regulators. Consequently, alternative solutions, such as reconfiguration and D-STATCOM placement, must be considered. In this paper, the optimization of electrical network configuration was carried out. Reconfiguration of the MV network topology.

4) *Reconfiguration of HTA network topology*

In light of the accelerated evolution of loads on distribution networks, it has been observed that the placement of capacitors, even when deployed in multiple configurations, is unable to effectively address the inherent imperfections in voltage and loss rates that are often induced by the increase in variable and perpetually growing consumption. It is frequently necessary to implement additional solutions to effectively address voltage wave failure, which is a critical parameter for evaluating the quality of supply. In this paper, we have investigated the potential of network reconfiguration associated with multiple capacitor point placement, utilising a genetic algorithm. The reconfiguration of a distribution network topology entails the automatic search for an optimal network scheme that best meets technical performance criteria, in particular quality of supply and minimal technical losses. This entails opening specific network switches in order to provide the shortest possible path for the power flow. The aforementioned topology reconfiguration was conducted via an algorithm developed and implemented in MATLAB/NGSAII.

Algorithmic method for network reconfiguration: An algorithm has been developed for the purpose of reconfiguring distribution networks. The fundamental strategy entails the initial integration of all fictitious branches, followed by the execution of the power flow and the calculation of the potential difference (PDD) between the two terminal nodes of each fictitious branch The initial selection of the branch to be closed is based on the one with the highest PDD, as this offers the greatest reduction in active losses and the lowest voltage deviation. Subsequently, the closing of the aforementioned fictitious branch will prompt the closure of a corresponding real branch within the network, thereby effecting a change in the network topology. The same action will be repeated and iterated for all fictitious network branches. It can be demonstrated that the closure of a fictitious branch of the network will result in the closure of a real branch of the network. Furthermore, the number of fictitious branches will correspond to the number of potentially possible configurations. It is therefore crucial to open branches in a sequential manner in order to maintain the radial structure of the network. For each configuration, the objective function is evaluated, and the optimal configuration is identified as the one with the smallest value. The second algorithm describes this scenario.

Algorithm 2: Method for Reconfiguration of a Distribution Network

```
Step 1: Reading data
Reading network data:
Node information matrix
Network branch information matrix
Information matrix of fictitious branches
Read tolerance $\epsilon$ ($\epsilon = 1e-8$)
Reading nominal network voltage
Read nominal network power
Step 2: Perform basic power flow, using the BFS method
```

Continued

```
Step 3: Calculate the relative ddp for each fictitious branch: $\Delta V^{(j)} = V_{i-1}^{(j)} - V_i^{(j)}$
with $V_{i-1}^{(j)}$ and $V_i^{(j)}$ respectively the voltages at the start and end nodes of fictitious branch $j$
Step 4: Identify the fictitious branch $k$ with the largest ddp, $\Delta V^k = \max\left(\Delta V^i\right)$
Step 5: Closing the fictitious branch $k$
Retrieve this branch's information from the dummy branch information matrix
    Add this information to the branch information matrix
    Identify the loop formed in the network by this fictitious branch $k$
    Count the number of branches Nk forming the loop
Step 6: For the Nk branches of the loop formed
    Open one branch of the loop at a time
    Update the branch information matrix
    Run the power flow with the BFS method
    Evaluate with formula 3.6 the objective function $F_i$ after opening
the $i^{th}$ loop branch
Step 7: Identify the optimal configuration for the fictitious branch $k$
identify the minimum value of the objective function
    identify the branch $i$ of the open loop for which the objective function is minimal
    identify the loop formed in the network by this fictitious branch $k$
    keep this branch of the loop open and update the branch information matrix
Step 8: Update the number of fictitious branches
$N = N - 1$
Step 9: Check if $N = 0$
    If yes, go to Step 11.
    If no, go to next step
Step 10: Update the dummy branch information matrix, taking into account the remaining dummy branches
Step 11: Display final results and stop
```

5) *Results and discussion of MV network topology optimisation*

The study network is based on a real network of the Société Béninoise D'énergie électrique in Benin. The network is radial and lacks the capacity for loopback in the event of a disturbance. In order to optimise the network topology, it is proposed that loopback branches be created. The configuration of the network with the inclusion of capacitors is illustrated in Figure 3. Given the overhead configuration of the MV network in this area, it is essential to construct loops that are integral to the reconfiguration process. The aforementioned loops were therefore evaluated and positioned. The results of the reconfiguration are presented in Table 4. Table 4 illustrates that subsequent to reconfiguration, losses were diminished by 65.67% in comparison to the placement of multiple capacitors, and minimum voltage was enhanced by 1.05%. This demonstrates that reconfiguration is an effective and cost-efficient method for enhancing the technical performance of a distribution network. It is crucial for operators to adapt and design network structures in a manner that facilitates reconfiguration. It can be stated that all nodes are practically non-violating. Indeed, the voltage deviation is only 0.21%, in stark contrast to the initial network where it was 5.26%. This represents an improvement of almost 96%.

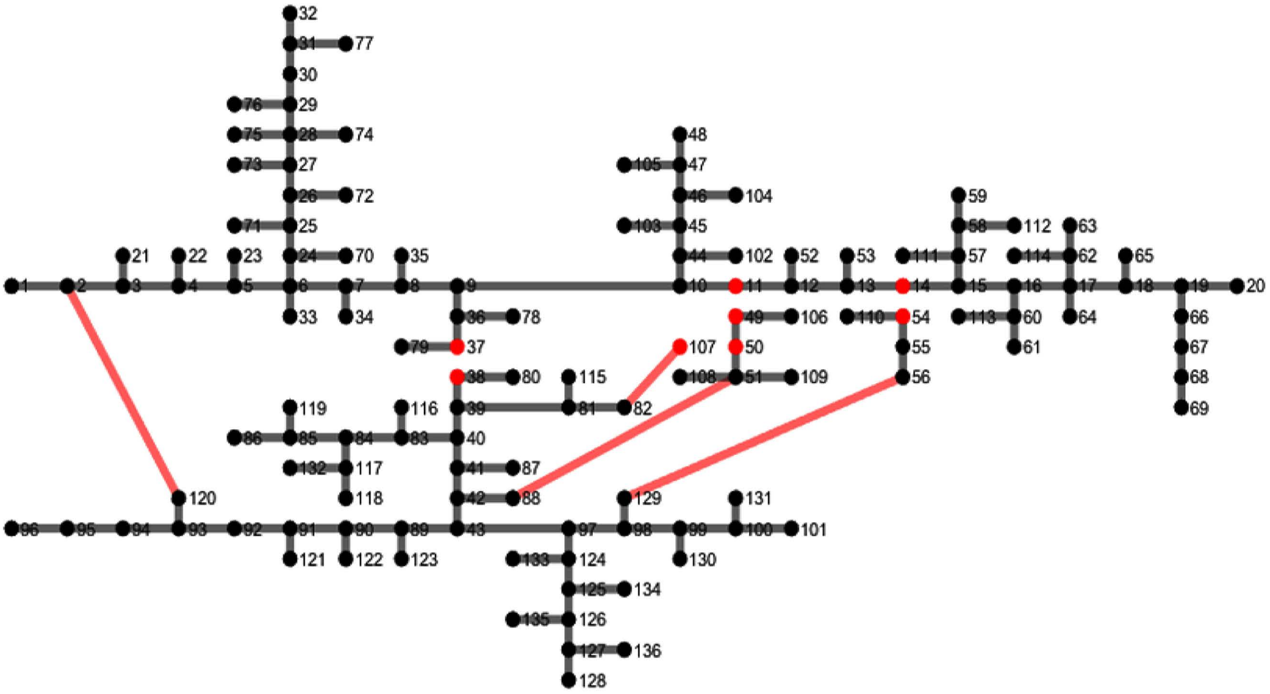

Figure 3. Configuration of the reconfigured MV network.

Table 4. Multiple positioning result.

Parameters	Initial case	Mono placement	Mono placement	Multi placement
Vmin/node	0.9/128	0.945/128	0.938/128	0.948/20
Rate of improvement		4.76%	−0.746%	1.05%
Voltage deviation (%)	5.26	0.52	1.27	0.21
Active losses	425.08	366	333	201
Active loss reduction rate		13.89%	21.55	65.67%
Reactive losses	435.09	360	338	245
Reactive loss reduction rate		20.85%	6.50%	37.95
Open branches				38, 49, 54 and 82

Figure 4 illustrates the voltage profile subsequent to reconfiguration. The curve derived from the voltage profiles is markedly higher than that of the initial state

of the network, thereby confirming the performance gains resulting from distribution network reconfiguration. This proves the effectiveness and efficiency of the aforementioned tool for improving the performance of a distribution network [11].

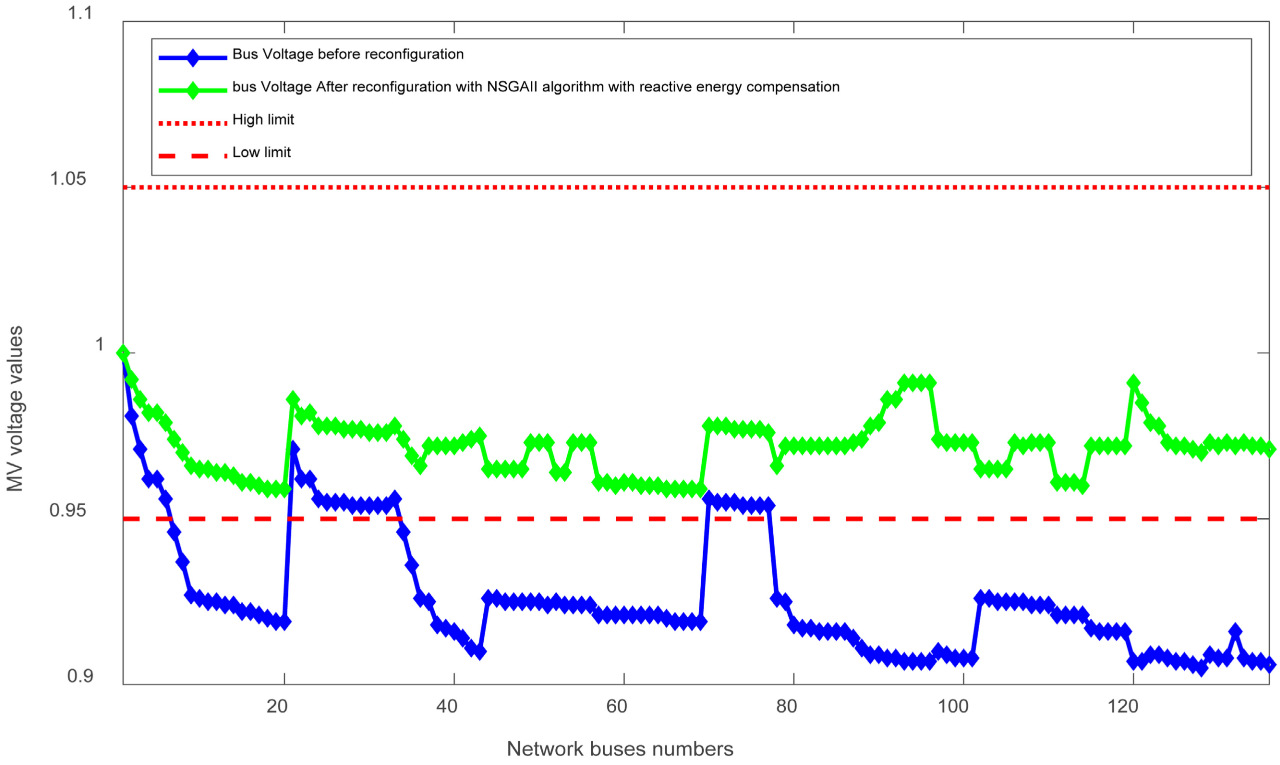

Figure 4. Voltage profile after reconfiguration with NSGAII algorithm with reactive energy compensation.

6. Conclusion

As a result of applying the optimisation method based on NSGA-II, it was found that single and multiple placements of capacitors contribute to a significant improvement in the technical operating parameters of a network. Voltage deviations improved with the application of performance tools ranging from single placement to reconfiguration. Reconfiguration is shown to be an effective tool for improving distribution network performance. It is recommended that distribution network operators design network topologies that favour reconfiguration, taking into account the conditions already required in the definition of the structure, depending on the desired reliability and the sensitivity of the loads to be supplied [11].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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