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# DSTATCOM Positioning in Radial Distribution Networks Using BVSI and Genetic Algorithm

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**Abstract:** The distribution networks of African cities are for the most part in degradation of the required quality due to the exponential evolution of the loads due to demography and industry. In this paper, a hybrid approach based on an analytic-metaheuristic method called (BVSI-GA) developed in the MATLAB environment was used to dimension and position in an ultra-optimal way a DSTATACOM in a quasi-disaster network of Maradi in Niger. Indeed, the positioning of a DSTATCOM with a power of 1840 kVAr at node 40 in this 123-bus distribution network has contributed to reduce the losses in this network by 19.08% with a voltage profile improvement of 2.44%. On the other hand, the exploration of a multiple positioning in order to better secure and make this 123-node network more reliable in case of failure of any of the multiple DSTATACOMs contributed to reducing losses by 25.76%, i.e., a performance improvement of 6.68% compared to the mono-DSTATACOM. As for the tension profile in this case was improved by 2.78% compared to the initial case and by 0.34% to the mono positioning case. The method used in this study is accessible to operators and is effective in predicting and performing distribution networks in African countries, which are nowadays confronted with various contingencies that must be controlled within the limits of tolerable time.

**Keywords:** Genetic Algorithm (GA), Bus Voltage Stability Index (BVSI), Distribution Static Compensator (DSTATCOM), Radial Distribution System (RDS)

## 1. Introduction

Electricity plays an extremely important role in our modern environment which has become very industrialized. The electrical systems that constitute the transmission vector of this electricity are made up of several electrically connected components, the failure of one of which can hinder the operation of the entire system. Thus, the reliability of each of its components is a determining factor in providing quality electricity to consumers whose rights are not only strongly protected by regulators but also have become very demanding as to the quality of the service provided to them. Nowadays, most of the electrical networks in some African countries have overloads on the distribution transformers due to the rapid growth of the loads and the increase of the population. Indeed, investments in distribution networks often lag behind the need to invest. This time lag is often due to delays in project maturity, the constraints of social and environmental impact studies and the rarity of resources that distributors are sometimes confronted with. For example, it is observed that about 13% of the power produced is lost in radial distribution systems due to the excessive joule losses that are generated in transformers and lines [1]. The application of innovative technical means to these networks can lead to efficient networks that are technically and economically viable. There are several compensation techniques to improve the performance of distribution networks [2]. Examples include shunt capacitors, voltage regulators, distributed generation, FACTS devices. DSTATCOM is a D-FACTS (Distribution Flexible AC transmission) with advantages such as power factor control, low losses, small size, automatic operation, long life, and no operating problems such as resonance or harmonics [3]. On the other hand, improper placement of DSTATCOM in the power system can have adverse effects on system stability and reliability and result in additional losses [4]. The DSTATCOM is a static synchronous compensator that is composed of an energy storage capacitor, a DC/AC converter and a coupling transformer. The DSTATCOM components are capable of generating and or absorbing variable reactive or active power in order to maintain the specific parameters of a node within the normative ranges [5]. In recent years, researchers have proposed different methods to determine the location and size of DSTATCOM in RDS in order to reduce power losses and improve the voltage profile. In 2012, V. S. Chauhan et al. [6] identified the optimal location of DSTATCOM on different transmission test networks using evolutionary algorithms, namely Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO), and Plant Growth Optimization (PGO) techniques. The results obtained by the different algorithms were found to be identical. In 2013, A. Bagherinasab et al. [7] used a hybrid method combining the GA genetic algorithm and ACO ant colony optimization for optimal DSTATCOM placement. They found that this method effectively minimizes the network losses. Three DSTATCOMs were applied to the IEEE 30-node network. In 2014, S. A. Taher et al. [3] used the immune algorithm (IA). Comparative results were obtained on IEEE 33 and 69 bus test systems with encouraging optimization with respect to DSTATCOM location and size. In 2015, T. Yuvaraj et al. [8] proposed a new method combining VSI and Bat Algorithm (BA) to optimize the placement of multiple DSTATCOMs in IEEE 33 and 69 bus systems for improved voltage profiles and loss reduction. In 2016, K. R. Devabalaji et al. [9] hybridized the loss sensitivity factor (LSF) and bacterial search optimization algorithm (BFOA) for optimal allocation of DSTATCOM and DG on IEEE 33 and 119-bus systems. The results obtained demonstrate the outperformance and efficiency of the proposed methodology on the use of artificial intelligence. In 2017, M. Sedighizadeh et al. [10] used the imperialist competitive algorithm (ICA) to optimize IEEE 33 and 69 bus systems by localization and sizing of DSTATCOM. They estimated that the performance of ICA is slightly better than other meta-heuristic algorithms. In 2018, A. Oloulade et al. [11] used the ant colony algorithm to determine the best position and size of DSTATCOM in the 41-node network of Beninese Electricity Company (SBEE). They noted that the optimized DSTACOM contributes to minimizing losses and improving the voltage profiles of the feeders. In 2019, K. Padmavathi et al. [12] proposed the firefly (FA) algorithm to accurately size and position DSTATCOM. The performance of this algorithm was compared with the Immune (IA) algorithm. In 2020, T. ZHANG et al. [13] optimized the placement of multiple DSTATCOMs in the IEEE 30-bus system by the improved technique of the harmony search optimization algorithm (DEHS). The obtained results revealed the superiority of the proposed optimization algorithm over the conventional adaptive multi-objective harmony search algorithm. In 2021, O. Montoya et al. [14] used combinatorial optimization on a new version of the vortex search algorithm (DCVSA). The discrete coding determines the nodes and the continuous the sizes of the DSTATCOMs. Good results were obtained in the IEEE 33 and 69 bus test starts. The references cited in this article, far from being exhaustive, attest to the importance of the D-FACTS DSTATCOM compensation device in improving technical performance in RDS. In this work a hybrid technique that combines genetic algorithm (GA) and bus voltage stability index (BVSI) is proposed for optimal DSTATCOM placement. This combined technique reduces the exploration area and is effectively used to find the optimal size and location of DSTATCOM. To validate its effectiveness, the method is tested on a 69-bus IEEE system network and applied to the 123-node distribution network of the Maradi district in Niger.

## 2. Problem Formulation

The objective of placing DSTATCOM in the RDS is to improve the technical and environmental reliability of the power system. This problem is formulated as a multi-objective function with several criteria and constraints including the stability index, the cost of lost energy, the voltage at the nodes. In this paper, the used DSTATCOM is modeled as an ideal controllable reactive power source that can inject or absorb reactive power with the following constraint.

$$0 \leq Q_{DSTATCOM}^{KVAr} \leq 10000\ KVar \quad (1)$$

Where $Q_{DSTATCOM}^{KVAr}$ is the reactive power injected to the network by the DSTATCOM.

*A. Bus Voltage Stability Index (BVSI)*

BVSI, a new concept developed in our research work on multi-capacitor positioning [15]. Based on the ratio of incoming voltage to outgoing voltage of an HV line, it is used in this paper to identify the voltage vulnerabilities of the network and to reduce the exploration area of the genetic algorithm. Considering a two-node system into which an elementary generator is injected shown in Figure 1.

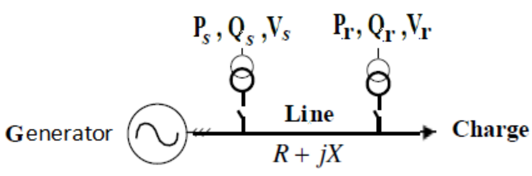


***Figure 1.*** *Two Bus for radial system.*

The voltages Vs and Vr are given by the power flow solution. The voltage at any node "i" is then equal to:

$$\bar{V}(i) = \bar{V}(i-1) - \bar{Z}(i)\bar{I}(i) \tag{2}$$

$$\begin{cases} \bar{Z}(i) = R(i) + JX(i) \\ \bar{I}(i) = \left(\frac{\bar{S}(i)}{\bar{V}(i-1)}\right)^* \end{cases} \tag{3}$$

With respectively $\bar{Z}(i), \bar{I}(i)$, $\bar{S}(i)$ the impedance of the branch, the current in this branch and the apparent power at the beginning of this branch. The BVSI is given by the expression (4). The nodes with low BVSI values in the range [0,1] among many others are chosen as the most appropriate location to install a DSTATCOM.

$$BVSI = \frac{3V_r - V_s}{2V_r} \tag{4}$$

*B. Calculation of the Power Flow*

To evaluate the electrical state of the network that must precede the identification of vulnerabilities, we used the load flow method that is based on Kirchhoff's laws [16].

Calculation of current injections at the different nodes as follows:

$$\bar{I}_i = \left(\frac{S_i}{V_i}\right)^* \tag{5}$$

Calculation of branch currents by:

$$[J] = [BIBC].[I] \tag{6}$$

Calculation of the voltage drops in each branch by:

$$[\Delta V^{k+1}] = [BCBV].[J] \tag{7}$$

Calculation of new nodal voltages, $[V^{k+1}]$ by:

$$[V^{k+1}] = [V^0] - [\Delta V^{k+1}] \tag{8}$$

Calculate the BVSI at each node, by:

$$\mathrm{BVSI} = \frac{3V_{i+1} - V_i}{2V_{i+1}} \tag{9}$$

Calculate total active loss:

$$P_{T.loss} = \sum_{i=1}^{nl} P_{loss,i} = \sum_{i=1}^{nl} R_i * |J_i|^2 \tag{10}$$

Calculate total reactive loss:

$$Q_{T.loss} = \sum_{i=1}^{nl} Q_{loss,i} = \sum_{i=1}^{nl} X_i * |J_i|^2 \tag{11}$$

*C. Objective Function*

The objective function (F) is formulated by considering the minimization of the total power losses and the size of the DSTATCOM while satisfying the voltage and current constraints.

$$F = K_e\,(T * P_{T.loss}) * K_c\left(COST_{DSTATCOM_{year}}\right) * \left|\left(\prod_{j=1}^{nl} OC * \prod_{j=1}^{nb} OV\right)\right| \tag{12}$$

*D. Constraint*

Additional inequality constraints are also considered for this problem. These are [17]:

1) Voltage Deviation Limit:

$$OV = \begin{cases} 1;\ \text{if } 0.9\ \text{pu} \le V_b \le 1.1\ \text{pu} \\ \exp(\mu|1 - V_b|);\ \text{otherwise} \end{cases} \tag{13}$$

2) Line Current Limits:

$$OC = \begin{cases} 1;\ \text{if } I_j \le 520\ \text{A} \\ \exp\left(\lambda\left|1 - \frac{I_j}{I_{max}}\right|\right);\ \text{if } I_j > 520\ \text{A} \end{cases} \tag{14}$$

*E. Cost of DSTATCOM:*

The investment cost of DSTATCOM per year can be calculated using equation (15) as follows [18]:

$$COST_{DSTATCOM\,year} = COST_{DSTATCOM} * \frac{(1+B)^{nDSTATCOM} * B}{(1+B)^{nDSTATCOM} - 1} \tag{15}$$

*F. Annual Cost of Energy Saved (ACES):*

The annual cost of energy saved (ACES) is the difference between the total cost of energy losses before installation and the total cost of energy losses and the annual cost of DSTATCOM after installation in the network and is given by equation (16).

$$ACES = K_e\,(T * P_{T.loss}) - K_e\left(T * P_{T.loss}^{\text{with DSTATCOM}}\right) - K_c\left(COST_{DSTATCOM_{year}}\right) \tag{16}$$

## 3. Contextualized Genetic Algorithm

The contextualized genetic algorithm is used to optimally size the DSTATCOM. The positions of these DSTATCOMs on the network are identified using the BVSI concept designed for this purpose. BVSI is an analytical tool that identifies the critical nodes in a network. It is based on the ratio that compares the input and output voltages of a system. The algorithm consists of creating a population of N chains around the nodes identified by the BVSI to start in an ideal area in the solution space. The individuals in the created population are evaluated by calling the objective function. The best individuals are then selected (roulette) in pairs to reproduce a generation of individuals using the crossover and mutation operators with a probability of (0.8) and (0.3) respectively, which will be evaluated again for the next generation. Thus the evolution loop is repeated until the natural goal is reached.

Proposed Work Implementation: This new GA-BVSI combination approach defined in this paper is designed to improve the technical and environmental performance of a distribution network. The algorithm designed for this purpose is described below:

1) Step 1: Set line data and bus data.
2) Step 2: Estimate the total power loss, bus voltages and BVSI using forward–backward sweep method.
3) Step 3: Identify the best DSTATCOM locations using BVSI.
4) Step 4: Define objective function.
5) Step 5: Generate the initial population, input number of DSTATCOM.
6) Step6: Run GA to optimize the size of DSTATCOM.
7) Step7: Evaluate the objective function for each population.
8) Step 8: Check the termination criterion (if yes go to step 9, otherwise go to the step 6.).
9) Step 9: Display the optimal solutions.

# 4. Results and Discussion

The present optimization approach described above is applied to optimize the operation of the 69-node IEEE network for the validation of the tool and method used in our research. This algorithm was validated and its performance in terms of accuracy and reliability was then used to optimize the operation of the 123-node network of the city of Maradi in Niger. The parameters of the objective function are presented in Table 1, where $COST_{DSTATCOM}$ is the investment cost in the allocation year, $nDSTATCOM$ is the life of the DSTATCOM, B is the rate of return, $K_e$ is the cost of losses, λ and μ are positive constants, $K_c$ is the time duration proportion, and T is the number of hours per year.

***Table 1.*** *Parameters of the objective function.*

| $COST_{DSTATCOM}$ | $n_{DSTATCOM}$ | B | $K_e$ | λ | μ | $K_c$ | T |
|---|---|---|---|---|---|---|---|
| ($/kV Ar) | (year) | ($/kWh) | | | | | |
| 50 | 30 | 0.1 | 0.06 | 2 | 1 | 1 | 8760 |

## *4.1. IEEE 69-Bus Distribution Network*

The data of the lines and buses of this network are taken from the research by S. A. Taher et al. [3]. The basic values are 100MVA and 12.66KV. The results of the simulation run under the Matlab environment are presented in Table 2 for a DSTATCOM and Table 3 for a multiple positioning. The initial active and reactive power losses without using DSTATCOM for the peak load of this network are 225.05 kW and 102.2 kVAr. The minimum voltage is 0.9091 p.u at node 65 and the minimum BVSI is 0.8265 p.u at node 64.

***Table 2.*** *69-bus test system performance analysis.*

| | | Base case | (Proposed GA & BVSI) | GA [3] | (PeSOA & FUZZY) [19] | (BAT & VSI) [8] | (WOA & VSI) [20] | IA [3] | (BFOA & LSF) [8] |
|---|---|---|---|---|---|---|---|---|---|
| SESSION (i) SINGLE DSTATCOM | Optimal (kVAr) & Location | - | 1200 (61) | 1918.39 (61) | 1330.4 (61) | 1150 (61) | 1300 (61) | 1704.42 (61) | - |
| | Ploss (kW) | 225.05 | 152.5 | 165.4 | 152.04 | 153.36 | 151.09 | 157.5 | - |
| | % Reduction in Ploss | - | 32.22 | 26.50 | 32.42 | 31.9 | 32.84 | 30 | - |
| | Qloss (kVAr) | 102.2 | 70.6 | 75.20 | 70.54 | 71.26 | - | 72.4 | - |
| | % Reduction in Qloss | - | 30.91 | 26.41 | 30.97 | 30.27 | - | 29.2 | - |
| | Vmin (p.u) | 0.9091 | 0.9289 | 0.9392 | 0.9307 | 0.9278 | 0.9389 | 0.9353 | - |
| | ACES ($) | - | 30,738 | - | - | 31,573 | - | 26,438 | - |
| | BVSImin | 0.8265 | 0.8625 | - | - | - | - | - | - |

### *4.1.1. Session (i): System with Single DSTATCOM*

In this system (Table 2), the DSTATCOM is positioned at node 61 with an optimal size of 1200 KVAr. The active losses after compensation have increased to 152.5 kW. While in the research of S. A Taher et al. [3], T. Yuvaraj et al. [8], K. Subbarami et al. [19] and P. Balamurugan et al. [20], the DSTATCOM is sized at node 61, but with a respective size of 1918. 39 KVar; 1704.42 KVar; 1150 KVar; 1330.4 KVar et 1300 KVar for respective losses after compensation of 165.4 KW; 157.5 KW; 153.36 KW; 152.04 KW; 151,.09 KW. It is observed that the tools used by these different authors all resulted in the identification of node 61 like our tool. This similarity of results shows the performance, accuracy and relevance of our tool, i.e., BVSI-GA, to position a compensator in a distribution network. The optimal power of DSTATACOM found is 1200kVAr contrary to the other authors who used the methods and tools (BAT-VSI) [8], GA [3], AI [3], (PeSOA_FUZZY) [19] and (WOA_VSI) [20] who found higher power ratings with losses that remain relatively identically to the 152.5kW. These very efficient results confirm the optimality of the GA-BVSI tool and its robustness. It can then be deduced that the optimal sizing to improve the performance of the 69-bus network is more efficient and less expensive with the methods: (GA-BVSI) proposed and (BAT-VSI) in [8] than with the methods: simple genetics in [3], immune algorithm in [3], combined penguin algorithm in [19] and combined whale algorithm in [20]. In view of its accessibility and technical performance and its ease of finding weaknesses in an electrical system, its use can be strongly recommended to distribution network managers.

### *4.1.2. Session (ii): System with Multiple DSTATCOM*

In order to validate the developed GA-BVSI algorithm, it is applied to a test network and the results are compared to the work of the authors of BAT [8], BFOA [8] and WOA [20]. As a result of this application, it is observed two

DSTATCOMs optimally positioned at nodes 61 and 17 with a total power of 1420 KVAr (Table 3). The losses in this network went from 225.05 KW to 147.56 KW, a reduction of 34.43%. The positioning of two DSTATCOMs contributed to a significant reduction in losses. While comparing these results with those of the authors of [8, 20] who used respectively the BAT, BFOA and WOA method, we notice that their positioning generated powers of 1550 kVAr, 1910 kVAr and 1600 KVAR, that is to say respectively an increase of 8.38%, 25.65% and 11.25%. It can be deduced that the determination of the power requirement of DSTATCOM to compensate the network is more optimal with the GA-BVSI method than with the BAT, BFOA and WOA method. This optimization of power ratings has a positive impact on installation costs, maintenance and operating results. It can then be concluded that the BVSI - GA method is more indicated and recommended for operators who are confronted with the sizing of compensators to improve the technical performance of their network. Figure 2 shows the voltage profile improvements of this network.

***Table 3.*** *69-bus test system performance analysis.*

| | | Base case | (Proposed GA & BVSI) | GA [3] | (PeSOA& FUZZY) [19] | (BAT& VSI) [8] | (WOA& VSI) [20] | IA [3] | (BFOA & LSF) [8] |
|---|---|---|---|---|---|---|---|---|---|
| SESSION (ii) MULTIPLE DSTATCOM | Optimal (kVAr) & Location | - | 1160 (61) | - | - | 330 (15) | 350 (17) | - | 480 (15) |
| | | - | 260 (17) | - | - | 1220 (61) | 1250 (61) | - | 1 |
| | Total kVAr | - | 1420 | - | - | 1550 | 1600 | - | 1910 |
| | Ploss (kW) | 225.05 | 147.56 | - | - | 146.73 | 146.34 | - | 148.07 |
| | % Reduction in Ploss | - | 34.43 | - | - | 34.78 | 34.96 | - | 34.19 |
| | Qloss (kVAr) | 102.2 | 68.60 | - | - | 68.43 | - | - | 68.76 |
| | % Reduction in Qloss | - | 32.87 | - | - | 33.04 | - | - | 32.72 |
| | Vmin (p.u) | 0.9091 | 0.9292 | - | - | 0.9299 | 0.9417 | - | 0.9332 |
| | ACES ($) | - | 32754.98 | - | - | 32923.72 | - | - | 30311.41 |
| | BVSImin | 0.8265 | 0.8633 | - | - | - | - | - | - |

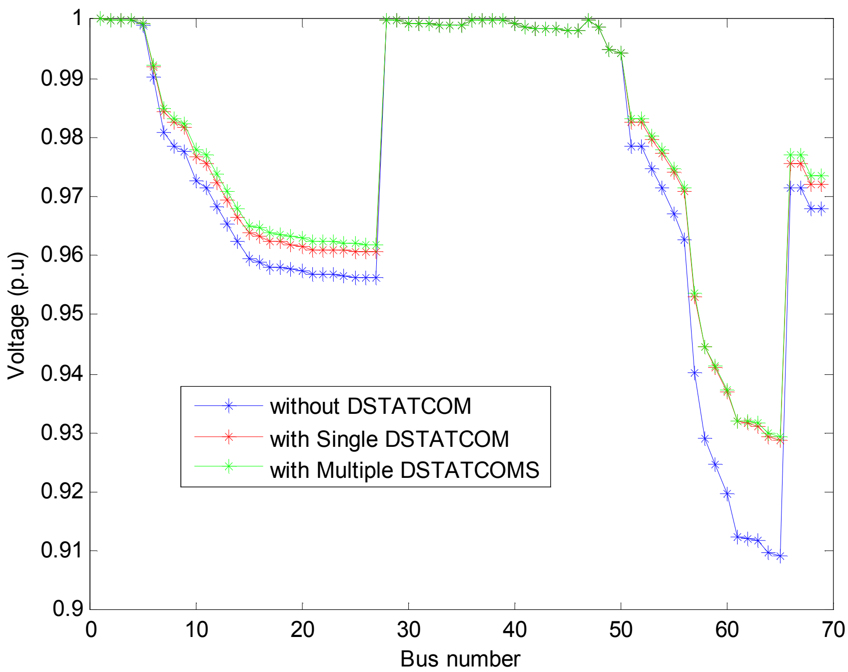


***Figure 2.*** *69-bus system voltage profile optimization.*

### *4.2. 123-Bus Ville-Madarounfa Rural Distribution Network*

Figure 3 shows the diagram of the study network. The two HV Ville-Madarounfa feeders in Maradi (Niger) constitute a real distribution system with a service voltage of 20 kV. It is constituted of 123 nodes. The parameters of this network are taken from the data bank of the NIGELEC site in Maradi. The peak load for this study system is 9.588 MW and 5.9784 MVAr. Initially the calculated power losses are 614.1898 kW and 309.8790 kVAr (Session (i)). There are also 28 nodes that are out of control with a minimum voltage of 0.8917pu at node 31, but no loaded lines. The minimum BVSI is found at node 31 with a magnitude of 0.7952 p.u. For a single positioning (Session (ii)), the calculated DSTATCOM size is 1840 KVar at node 40, the active losses decreased from 614.1898 kW to 496.9649 KW, a reduction of 19.08%. The maximum loss reduction in this network is obtained after positioning three DSTATCOMs (Session (iii)) at nodes 12 (820 KVar), 28 (1400 KVar) and 97 (1215 KVar) respectively. The losses went from 614.1898KW to 455.9255KW, a reduction of 25.76%. The results of the simulation are presented in Table 4. Figure 4 shows the voltage profiles for each of the above situations.

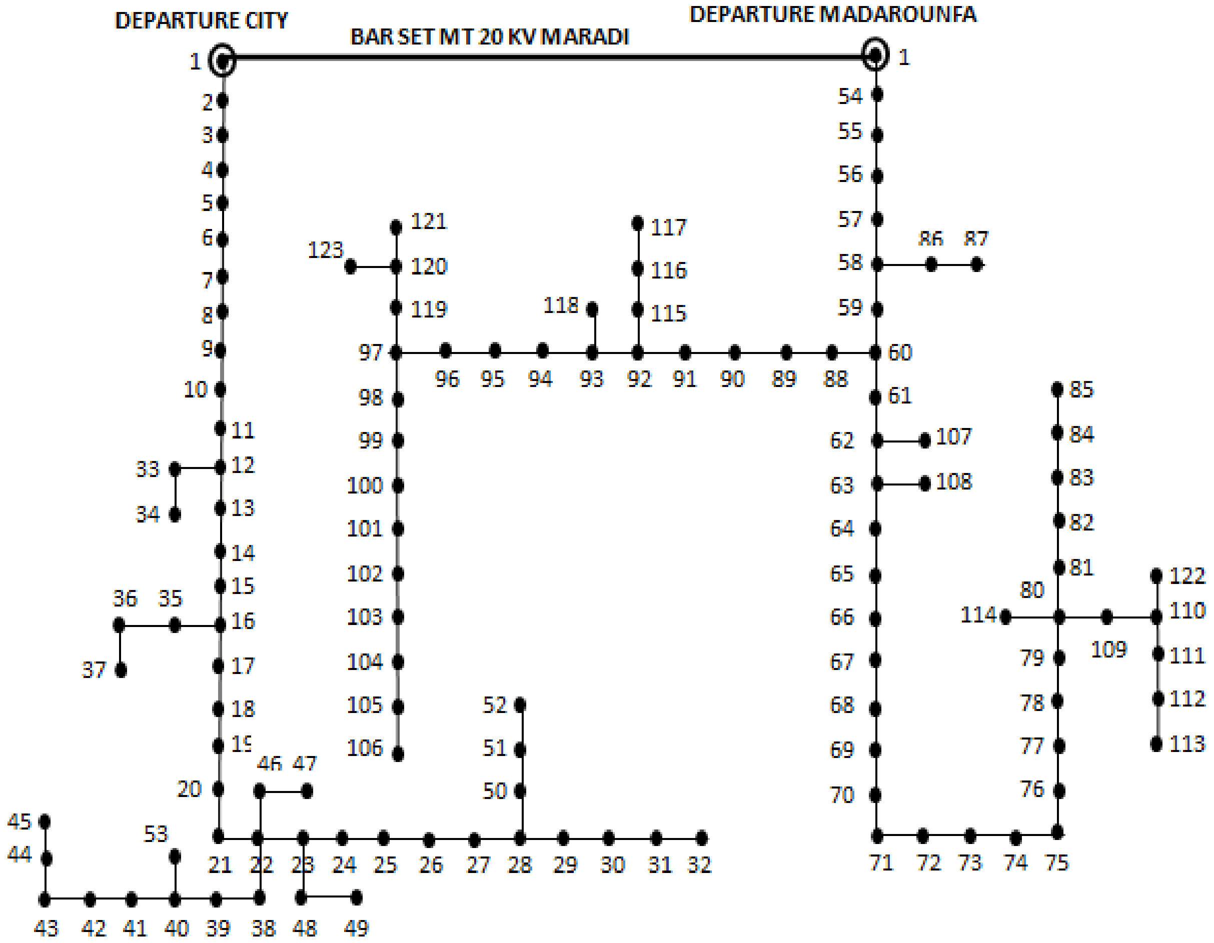


***Figure 3.*** *Single line diagram of the two 123 Bus HV feeders.*

***Table 4.*** *123-bus system performance analysis.*

| **Proposed Method** | | |
|---|---|---|
| Session (i): Without Compensation | Ploss (kW) | 614.1898 |
| | Ploss (kVar) | 309.8790 |
| | BVSImin (p.u) | 0.7952 |
| | Vmin (p.u) | 0.8917 |
| Session (ii): With single DSTATCOM | Size in kVAr (location) | 1840 (40) |
| | Ploss (kW) | 496.9649 |
| | % Ploss Reduction | 19.08% |
| | Ploss (kVar) | 251.9021 |
| | BVSImin (p.u) | 0.8344 |
| | Vmin (p.u) | 0.9135 |
| | ACES ($) | 92925.429 |
| Session (iii): With Multiple DSTATCOMs | Size in kVAr (location) | 820 (12)<br>1400 (28)<br>1215 (97) |
| | Ploss (kW) | 455.9255 |
| | % Ploss Reduction | 25.76% |
| | Ploss (kVar) | 229.8464 |
| | BVSImin (p.u) | 0.8399 |
| | Vmin (p.u) | 0.9165 |
| | ACES ($) | 120416.649 |

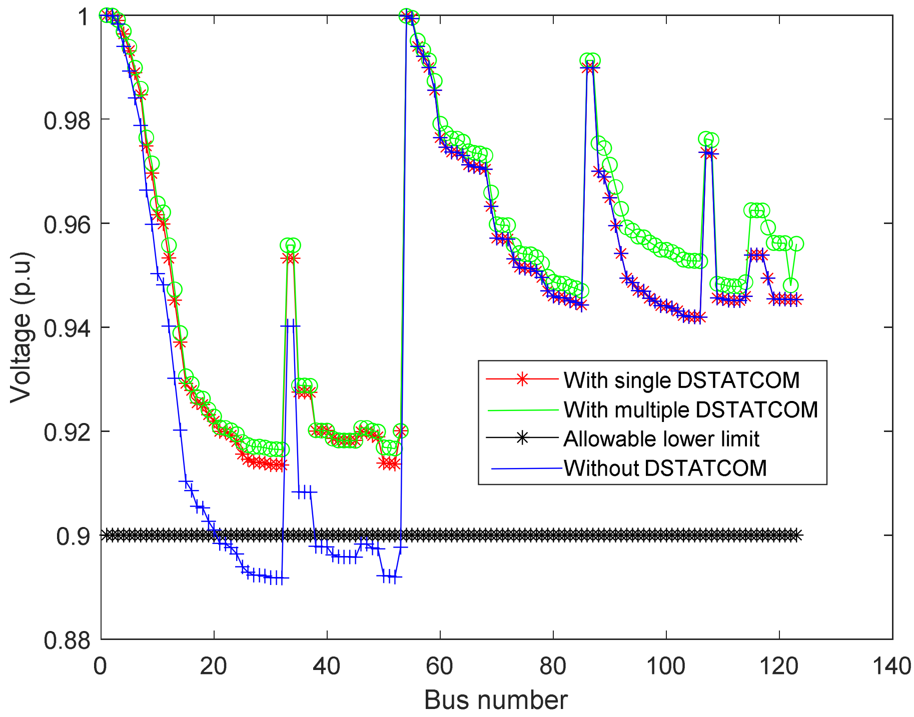


***Figure 4.*** *123-bus system voltage profile optimization.*

## 5. Conclusion

In this paper, a two-step methodology was presented to identify candidate nodes that could receive a DSTATCOM to improve the technical performance of the Maradi MV network in Niger. The mono DSTATACOM positioning consisted in positioning an 1840 kVar compensator at node 40. The result of this positioning is a reduction in network losses of 19.08% and an improvement in voltage profile of 2.44%. With this optimal power of 1840 kVAr, it was found that no node is outside the normative limits and that the network has stabilized well, generating loss reduction proportions that can generate treasury flows to the benefit of the Niger Distribution Company. As for the multiple positioning, it consisted in positioning three DSTATCOM of size and node 820 KVar (12), 1400 KVar (28) and 1215 KVar (97) respectively, inducing a loss performance of 25.76%. This multiple positioning of multiple compensators is of technical interest in the event of a short circuit that will lead one or two of the DSTATACOMs to be isolated from the network. It will prevent disasters that could collapse the network. Given that the loads evolve very quickly on the distribution networks and that this exponential evolution remains the main cause of the voltage contingency situations on the said networks. However, in this paper it was not simulated the occurrence of contingencies on the DSTATCOM in order to apprehend the successive behavior of the network, nor the power supply of the DSTATCOM device which could be an EV parking. The BVSI-GA method, which is an analytical-metaheuristic method, constitutes a performing, fast and reliable tool to study and predict the reliability and security of an electric system of the size of African countries.

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