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Optimal Location and Sizing of a D-STATCOM in Electrical Distribution Systems to Improve the Voltage Profile Considering the Restriction of Harmonic Injection through the JAYA Algorithm

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Abstract: This study focuses on the application of the JAYA algorithm to optimize the implementation and sizing of a distribution static synchronous compensator (DSTATCOM) in distribution systems to reduce power losses and enhance voltage profiles, ensuring a total harmonic distortion of voltage (THDv) below 3% at all system nodes. The algorithm, developed and modelled in MATLAB, addresses power flow solutions and analyzes harmonic influence from implementing a DSTATCOM as reactive compensation via a non-iterative harmonic penetration analysis. Successful algorithm implementation results in a significant reduction in both active and reactive power losses in 33- and 34-node systems while maintaining a THDv below 3% at all nodes. Although imposing the THDv limit constraint reduces power loss, this compensation ensures low THDv levels in the voltage. In contrast to existing literature that focuses on power loss reduction via reactive compensation, this work addresses and controls the inclusion of harmonics in the electrical network as a consequence of such reactive compensation, marking a novel contribution to the field.

Keywords: optimal location and dimensioning; JAYA algorithm; D-STATCOM; minimization of power losses; voltage profile

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1. Introduction

Reactive compensation, a crucial strategy in the management of electrical systems, is used to attenuate the power losses present in the system. However, its impact goes far beyond simply reducing these losses. In addition to this effect, a series of benefits are triggered that collectively contribute to the optimization of the system. The marked voltage profile improvement is one of the most outstanding reactive compensation results. Since inadequate voltages can cause various problems in the operation of electrical equipment and devices, this improvement is essential to ensure stable and efficient operation. Likewise, work is being conducted on raising the power factor, representing the relationship between the active power consumed and the total apparent power. Increasing this factor maximizes active power utilization, minimizing losses from reactive power [1,2]. Another relevant aspect of reactive compensation is its impact on power transmission capacity. By mitigating the reactive currents in the system, additional capacity is released to transport active power. This can be especially beneficial in high-demand situations, avoiding network congestion and improving overall system efficiency [3]. In summary, reactive compensation is not only limited to reducing power losses. Its scope extends to the optimization of the voltage profile, the increase in the power factor and the improvement of the power transmission capacity. These combined effects contribute significantly to electrical systems' efficient and reliable operation [4,5].

This improvement in power transmission capacity is achieved with flexible alternating current transmission systems (FACTS); a device of this type is the DSTATCOM, capable of absorbing or delivering reactive power depending on the system requirement. These devices can be incorporated into all nodes of the system. However, an inadequate location can become counterproductive for the system's proper operation [6,7].

In this way, implementing optimization techniques for the location and size of reactive compensation devices translates into substantial improvements in the voltage profile and the reduction in power losses in electrical systems. This strategic approach contributes to a more efficient and reliable operation and positively impacts daily life by ensuring a more stable and sustainable electricity supply.

This optimization problem has been extensively addressed in the literature, leading to the proposal of various methodologies to tackle and solve this issue. In [8], an immune algorithm (AI) is implemented to size and locate the optimal connection point, improving the voltage profile, currents, power losses, and the installation cost of DSTATCOM; the author implements the technique in the 33- and 69-bar systems. In [7], the implementation of a hybrid immune and genetic algorithm (IA-GA) is proposed to size and locate the optimal connection point to reduce power losses, as well as the annual cost of operation of the DSTATCOM; this technique is performed on the 33-bar test system. In [9], the implementation of the improved bacterial foraging search algorithm (IBFA) is proposed; the objective function seeks to reduce power losses and improve both stability and the voltage profile. This proposal is implemented in a 78-bar system. In [10], it is proposed to implement an analytical technique to optimally determine the location and dimensions of distributed generation (DG) and DSTATCOM; this proposal is carried out in the 34- and 69-bus systems. The author proposes improving the voltage profile as well as reducing power losses. In [11], the implementation of the differential evolution algorithm is proposed to locate the DSTATCOM optimally, considering the maximization of a net cost savings/benefit analysis approach while minimizing the power lost in the network. In [12], the optimal location and size of a STATCOM are addressed to improve the voltage stability margin; this is achieved via multi-criteria optimization by applying the CPF method to adjust the objective function. Ref. [13] presents a multi-objective optimization approach to locate and size the DSTATCOM in radial distribution networks optimally, using the whale optimization algorithm (WOA) to reduce power losses, improve the voltage profile and increase the system reliability. The authors of [14] address the simultaneous placement of renewable distributed generation (DG) and DSTATCOM in a radial distribution system to minimize power losses using the loss sensitivity factor and the hybrid lightning search algorithm-simplex method.

By carefully examining the current research landscape, it is observed that most researchers focus on addressing the problems of the localizing and sizing of reactive compensation using approaches based on heuristic techniques. In this context, the predominant objective is minimizing power losses inherent to the electrical system while constantly seeking to significantly improve the voltage profile in the network and achieve economic optimization. However, the influence of harmonics in the electrical system needs to be considered and included.

Within this context, it is essential to address the existing research gap and explore the integration of harmonics consideration into modelling heuristic techniques. This approach will not only enrich the understanding of reactive compensation but also enable the development of more comprehensive and effective solutions to current challenges in power system management. For this reason, in this document, in modelling the JAYA algorithm via simple harmonic penetration analysis, the incorporation of the harmonics generated via reactive compensation is addressed.

2. Materials and Methods

The present research study is distinguished by its innovative approach by integrating the power of MATLAB in combination with the specialized tool Matpower, using the JAYA optimization algorithm for the optimal determination of the location and sizing of the reactive compensation while taking advantage of Matpower to carry out the rigorous calculation of the power flows in the study systems, thus providing an outstanding level of precision in the analysis. It seeks to complement and expand the previously mentioned research. It presents a new horizon by introducing a fundamental restriction in the algorithm: establishing the maximum THDv that the bars can withstand due to the strategic incorporation of reactive compensation via the DSTATCOM.

The results anticipated, as a result of implementing the JAYA algorithm, a broadened spectrum of substantial improvements: a significant decrease in both the average and maximum voltage deviation is expected, together with a marked reduction in power losses, all within the framework of the ambitious goal that the THDv registered in each bus remain below the 3% limit, thus establishing an optimal energy quality threshold and guaranteeing the viability of reactive compensation in the analyzed system.

2.1. Simple Harmonic Penetration

After an exhaustive evaluation, the simplified harmonic penetration method is chosen, which is the ideal instrument to accurately calculate the total harmonic distortion index in voltage (THDv) in all the system bars by incorporating the DSTATCOM. In this instance, the DSTATCOM is conclusively defined as a harmonic enhancing source characterized by a 6-pulse converter. The manifestation of the harmonic spectrum inherent in this configuration is shown graphically in Figure 1.

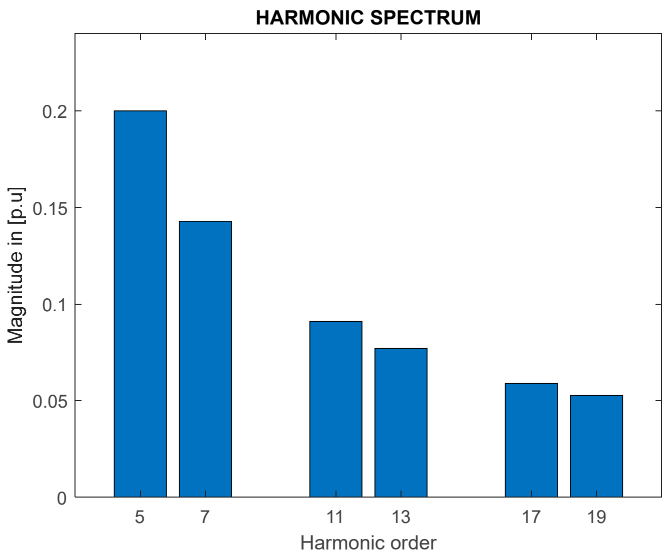


Figure 1. Typical harmonic spectrum of a 6-pulse converter.

Harmonic penetration is based on the fact that it does not consider the harmonic interaction between the network and the non-linear elements [15].

To determine the voltage of the bars via the inclusion of a harmonic generating source, the following equation is implemented:

$$V_i^h = Z_i^h * I_i^h \tag{1}$$

where V_i^h is a vector made up of all the voltages of each system node at a frequency "h". The term Z_i^h refers to the inverse of the admittance matrix considering the harmonic modelling for each harmonic "h". I_i^h is also a vector of dimension "i", where all the elements are 0, except for the bars where the harmonic generating devices are located. These values, different from 0, are calculated as a certain quantity of the current determined at fundamental frequency; this quantity is determined based on the harmonic spectrum of the harmonic generating source [5].

2.2. Harmonic Distortion

The calculation of the total voltage harmonic distortion for each node is conducted using the following equation:

$$THDv = \frac{\sqrt{\sum_{h=2}^{inf}\left(V_h{}^2\right)}}{V_1} \tag{2}$$

V_1 is the node voltage at the fundamental frequency, and V_h is the harmonic "h" order voltage.

2.3. JAYA Algorithm

JAYA algorithm, proposed in 2016 by Venkata Rao in [16], is based on the concept that the solution obtained for a given problem should be directed towards the most favourable solution and avoid the worst solution.

JAYA is a population-based algorithm characterized by not depending on specific control parameters, which makes it easier to implement. It only requires using standard control parameters such as the number of design variables, the maximum number of generations and the size of the population [16–18].

2.4. JAYA Algorithm Focused on the Optimal Location and Sizing of the DSTATCOM

The JAYA algorithm was implemented in the MATLAB software(2021 B), and the power flow calculation was performed using the Newton–Raphson algorithm proposed by Matpower.

For the implementation of the algorithm, two variables were determined: the first, the reactive power that the device must inject or absorb, and the second, the bar where the device is located.

The objective function is the minimization of the average voltage deviation and the reduction of power losses in the feeders.

$$OF : minP1 \, * \, DPV + P2 \, * \, S_{loss}/S_{loss\_initial} \tag{3}$$

where $P1$ and $P2$ are weighted by which the improvement priority is determined, either the voltage profile or the power losses, and the lost power is defined as the sum of the power sent from node "i" to node "j" and the power transmitted from node "j" to node "i". The equation outlined in [15] determines the average voltage deviation.

$$DPV = \frac{\sum_{i=}^{n}|V_{di} - V_i|}{n} \tag{4}$$

where V_{di} is the desired voltage value at node "i", V_i is the real voltage value of node "i", and "n" is the number of bars in the system.

2.4.1. Restrictions

The constraints used in the algorithm are the following:

$$V_{min} \, \leq \, V_i \, \leq V_{max} \tag{5}$$

$$Q_{min} \, \leq \, Q_i \, \leq Q_{max} \tag{6}$$

$$maxTHD_v \, \leq THD_{v\_max} \tag{7}$$

where the minimum and maximum voltage limits are 0.90 and 1.10, respectively, the limits of the reactive power that can be injected or absorbed via the DSTATCOM are determined with the following criteria: the maximum value is obtained by adding the reactive power of the entire system, while the minimum value is calculated as the negative of the maximum power. The $maxTHD_v$ value is determined as the maximum THD_v value of all the bars in the system, and its limit is 3%, that is, the THD_{v_max}.

2.4.2. Pseudocode

Step 1: Initialize the population size PS, termination criterion Ter_cr, priority of the weights $P1$, $P2$, the number of design variables NVD, minimum and maximum limit of reactive power injected via the DSTATCOM; Q_{min} Q_{max}, maximum limit of THD_v acceptable THD_{v_max}, the number of system bars $nBar$ and the initial power losses of the system $S_{loss\_initial}$.
Step 2: Determine the values of the population $X_{j,k,i}$ considering the limits Q_{min} , Q_{max}, and $nBar$.
Step 3: Evaluate the initial population in the objective function OF.
Step 4: Identify the values of the population particle with which the best $X_{j,best}$ and worst result $X_{j,worst}$ in the OF. The best solution is when OF is minimum, and the worst solution is when OF is maximum.
Step 5: Modify the population with the values obtained in Step 4 using the following equation: $X_{j,k,i}^{new} = X_{j,k,i} + r1_{j,i}\left(X_{j,best,i} - \left|X_{j,k,i}\right|\right) - r2_{j,i}\left(X_{j,worst,i} - \left|X_{j,k,i}\right|\right)$.
Step 6: Evaluate the new population in the OF.
Step 7: Update the population to $X_{j,k,i}^{new}$ if the result obtained with $X_{j,k,i}^{new}$ is better than that obtained with $X_{j,k,i}$.
Step 8: Repeat steps 1–7 until the completion criterion has been satisfied.
Step 9: Show the optimal result.

The OF is determined via the results obtained from the power flow using Newton–Raphson considering the values of the population (power delivered via the DSTATCOM $X_{1,k,i}$ in the bar $X_{2,k,i}$).

To determine the $THDv$ in all bars as a consequence of the incorporation of DSTATCOM, the following subroutine is used.

Step 1: Obtain data for the following: Vi, $X_{1,k,i}$ and $X_{2,k,i}$
Step 2: Calculate

- Z_{barra} matrix for harmonics 5, 7, 11, 13, 17 and 19;
- Harmonic current as a function of the harmonic spectrum of the 6-pulse converter $I_i^h = \frac{Q_{DST}}{V_i} * spectrum^h$;
- Voltages for each harmonic in all buses $V_i^h = Z_{bus}^h * I_i^h$;
- Calculate the $THDv$. $\%THD_v = \sqrt{\frac{\sum_{n=2}^{H}(V_i)^2}{V_n}} * 100\%$.

Step 3: Export results.

3. Test Systems and Case Studies

The systems in which the proposed model will be used are the 33- and 34-bar systems; a description of the proposed test systems is presented below.

This proposed system has a base power of 10 [MVA] and a base voltage of 11 [kV]. The total load connected to the system is 4636 [MW] of active power and 2873 [MVAr] of reactive power. The graphical representation of the system is shown in Figure 2.

The 33-bar system establishes a base voltage of 12.66 [kV] and a base power of 10 [MVA]. The total load installed in this system is 3715 [MW] of active power and 2.3 [MVAr] of reactive power. The graphic representation of the system is presented in Figure 3.

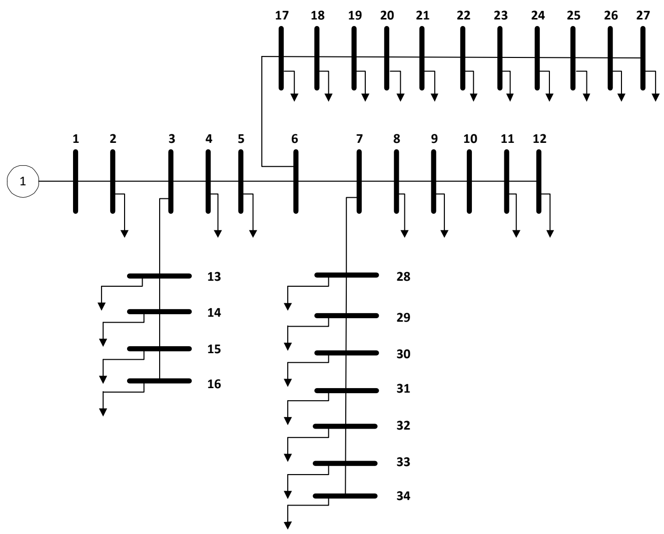


Figure 2. The 34-bar system.

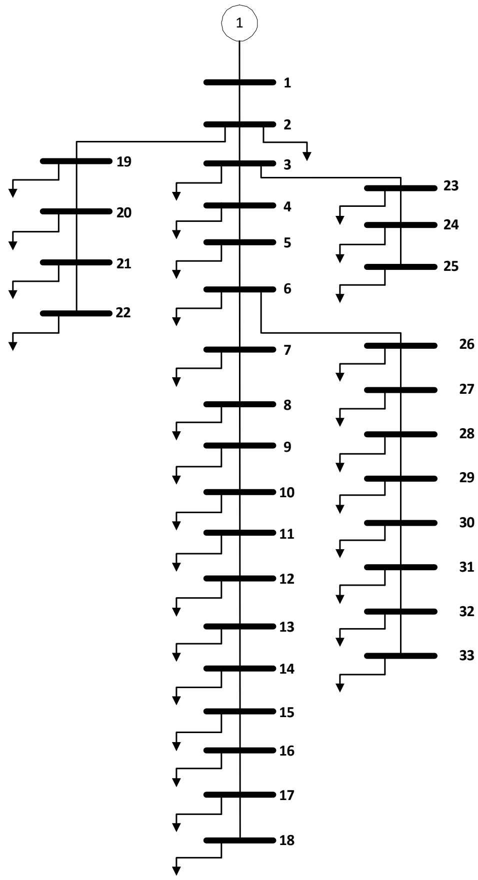


Figure 3. The 33-bar system.

With the application of the proposed methodology in the two case studies, the results are presented for each system analyzed considering scenarios with and without harmonic restriction. The first analysis scenario does not incorporate the harmonic injection restriction, while the second scenario does include said restriction. This restriction prevents the total harmonic distortion of the voltage in all the bars from exceeding the established 3% limit.

4. Results

This section presents the results obtained using the optimization model in the 33- and 34-bar test systems.

4.1. 33-Bar System

In scenario 1, without the harmonic injection constraint, the algorithm converges on the optimal solution of incorporating the DSTATCOM at bus 30 with a capacity to deliver 1300 [kVAr]. With this incorporation of DSTATCOM, the voltage profile presents an improvement concerning the initial or base case; this is graphically evidenced in Figure 4.

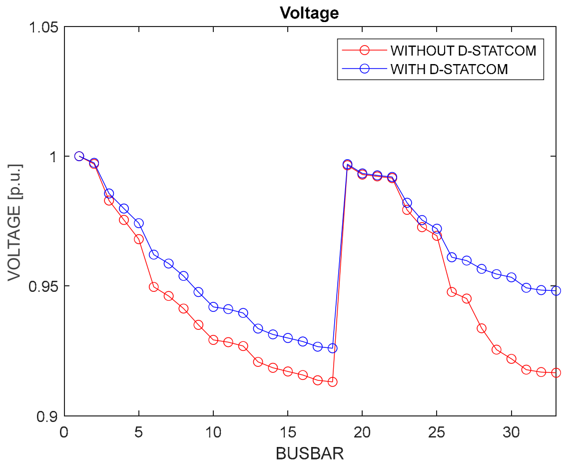


Figure 4. Voltage profile in scenario 1 for the 33-bar system.

The red line represents the voltage level at each node in the scenario without reactive compensation. The blue graph represents the voltage profile when incorporating a DSTATCOM of the power and at the location determined using the algorithm.

In addition to the improvement in the voltage profile, there is evidence of a reduction in the power losses of the system under study; this reduction can be seen in Figure 5.

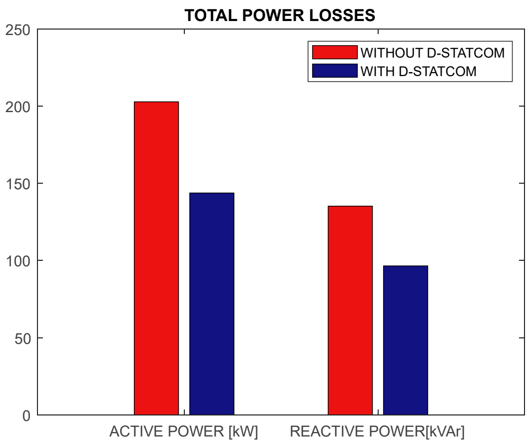


Figure 5. Lost power in scenario 1 for the 33-bar system.

Both active and reactive power losses are reduced by incorporating DSTATCOM.

Implementing a DSTATCOM of 854 [kVAr] in bus 27 is achieved by making the optimal location and dimensioning with the harmonic injection restriction. With this incorporation, an improvement is made in the voltage profile, reducing the voltage deviation, and both active and reactive power losses are also reduced; this can be evidenced in Figures 6 and 7, respectively.

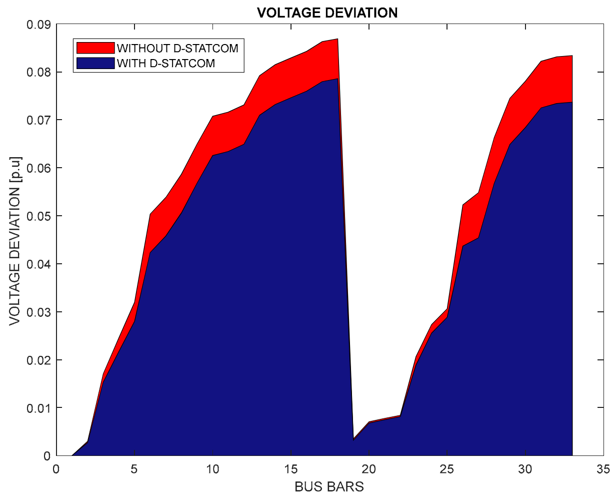


Figure 6. Voltage deviation in scenario 2 for the 33-bar system.

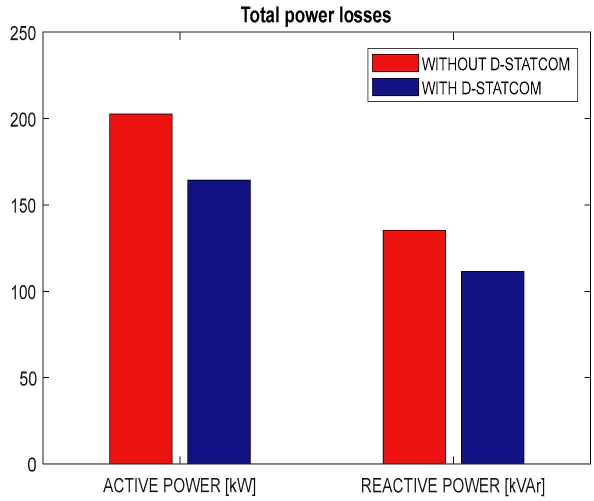


Figure 7. Power losses in scenario 2 for the 33-bar system.

As can be seen, there is a reduction in the voltage deviation, which indicates a better voltage profile; in other words, the voltage in the system bars has values closer to 1 per unit concerning the initial case; additional evidence is a reduction in both active and reactive power losses.

Because, in the present scenario, there is a restriction of harmonic injection, it must be evidenced that the THDv in all the bars, due to the incorporation of the DSTATCOM, must be less than 3%; this is evidenced in Figure 8.

The THDv in all nodes of the system remains at a value less than 3%; this is because, in the current scenario, the power of the DSTATCOM is restricted so that this low THDv is guaranteed in the system bars.

Table 1 details the results obtained by applying the optimization technique proposed in the 33-bar system, both for scenario 1 and scenario 2. Additionally, the values obtained are compared with the immune algorithm proposed by [8].

Compared to the immune algorithm, the results obtained using the proposed method improve the reduction in power losses in scenarios 1 and 2. The average voltage deviation, as well as the maximum voltage deviation obtained with the immune algorithm, is surpassed by the results obtained with the JAYA algorithm in scenario 1.

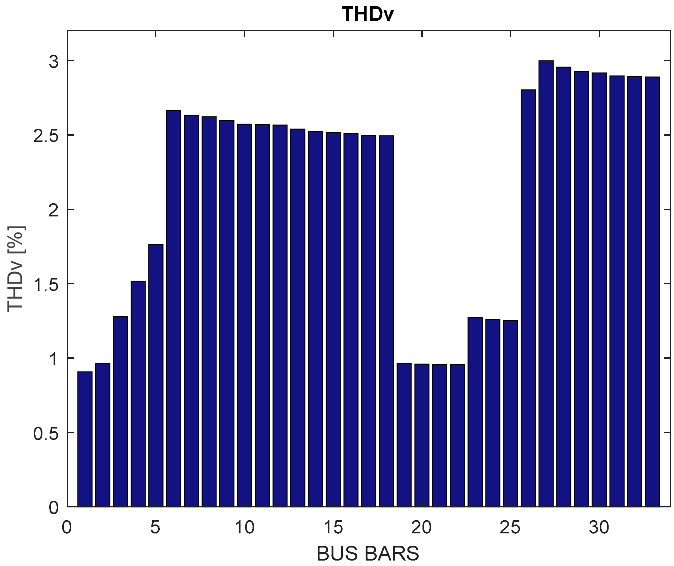
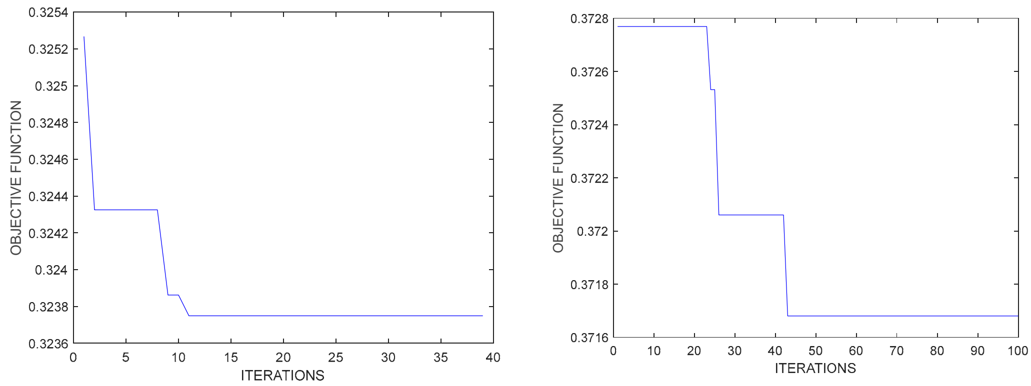


Figure 8. Voltage THD in scenario 2 for the 33-bar system.

Table 1. Results of the 33-bar system.

Scenario	Parameters	Proposed Method
Base	P Lost [kVW]	202.68
	Q Lost [kVAr]	135.51
	Average Voltage Deviation [p.u]	0.0515
	Maximum Voltage Deviation [p.u]	0.0869
	maxTHDv	0%
Compensated without THDv restriction (Scenario 1)	Installed capacity [kVAr] (location)	1300 (30)
	P Lost [kVW]	143.68
	Q Lost [kVAr]	96.48
	% Loss Reduction	29.02%
	Average Voltage Deviation [p.u]	0.0395
	Maximum Voltage Deviation [p.u]	0.0740
	maxTHDv	8.56%
Compensated with THDv restriction(Scenario 2)	Installed capacity [kVAr] (location)	854 (27)
	P Lost [kVW]	164.04
	Q Lost [kVAr]	111.19
	% Loss Reduction	18.7%
	Average Voltage Deviation [p.u]	0.0455
	Maximum Voltage Deviation [p.u]	0.0786
	maxTHDv	2.99%
Immune algorithm (After implementation)	Installed capacity [kVAr] (location)	962.49 (12)
	P Lost [kVW]	171.81
	Q Lost [kVAr]	No information
	% Loss Reduction	15.23%
	Average Voltage Deviation [p.u]	0.0404
	Maximum Voltage Deviation [p.u]	0.0742

The evolution of the objective function for the two scenarios of the 33-bar system is presented in Figure 9. This figure shows the behaviour of the objective function as a function of the iterations. The system converges because there are particles that satisfy all the restrictions. If no particles satisfy all the restrictions, the system does not converge, implying that there is no solution for the scenario.



(**a**) (**b**)

Figure 9. Evolution of the objective function for scenario 1 without THDv restriction (**a**) and scenario 2 with THDv restriction (**b**).

4.2. 34-Bar System

The results obtained in the scenario without the harmonic injection restriction, scenario 1, are presented. By implementing the proposed technique without restriction, the result is that the system must have a DSTATCOM of 1842 [MVAr] connected to bus 21. When implementing the DSTATCOM with the specified power and in the mentioned bus, there is a reduction in power losses and an improvement in the voltage profile. This is evidenced in Figures 10 and 11, respectively.

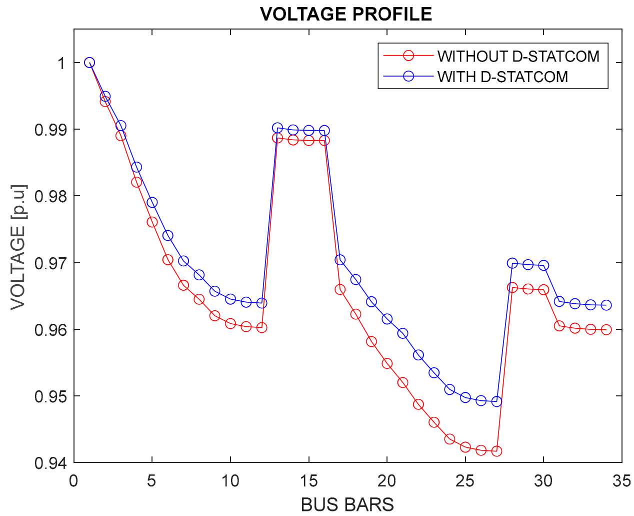


Figure 10. Voltage profile in scenario 1 for the 34-bar system.

To limit the total harmonic distortion of voltage in the system bars, the restriction is implemented in the proposed mathematical model; in this way, scenario 2 is obtained for the 34-bar system. In this scenario, the DSTATCOM must be added to bus 21 and inject 1476 [MVAr] into the network. With this implementation, it is possible to reduce both the voltage deviation and the power losses, ensuring that the THDv in all the bars is less than 3%.

In this configuration, similar to the unrestricted scenario, an improvement in voltage profile and a reduction in voltage deviation are observed.

Figure 12 graphically represents the reduction in the voltage drift and the improvement of the voltage profile.

Power losses in the current scenario are reduced as in the unrestricted scenario. Both active and reactive power losses for the 34-bar system are presented in Figure 13.

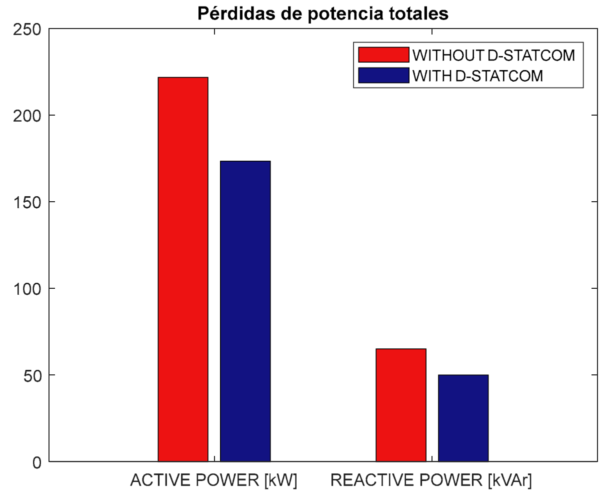
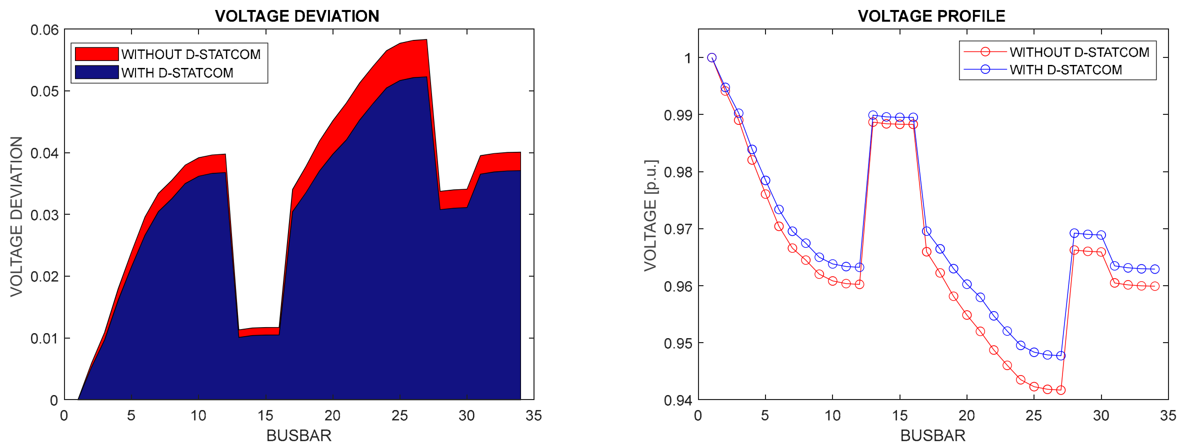


Figure 11. Power losses in scenario 1 for the 34-bar system.



(**a**) (**b**)

Figure 12. Voltage deviation in scenario 2 for the 34-bar system (**a**). Voltage profile in scenario 2 for the 34-bar system (**b**).

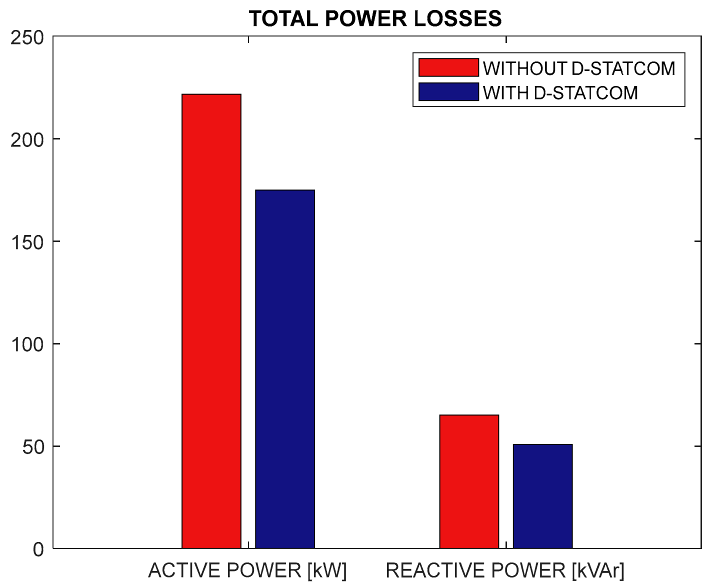


Figure 13. Power losses in scenario 2 for the 34-bar system.

Figure 14 demonstrates that in the study system, no bar exceeds the limit established for the THDv.

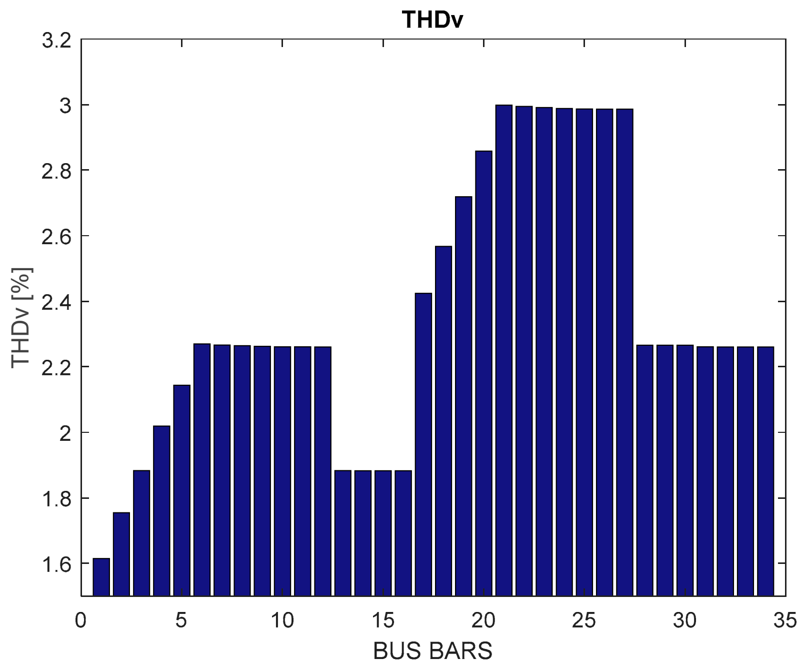


Figure 14. THDv in scenario 2 for the 34-bar system.

Table 2 details the results obtained for the case without the harmonic injection restriction and the scenario with the restriction.

Table 2. Results for the 34-bar system.

Scenario	Parameters	Proposed Method
Base	P Lost [kVW]	221.72
	Q Lost [kVAr]	65.11
	Average Voltage Deviation [p.u]	0.0342
	Maximum Voltage Deviation [p.u]	0.0583
	maxTHDv	0%
Compensated without THDv restriction (Scenario 1)	Installed capacity [kVAr] (location)	1842 (21)
	P Lost [kVW]	173.42
	Q Lost [kVAr]	50.029
	% Loss Reduction	21.89%
	Average Voltage Deviation [p.u]	0.0302
	Maximum Voltage Deviation [p.u]	0.0509
	maxTHDv	3.74%
Compensated with THDv restriction (Scenario 2)	Installed capacity [kVAr] (location)	1476 (21)
	P Lost [kVW]	174.895
	Q Lost [kVAr]	50.759
	% Loss Reduction	21.2%
	Average Voltage Deviation [p.u]	0.0309
	Maximum Voltage Deviation [p.u]	0.0522
	maxTHDv	2998%

The behaviour of the objective function for the scenario without the harmonics restriction and for the scenario with the harmonics restriction is presented in Figure 15. This graph represents the evolution of the value of the objective function as a function of the iterations. It can be seen that a satisfactory result is achieved for the two proposed scenarios.

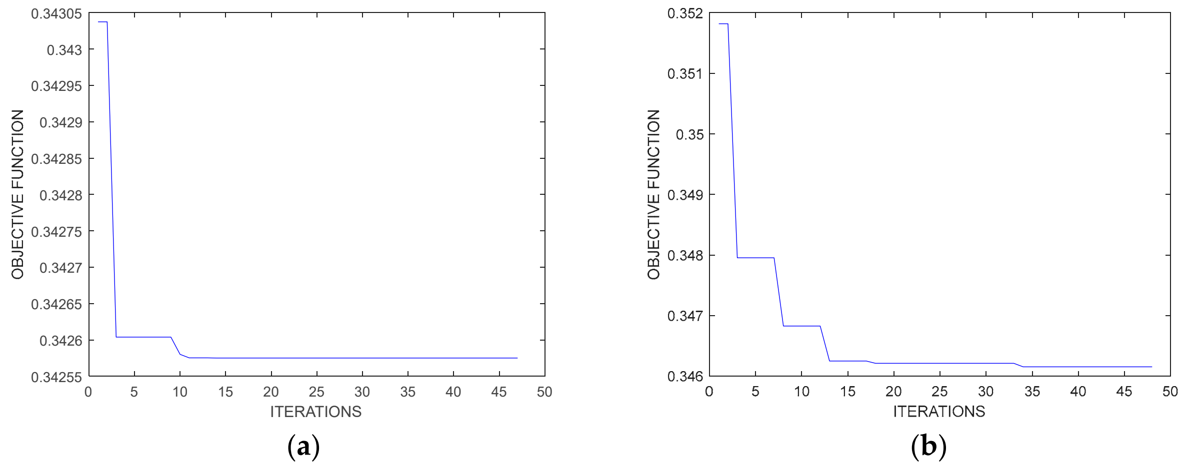


Figure 15. Evolution of the objective function in the 34-bar system for scenario 1 without THDv restriction (**a**) and scenario 2 with THDv restriction (**b**).

5. Conclusions

Through an exhaustive analysis and the implementation of the JAYA algorithm, the precise identification of the optimal location for integrating the DSTATCOM in the distribution 33- and 34-bar systems was achieved. This strategy proved highly effective in achieving optimal reactive power compensation, culminating in significantly reduced power losses and a palpably improved system voltage profile.

The results obtained via the JAYA algorithm underline the recommendation of placing the DSTATCOM devices on bars 27 and 21 for the 33- and 34-bar systems, respectively, with compensation capacities of 0.841 MVAr and 1.46 MVAr. This configuration has proven worth generating noticeable improvements compared to the initial conditions. In the 33-bar system, there was an 11.7% decrease in average voltage deviation, a 9.7% reduction in maximum voltage deviation, and a substantial 18.7% decrease in apparent power losses. For the 34-bar system, a 10.5% reduction in average voltage deviation, a 9.7% decrease in maximum voltage deviation, and a staggering 21.2% decrease in apparent power losses were achieved.

A significant achievement of this implementation is that the maximum total harmonic distortion in voltage (THDv) registered in both test systems is kept below the maximum limit established by 3%. This compliance demonstrates the effectiveness of the location and sizing strategy and the JAYA algorithm to improve power quality in the distribution systems analyzed substantially.

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Conflicts of Interest: The authors declare no conflict of interest.

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