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INVESTIGACIÓN

Optimal integration of D-STATCOMs in electrical distribution systems for investment and operating cost reduction by using a Master-Slave Methodology between GA/PSO

Integración óptima de D-STATCOMs en sistemas eléctricos de distribución para reducción de costos de inversión y operación utilizando una metodología Maestro-Esclavo entre el GA/PSO

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Abstract

Objective: The objective of this paper is to propose a methodology for the optimal location and sizing of D-STATCOMs within a distribution electrical system, with the aim to reduce the annualized operating costs related to the annual power energy losses and the investment costs associated with the installation of the D-STATCOM.

Context: This paper presents a hybrid methodology based on a master-slave strategy and the genetic and particle swarm optimization algorithms for solving the problem of optimal location and sizing of Distribution Static Compensators (D-STATCOMs), for reactive compensation in electrical distribution systems.

Methodology: In this paper was used a mathematical formulation that represents the effect of the location and sizing of D-STATCOMs in electrical distribution systems; by proposing a master-slave methodology combining the genetic algorithm and the particle swarm optimization algorithms as a solution method. Furthermore, with the aim to validate the effectiveness and robustness of the proposed methodology in this work, three comparison methods, two test systems, and multiple technical considerations were used to represent the electrical distribution systems in a distributed energy resource

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environment.
Results: The results obtained show that the proposed methodology is the most effective solution method for solving the problem, by achieving the greatest reduction in relation to the investment and operating costs. This methodology will allow the grid operators to identify the location and size of the D-STATCOMs within the electrical energy distribution system, with the lowest investment and operating costs in relation to other works reported in specialized literature.
Conclusions: The obtained results demonstrate that GA/PSO achieved the best performance, with the DCVSA comparison method in second place, and the GAMS solvers in third place. It is important to notice that it was not possible to evaluate the GAMS solvers on the 69 bus test system, because this solver failed the mathematical formulation that represented this electrical system. Based on previous results, it can be concluded that the GA/PSO is the most suitable optimization method used for solving the problem of optimal integration of D-STATCOMs in Distribution electrical systems for the grid.

Keywords: Distribution static compensator, electrical distribution planning, GAMS solvers application, metaheuristic optimization, optimal power flow, power loss minimization.

RESUMEN

Objetivo: El objetivo de este trabajo es proponer una metodología para la ubicación y dimensionamiento óptimo de D-STATCOM dentro de un sistema eléctrico de distribución, con el objetivo de reducir los costos operativos anualizados relacionados con las pérdidas anuales de energía eléctrica y los costos de inversión asociados con la instalación. del D-STATCOM.
Contexto: Este documento presenta una metodología híbrida basada en una estrategia maestro-esclavo entre los algoritmos genético y el de optimización de cúmulos de partículas para resolver el problema de localización y dimensionamiento de compensadores estáticos distribuidos (D-STATCOMs) para compensación reactiva en la red eléctrica de distribución.
Metodología: En este manuscrito fue empleado una formulación matemática que representa el efecto de la localización y dimensionamiento de compensadores D-STATCOMs en la red eléctrica de distribución; para lo cual se propone una estrategia maestro-esclavo entre los algoritmos genético y el de optimización de cúmulos de partículas como método de solución. Adicionalmente, con el objetivo principal de evaluar la efectividad y robustez del algoritmo fueron utilizados tres métodos de comparación, dos sistemas de prueba y múltiples consideraciones técnicas que representan las redes eléctricas de distribución de energía bajo un ambiente de recursos energéticos distribuidos.
Resultados: Los resultados obtenidos demostraron que la metodología de solución propuesta es la más efectiva de todos los métodos de solución empleados para resolver el problema aquí discutido. Logrando obtener la mayor reducción en los costos operativos del sistema con reducidos costos de inversión. Esta metodología permitirá a los operadores de red identificar la localización y dimensionamiento de los generadores dentro del sistema eléctrico de distribución de energía, con los menores costos de inversión en relación a otros trabajos reportados en la literatura especializada.
Conclusiones: Los resultados obtenidos demostraron que el GA/PSO alcanzó los mejores resultados, con el método DCVSA en el segundo lugar y los optimizadores de GAMS en tercero. Es importante notar que, en el sistema de 69 nodos no fue posible evaluar los optimizadores de GAMS, debido que estos fallan al solucionar el problema. Basado en los resultados anteriores, fue posible concluir que el GA/PSO es el método de optimización más adecuado para resolver el problema de localización y dimensionamiento de D-STATCOMs en redes eléctricas de distribución.

Palabras clave: Compensadores estáticos síncronos, planeamiento de sistemas eléctricos de distribución, aplicación de optimizadores GAMS, optimización metaheurística, flujo óptimo de potencia, reducción de pérdidas de potencia.

1 INTRODUCTION

In the last decades, with the development of the industrial society and the increase of population, it has been generated the need to improve the electrical distribution systems, in order to guarantee the quality and security of electrical services (Murray, W., Adonis, M., & Raji, A. (2021)), (Bahramara, S., Mazza, A., Chicco, G., Shafie-khah, M., & Catalão, J. (2020)), (Gil G., W., Montoya, O. D., Grisales-N., L. F., Ramírez V., C. A., & Molina C., A. (2020)). To carry out this task, in recent years different solution methodologies have been proposed which are based mainly on the integration of distributed energy resources for active and reactive compensation (Bahramara, S., Mazza, A., Chicco, G., Shafie-khah, M., & Catalão, J. (2020)), (Bouhouras, A. S., Sgouras, K. I., Gkaidatzis, P. A., & Labridis, D. P. (2016)). An example of this is the integration of distributed generators, capacitors, energy storage systems, and distribution static compensators among others (Mahmud, K., Khan, B., Ravishankar, J., Ahmadi, A., & Siano, P. (2020)), (Castillo, A. (2011)), (López, J. (2011)). Integrating these technologies on the grid is a revolutionary way to improve the technical and economic conditions of electrical distribution systems, and the focus of this research paper (Grisales-Noreña, L. F., Morales-Duran, J. C., Velez-Garcia, S., Montoya, O. D., & Gil-González, W. (2023)).

The optimal integration of D-STATCOMs in electrical grids has been widely studied in recent years. Due to the versatility and capacity of this kind of device, it has made reactive compensation and improved different technical and economic aspects to the grid: reduction of power losses, improve the voltage profiles, reduction of power flow on the lines, and operating costs among others (Montoya, O. D., Gil-González, W., & Hernández, J. (2021)). The positive impact of these devices on electrical networks is related to correct location and sizing, and this can only be achieved by using and adequate solution methodology (Eroğlu, F., Kurtoğlu, M., Eren, A., & Vural, A. M. (2023)), (Pedraza, A., & Reyes, D. (2015)). To obtain the major benefits through the integration of D-STATCOMs in the electrical grid, different works have been proposed in literature based on commercial software and metaheuristic optimization methods. An example of this is the works reported in (Montoya, O. D., Fuentes, J. E., Moya, F. D., Barrios, J. Á., & Chamorro, H. R. (2021)) where the solvers COUENNE and BONMIN of GAMS (General Algebraic Modeling System) were used, and a discrete version of the vortex search algorithm for reducing the annual operating and investment costs of a distribution grid in an environment of D-STATCOMs. By using specialized software, the authors (Montoya, O. D., Alvarado-Barrios, L., & Hernández, J. C. (2021)) proposed an exact mixed-integer nonlinear programming model decoupled into two convex optimization sub-problems for reducing the investment and operational cost of electrical distribution systems through the integration of D-STATCOMs. This formulation allows the authors to obtain a mixed-integer quadratic programming model as a function of the active and reactive power flow. The modified mathematical formulation was solved by using the branch and bound method. The proposed methodology was validated in the test systems of 33 and 69 buses. This paper demonstrates that the implementation of new solution methodologies for solving the problem of optimal integration of D-STATCOMs in distribution electrical systems will improve the results obtained in economic terms. When comparing the results obtained with other methodologies reported in literature, (Tolabi, H. B., Ali, M. H., & Rizwan, M. (2014)) proposed a multi-objective particle swarm optimization algorithm for optimal integration of D-STACOMs by considering the electrical reconfiguration. In this paper, they used an objective function that improved of voltage profiles, the power losses reduction, and the branches load potential. The authors (Gupta, A. R., & Kumar, A. (2016)) proposed energy savings by employing D-STATCOM placement in a radial distribution system under a reconfigured network, using the index vector method for radial distribution networks with and without reconfiguration.

As with previous studies, various works have been reported in the literature to enhance the technical and economic indices of the electrical network, and demonstrate the importance and advantages of installing D-STATCOMs on the electrical grid. The location and operation of D-STATCOMs in distribution electrical grids of different sizes is addressed in (Montoya, O. D., Alvarado-Barrios, L., & Hernández, J. C. (2021)). In this case, a MNLP model was used to present the problem with the aim of minimizing the annual operating costs of the grid by including the investment costs. By considering the behavior of different load profiles: residential, industrial, and commercial; a variable energy demand scenario was utilized. For solving the mathematical formulation, the authors used the software GAMS by considering a mono and multi-objective analysis. The simulations demonstrated that the location and operation of the compensator reactive power devices in the electrical systems improved the operational costs. (Belhamidi, M., Lakdja, F., Guentri, H., Boumediene, L., & Yahiaoui, M. (2023)) evaluated the impact of integrated and operated DSTATCOM of different sizes in an electrical network with the operation of wind turbines and variable power demand. The simulations were carried out by using the toll Simulink of MATLAB and demonstrated that the correct operation of D-STATCOMs on the grid improved the technical conditions of the grid. In (V., V. R. R., Doddi, B., Dixit, S., & B., L. (2023)) a multilevel control for operating D-STATCOMs in an electrical grid was proposed, based on closed loop controller, which allowed for improved technical conditions of the grid under a scenario of power variations. The simulation results were then compared with other control methodologies proposed in literature and demonstrated the robustness and flexibility of the proposed control strategy. (Akkad, A. F., Erdili, N., & Sosnina, E. (2023)) proposed a methodology based on a fuzzy logic controller by operating a D-STATCOM in an electrical grid with the aim to improve the effectiveness of this kind of technology in the technical parameters of the grid. (Ulloa de Souza, A. G. (2018)) proposed a mathematical optimization model by using MNLP solved with GAMS for the optimal location and sizing of the D-STATCOMs in distributed electrical systems. His ultimate aim was to improve the technical conditions of the grid. As test scenarios, it used the test systems of 33 and 69 buses and considered an objective function that reduced active power losses and improved the voltage profile by considering all operating restrictions of the grid.

By recognizing the importance of the problem of optimal integration and operation of D-STACOMs in electrical distribution systems, the aim of this work was to propose an efficient and robust solution methodology for this problem. In this paper, a master-slave methodology in combination with the genetic and particle swarm optimization algorithm was proposed. By using as objective function the reduction of the annual operating cost associated to the energy power losses and investment costs. Three comparison methodologies and two test systems were used to evaluate the effectiveness of the solution and methodology proposed. The obtained results demonstrate that the proposed methodology achieved the best solution. It was observed that as the size of electrical distribution systems increases, the proposed methodology outperforms the comparison methods.

As main contribution of this paper, it is important to mention the implementation of a new master-slave methodology based on the genetic algorithm and the particle swarm optimization method that allowed the improve results for solving the problem of optimal integration of D-STATCOMs and thus reducing the investment and operational costs.

Mathematical Formulation

The mathematical formulation used for optimal location and sizing of D-STATCOMs in electrical systems is presented in Equations (1) to (8). This mathematical formulation describes a non-linear and non-convex problem (Montoya, O. D., Alvarado-Barrios, L., & Hernández, J. C. (2021)), which is composed by a pondered multi-objective function with the same weight for both functions: 1, and a set of constraints describe the operation of electrical distribution system under a distributed generation environment. The entire mathematical formulation is described below.

Objective function:

$$minA_{cost} = f_1 + f_2 \tag{1}$$

The objective function in this paper used the reduction of the annual operative costs (A_{cost}) related to the annual power energy losses (f_1) and the investment costs associated to the installation of the D-STATCOM in electrical grid (f_2), see Equation (1).

$$f_1 = C_{kWh} T \sum_{h\in\mathcal{H}} \sum_{i\in\mathcal{N}} \sum_{j\in\mathcal{N}} Y_{ij} V_{ih} V_{jh} \text{coscos} \left(\delta_{ih} - \delta_{jh} - \theta_{ij}\right) \Delta_h \tag{2}$$

Equation (2) describes the annual power losses costs attributed to a year of operation (f_1), this equation considered the hourly behavior of the electrical system; where H and N are the sets that contain all the periods of times analyzed and the nodal buses that compose the electrical grid, respectively. In this equation C_{kWh} corresponds to the energy cost per kWh, T is a constant that allows for evaluating the horizon time used (1 year). Y_{ij} and δ_{ij} represent the magnitude and angle of the nodal admittance matrix associated with the nodes i and j. V_{ih} and V_{jh} represent the magnitudes of the voltage in the nodes i and j at the hour h, respectively; the variables δ_{ih} and δ_{jh} represents the voltage angle for the same buses at the same period. Finally, Δ_h is the time associated with the power flow analysis, 1/2 hour for this case (the power demand change in steps of 0.5 hours, see figure (4)).

$$f_2 = T\left(\frac{k_1}{k_2}\right) \sum_{k\in\mathcal{N}} \left(\alpha\left(Q_k^{D-STATCOM}\right)^2 + \beta Q_k^{D-STATCOM} + \gamma\right) Q_k^{D-STATCOM} \tag{3}$$

Furthermore, the Equation (3) represents the annual investment cost associated to the location of D-STATCOMs in electrical systems. In this equation, k_1 and k_2 are constants used for the annualization of the operating cost and useful life, respectively. α, β and γ are the constant that compose the mathematical model used to obtain the variable investment cost attributed to location of D-STATCOMs on the electrical grid, which is a function of the reactive power selected for each $D-STATCOM$ ($Q_k^{D-STATCOM}$).

Set of constraints:

The set of constraints that compose the mathematical formulation discussed here is presented from Equations (4) to (8).

$$P_{ih}^{g} - P_{ih}^{d} = \sum_{i \in \mathcal{N}} \sum_{j \in \mathcal{N}} Y_{ij} V_{ih} V_{jh} \cos\left(\delta_{ih} - \delta_{jh} - \theta_{ij}\right) \tag{4}$$

$$\mathcal{Q}_{ih}^{g} + \mathcal{Q}_{i}^{D-STATCOM} - \mathcal{Q}_{ih}^{d} = \sum_{i \in \mathcal{N}} \sum_{i \in \mathcal{N}} Y_{ii} V_{ih} V_{ih} \sin\left(\delta_{ih} - \delta_{ih} - \theta_{ii}\right) \tag{5}$$

$$V_{min} \leq V_{ih} \leq V_{max} \tag{6}$$

$$x_i \mathcal{Q}_{min}^{D-STATCOM} \leq \mathcal{Q}_{i}^{D-STATCOM} \leq x_i \mathcal{Q}_{max}^{D-STATCOM} \tag{7}$$

$$\sum_{i \in \mathcal{N}} x_i \leq N_{available}^{D-STATCOM} \tag{8}$$

Equation (4) and (5) represent the nodal active and reactive power balance, where P_{ih}^{g} and Q_{ih}^{g} correspond to the active and reactive power generated in the bus i on the period h; P_{ih}^{d} and Q_{ih}^{d} denote the active and reactive power demanded in the same bus and period. In Equations aforementioned, $Q_{ih}^{D-STATCOM}$ correspond to the reactive power injected by the D-STATCOM in the bus i on the period h. Equation (6) represent the voltage nodal bounds, where V_{min} and V_{max} are the minimum and maximum bus voltage allowed. The maximum $Q_{max}^{D-STATCOM}$ and minimum $Q_{min}^{D-STATCOM}$ reactive power limits are fixed for the $D-STATCOM$ located on the bus i are presented in Equation (7). Where x_i is a binary variable that takes a value of 1 if a $D-STATCOM$ is located on bus and 0 if not. Finally, Equation (8) limits the maximum number of $D-STATCOMs$ that are allowed to be installed on the distribution system.

Table (1) describes the parameters used for evaluating the mathematical formulation described in the last paragraph.

Table 1. Parameters used in the mathematical formulation.

Source: Authors.

Parameter	Value	Unit	Parameter	Value	Unit
C_{kWh}	0.1309	US$/kWh	T	365	Days
Δ_h	0.50	h	α	0.30	US$/MWh^3
β	-305.10	US$/MWh^2	γ	127380	US$/MWh
k_1	6/2190	1/Days	k_2	10	Years

Master-Slave methodology: GA/PSO

For solving the problem of optimal location and sizing of $D-STATCOMs$ in distribution electrical systems, in this paper a master-slave methodology was used with a combination of the Genetic Algorithm of Chu & and Beasley (GA) and the Particle Swarm Optimization algorithm (PSO). In master slave the GA is entrusted to solve the location problem and in the slave stage the PSO solves the sizing problem for each possible solution proposed by the master stage. The proposed methodology is described and explained below.

Master stage: Genetic Algorithm (GA)

In the master-slave methodology proposed implemented the GA in the master stage. This optimization method using an initial population generated through an aleatory process, which was combined with the generation of new decedents (created using the criterion of selection, recombination, and mutation), with the aim to obtain the optimal location of the $D-STATCOM$ inside the distribution electrical system.

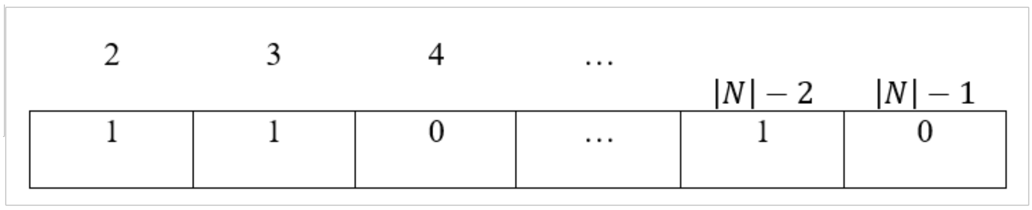

Figure 1. Binary codification for D-STATCOM location problem.

Source: Authors.

Figure (1) presents the codification used for solving the location problem, this codification is composed by a vector of $1 \times N - 1$, where $N - 1$ corresponds to the number of nodes that compose the distribution system, without considering the slack bus. By assigning a value of 1 when a $D-STATCOM$ is located on the bus and 0 if not.

Algorithm 1 Pseudo-code proposed for GA used in master slave

Data: Read data of electrical grid and GA parameters.
for $t = 1$: number of generational cycles **do**
  if t==1 **then**
    Generate the initial population;
    Evaluate the objective function and constrains for each individual by using the slave stage (Sizing problem);
    Select the best solution of the population as incumbent;
  else
    Generate an descendent by using selection, recombination and mutation;
    Evaluate the objective function and constrains for descendent by using the slave stage (Sizing problem);
    Replace the worst individual of the population with the descendent if the descendent improve its objective function;
    Update the incumbent.
    if the stopping criterion has been met **then**
      Finish the optimization process;
      Solution found;
      Print results;
      Break;
    else Continue;
    end if
  end if
end for

The pseudo-code that represents the optimization process of the GA used in the master stage is described in Algorithm (1). In this algorithm, it can be appreciated that the first iteration generates the initial population through an aleatory process. Then, the objective functions and constraints of all individuals in the population are evaluated by using the slave stage, which is entrusted to the sizing of each D-STATCOM located on the electrical system. Subsequently, it selects the best solution of the problem with the individual with the minor value of annual cost (incumbent).

From the second iteration until the completion of the iterative process of the GA, each iteration generated a new descendant through of the selection of individuals of the current population as parents (four in this particular case), which are recombined and mutated for generating the t descendant. Then, it is evaluated the objective function and constraints related to this descendant by using the slave stage. After this, if and only if, the objective function obtained for the descendant improves the objective function of the worst parent, the descendant would replace this inside the population. Subsequently, it would be update the incumbent of the problem. Finally, it was verified that the stopping criterion would be achieved when the maximum number of generational cycles and the maximum iteration number was completed without improvement.

Slave stage: Particle swarm optimization method (PS)

2	3	4	…	$\|N\|-2$	$\|N\|-1$
1,5	0,12	0	…	0,3	0

Figure 2. Continuous codification for D-STATCOM sizing problem.

Source: Authors.

The slave stage is responsible for sizing the $D-STATCOMs$ located in each configuration proposed by master stage. To carry out this task, a vector codification was used with continuous variables, see Figure (2). In this figure, it can be appreciated that in an example mode, for buses 2,4 and N-2 were assigned values of reactive power between the minimum and maximum values allowed by $D-STATCOMs$ located in such buses.

Algorithm 2 Pseudo-code for the PSO algorithm

```
Data: Read electrical systema data and PSO parameters.
for t = 1 : tmax do
    if t==1 then
        Generate the particles swarm in a randomly;
        Evaluate the objective function and constrains for each particle by using the hourly power flow method based on SA;
        Select as best particle solution and position the solution and position presented by each particle;
        Select as best swarm solution and position the best solution presented by the swarm particles and its position associated;
    else
        Calculate the velocity vector;
        Update the position of the particles swarm;
        Evaluate the objective function and constrains for each particle by using the hourly power flow method based on SA;
        Update best particle and swarm solution and position;
        if the stopping criterion has been met then
            Solution found;
            Finish optimization process;
            Return the sizing values for D-STATCOMs to the master slave;
            Break;
        else Continue;
        end if
    end if
end for
```

Algorithm (2) presented the iteration process related to the PSO algorithm used for solving the sizing problem. In this algorithm, it can be observed that the first iteration generated the particles swarm in an aleatory way. This first population corresponding to the sizing of D-STATCOMs proposed for a location configuration assigned by the master slave. Then, it is evaluated the objective function and constraints for each particle of the swarm. This is possible solving the power flow problem through an hourly power flow SA method (explained in the next subsection of this document), by using an objective function to reduce the annual cost that it is evaluated in each operation period. Then in the first iteration, it assigned the objective function and position for each particle as the best solution and position achieved by each particle. Subsequently, the best solution found inside the swarm and the position associated to this solution, it is selected as incumbent of the sizing problem.

The second iteration until the last, for each iteration, is calculated by a velocity vector which is responsible for updating the position of the particles in the solution space (Grisales-Noreña, L. F., Gonzalez, D., & Ramos-Paja, C. A. (2018)), (Grisales-Noreña, L. F., Montoya, O., & Ramos-Paja, C. A. (2020)). Then, the new position of the swarm is evaluated with the objective function and constraints for each particle using the hourly power flow method based on successive approximations. Updating the best solution and position of each particle in each iteration continues if the solution achieved in the current iteration improves the solution of the last. Afterwards, it has updated the incumbent of the sizing problem. Finally, the iteration process finishes if the stopping criterion has been met, in other case this continues. For this paper, the PSO used a stopping criterion of the maximum number of iteration and a maximum number of iterations without improvement. Finally, the slave stage returns the best solution found to the master stage when the iterative process finished. This solution corresponding to the sizing of D-STATCOMs located for each individual proposed for the master stage.

Hourly power flow bases on Successive Approximation method (SA)

In each iteration of the proposed methodology, it generates a population of individuals related to different solutions for the problem studied in this paper. Each individual proposed for the master-slave must be evaluated for obtaining its effect in the objective function of the problem, as well as to validate and satisfy all sets of constraints that describe the operation of a distribution electrical system in a scenario of D-STATCOM operation and variable power demand. To carry out this labor, an hourly version of the successive approximation method reported in (Grisales-Noreña, L. F., Montoya,

O. D., Cortés-Caicedo, B., Zishan, F., & Rosero-García, J. (2023)) and (Montoya, O. D., Garrido, V. M., Gil-Gonzalez, W., & Grisales-Norena, L. F. (2019a)), (Montoya, O. D., Garrido, V. M., Gil-Gonzalez, W., & Grisales-Norena, L. F. (2019b)) was used. The algorithm (3) that represents the iteration process of the used hourly power flow method is presented and described below:

Algorithm 3 Pseudo-code for the hourly power flow method based on SA

Data: Read electrical systema data location and power dispatch proposed for the D-STATCOM.

for $t = 1 : 48$ **do**

  Load the power demand for the hour t;

  Load the location and power dispatch of reactive power for the D-STATCOMs for the hour t;

  Solve the power flow for the hour h using the SA (Montoya et al., 2019b);

  Calculate the operation cost for the hour h;

  Calculate the set of constraints for the hour h;

end for

Calculate f_1,f_2 and A_{cost}

Return the A_{cost} to the -slave stage;

The hourly power flow used in this paper, in the first step, is loading the power demand for the hour t of the loads connected to the electrical distribution system. Then, the hourly power flow loads the location and power dispatch of reactive power for the D-STATCOMs for the same hour. Subsequently, by using the SA reported in (Montoya, O. D., Garrido, V. M., Gil-Gonzalez, W., & Grisales-Norena, L. F. (2019b)), it calculated the operational costs and the set of constraints that formulated the problem for the hour t. This process continued until all hours that compose the horizon time were analyzed, in this case 24 hours, represented in 48 steps of 0.5 hours. Finally, by considering the operation and investment cost, it calculated the A_{cost}; by returning the objective function value to the master-salve methodology.

Test Systems, Comparison Methods and Test Scenarios

To verify the effectiveness of the master-slave methodology proposed this paper, the test systems of 33 and 69 buses were used. Solving the problem of optimal integration of distributed resources has been implemented as reported in specialized literature (Grisales-Noreña, L. F., Gonzalez, D., &

Ramos-Paja, C. A. (2018)), (Moradi, M. H., & Abedini, M. (2012)) It is described in the next subsections.

It is important to highlight that the average time of the solution for methodologies was 38 minutes. This is a negligible time in relation to the time considered within the planning horizon time (years). Therefore, the authors of this manuscript did not consider adequately to carry out an analysis of the processing times required by the solution methodologies here analyzed.

33 nodes test system

This electrical test system is composed of 33 nodes, 32 branches, multiple constant power loads and a unique slack generator. Figure (3)(a) presents the electrical diagram and its technical information is explained in (Grisales-Noreña, L. F., Gonzalez, D., & Ramos-Paja, C. A. (2018)).

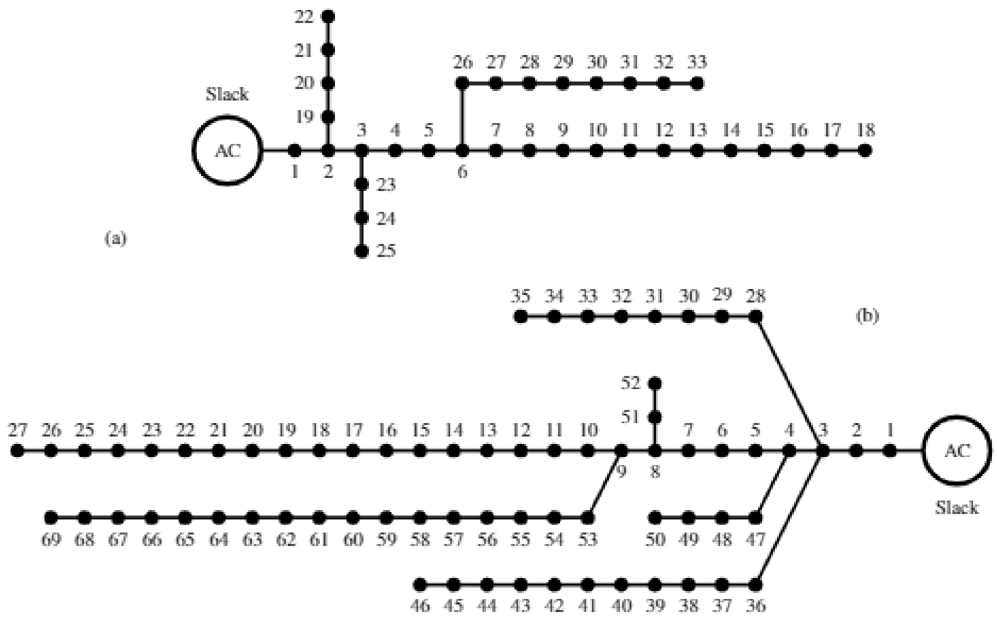

Figure 3. Electrical configuration of test systems used (a) 33 nodes test systems, and (b) 69 nodes test system., (Montoya, O. D., Gil-González, W., & Hernández, J. (2021)).

Source: Authors.

69 bus test system

The electrical configuration of this test system is presented in Figure (3)(b). This system is composed of a unique slack generator, 33 buses, 69 branches and different power constant loads localized in the different buses of the system. Base values were employed with 12,66 kV and 100 kVA, respectively. All technical parameters of this test system are described in (Grisales-Noreña, L. F., Gonzalez, D., & Ramos-Paja, C. A. (2018)).

Comparison methods, test scenarios and considerations

Comparison methods, test scenarios and considerations: Comparison methods in this paper were used which include two solvers of the specialized software General Algebraic modeling System (GAMS): BONMIN and COUENNE solvers, and the discrete version of the vortex search algorithm (DCVSA) (Montoya, O. D., Gil-González, W., & Hernández, J. (2021)) which used the tuning parameters proposed by the authors. For the proposed GA/PSO, the parameters were tuned by using a PSO algorithm obtained from the values reported in Table (2).

Table 2. Parameters of master–slave methodology proposed.

Source: Authors.

Method	**GA**	**PSO**
Numbers of particles	12	30
Selection method	Tournament	Cognitive and social component: 1,4
Update population method	Cross over: simple	Speed (max-min): (0,1 – 0,1) Inertia (max-min): (0,7 – 0,001)
Mutation	Binary simple	R1=R2: Random
Stopping criterion	Gerational cycles: (200) Iteration without improve: (50)	Maximum iterations: (200) Iteration without improve: (50)

In addition, it is used a maximum number of three D-STATCOMs to be located in the distribution system by considering all buses of the electrical grid as candidates for location, except the Slack bus.

Furthermore, as reactive power bounds were considered, a minimum and maximum value of 0 MVAr and 2 MVAr were used, respectively. Finally, due to the mathematical formulation proposed in this paper, the hourly variation of active and reactive power demand on the electric systems in periods of 0,5 hours for a day of operation were selected (48 periods), see Figure (4). This figure illustrated the typical behavior in power demand of a electrical distribution systems of Colombia (Montoya, O. D., & Gil-Gonzalez, W. (2020)), used for both test systems.

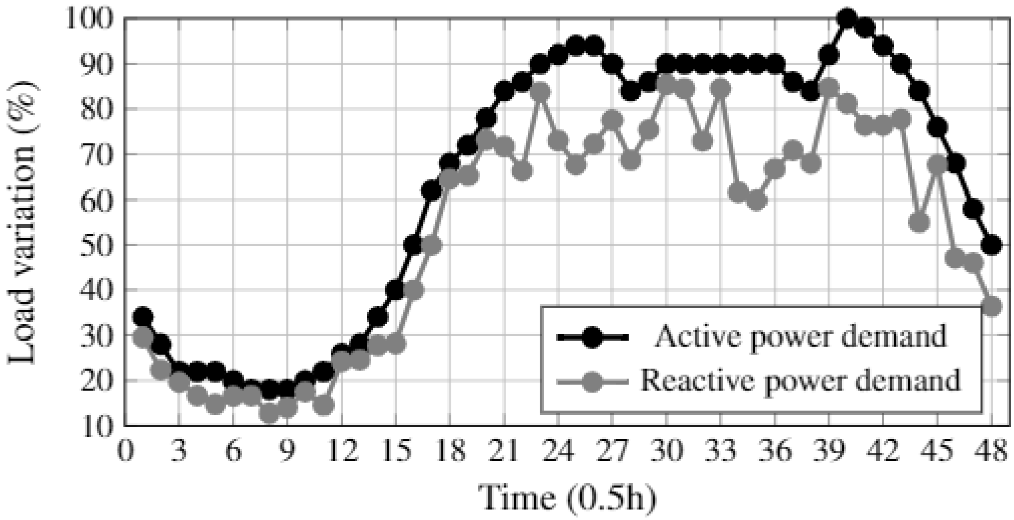

Figure 4. Typical behavior of the active and reactive power consumption in a Colombian electrical distribution system. (Montoya, O. D., Alvarado-Barrios, L., & Hernández, J. C. (2021)), (Montoya, O. D., & Gil-Gonzalez, W. (2020)).

Source: Authors.

Simulation Results

To run all simulations, this paper used the software GAMS for commercial solvers and the Matlab software for the solution methods based on sequential programming. The software ran on a PC with an AMD Ryzen7 3700 2,3 GHz processor and 16,0 GB RAM, running on a 64 bits version of Microsoft Windows 10. In the next subsection the results were analyzed for each test system:

33 nodes test system

Table (3) presents the results obtained for the different solution methods for solving the problem of optimal integration of D-STATCOMs in electrical distribution systems. This table showsleft to right the following information: the solution method used, the location and size in MVAr of the different D-STATCOMs on electrical system, and the annual cost related to the integration of these devices in US$ per year.

Table 3. Results obtained for 33 nodes sytems.

Source: Authors.

Method	**Location (Size node (MVar))**	A_{cost} **(US$/year)**
Base case	-	112740,90
COUENNE	$\{16\,(0,0109)\,,\ \ 17\,(0,0224)\,,\ \ 18\,(0,2065)\}$	107589,50
BONMIN	$\{17\,(0,0339)\,,\ \ 18\,(0,0227)\,,\ \ 30\,(0,2395)\}$	102447,29
DCVSA	$\{14\,(0,1599)\,,\ \ 30\,(0,3591)\,,\ \ 32\,(0,1072)\}$	98497,90
GA/PSO	$\{14\,(0,1599)\,,\ \ 30\,(0,3497)\,,\ \ 31\,(0,1166)\}$	98511,63

The Figure (5) presents the reduction obtained by the different solution methods with respect to the base case. In this figure, it can be appreciated that all solution methods reduce the annual costs, by obtaining a reduction of 4,56 % (COUENNE), 9,13 % (BONMIN), 12,63 % (DCVSA) and 12,62 % (GA/PSO) in relation to the base case. By analyzing these results, it can be appreciated that the proposed methodology created the second greatest savings with an annual cost of $98511,63US/year$, surpassed only by DCVSA by 0,01 %. With respect to the GAMS solvers, the GA/PSO reduced the annual cost by 8,05 % and 3,49 %, respectively.

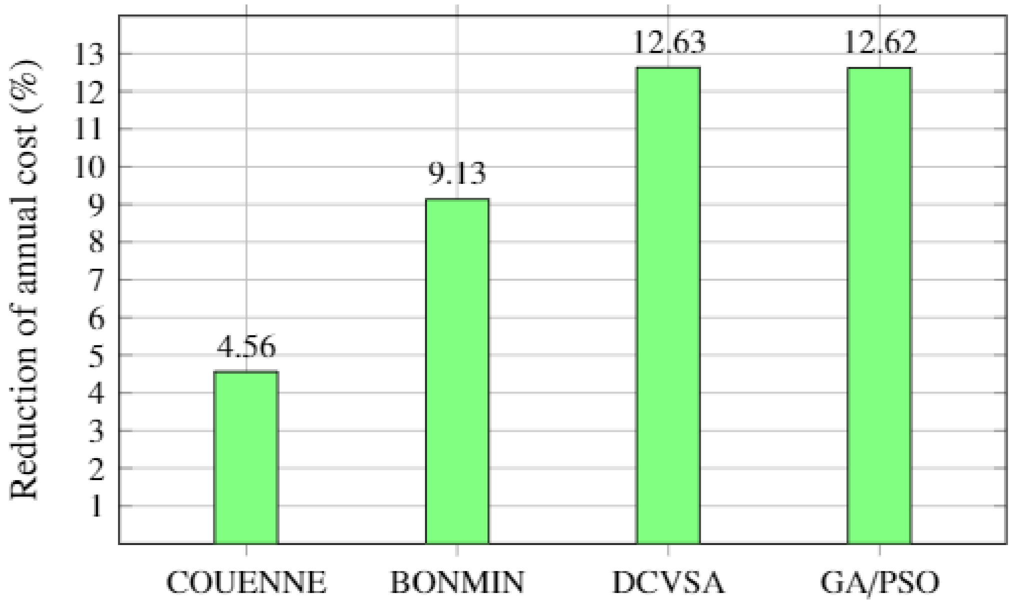

Figure 5. Reduction obtained in annual cost by the solution methods in 33 nodes test systems with respect to the base case.

Source: Authors.

The operational and investment costs provided by each solution and the base case is presented the Figure (6), where is possible to identify that greater investments were made by the DCVSA and GA/PSO corresponding to $7,97{\cdot}10^3$ US$. Furthermore, due to the greater investment in D-STATCOM devices which lower operational costs to $90,53 \cdot 10^3 US\$$ (DCVSA) and $9,54 \cdot 10^3 US\$$ (GA/PSO). By observing these results, it is possible to notice that the GA/PSO is just 0,01 % lower than the best solution (DCVSA) while maintaining an average reduction of 4,54 % with respect to the other methodologies.

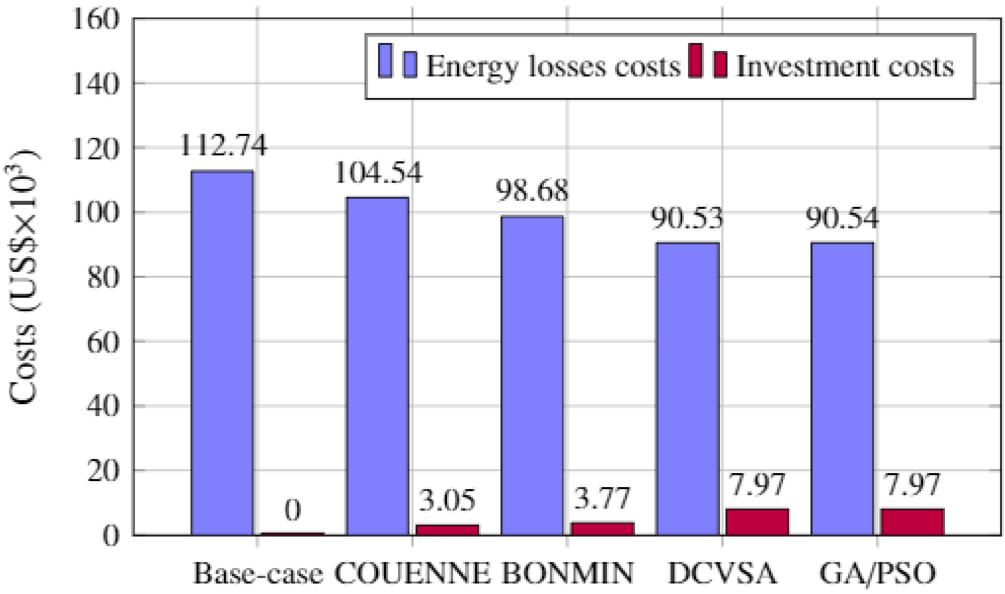

Figure 6. Comparison of the operative and investment costs for 33 bus.

Source: Authors.

69 nodes test system

For this test system, it was not possible to obtain the results for the GAMS solvers, since both solvers failed to solve the mathematical formulation for the 69 nodes test systems. This shows the effectiveness and robustness of the solution methods based on sequential programming of the proposed methodology. In this way, Table (4) presents the results obtained by the DCVSA and GA/PSO for 69 nodes test systems.

Table 4. Results obtained for 69 nodes systems.

Source: Authors.

Method	**Location (Size node (MVar))**	**A_{cost} (US$/year)**
Base case	-	119715,63
DCVSA	$\{21\,(0,0839)\,,\ \ 61\,(0,4601)\,,\ \ 64\,(0,1139)\}$	102990,80
GA/PSO	$\{21\,(0,0839)\,,\ \ 61\,(0,4600)\,,\ \ 64\,(0,1139)\}$	102990.79

In the last table (4), it was possible to observe that both solution methods select the same nodes for located the D-STATCOMs in distribution electrical system, and the fixed size for each device are similar by providing an average reduction of the annual costs in both solutions of 13,97 %, see Figure (7).

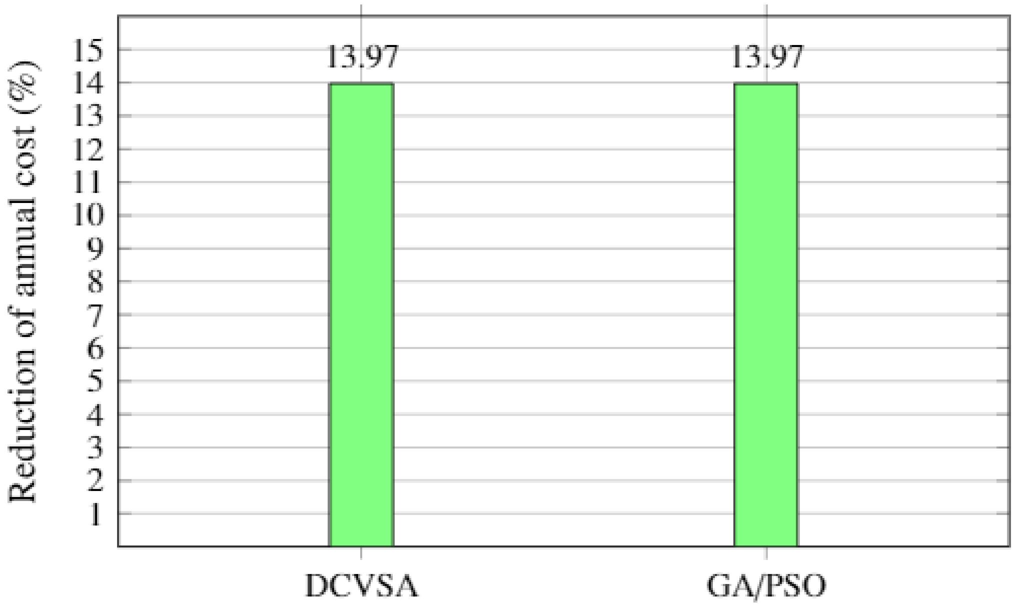

Figure 7. Reduction obtained in annual cost by the solution methods DCVSA and GA/PSO in 69 nodes test systems with respect to the base case.

Source: Authors.

Figure (8) illustrated the operational and investment costs for both solution methodologies by achieving in both cases a value of $94,61 \cdot 10^3 US\$$ and $8,37 \cdot 10^3 US\$$, respectively.

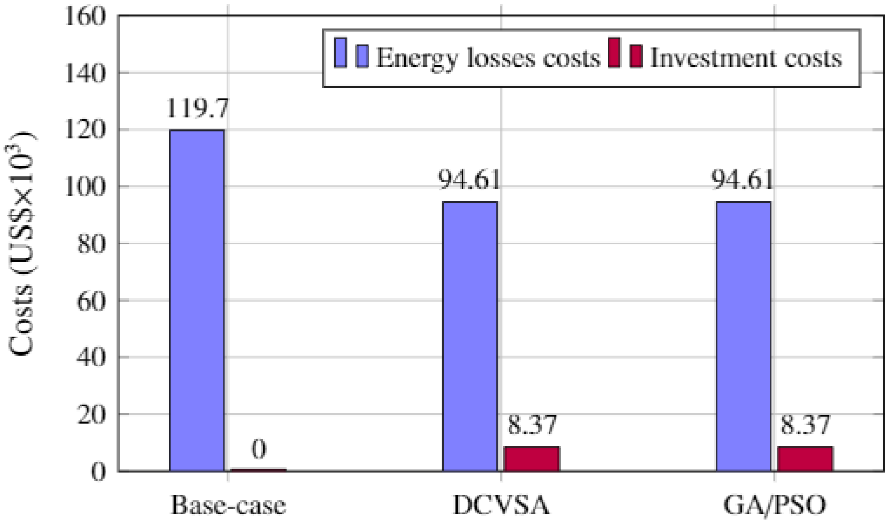

Figure 8. Comparison of the operational and investment costs for 33 bus

Source: Authors.

However, a closer look at results reported in Table (3) reveals that the GA/PSO was the solution methodologies that reported the best solution, by providing a reduction of the annual operating cost of $8,3510^{-6}$ % with respect to the DCVSA. This is a lower difference, but this value demonstrates that the proposed methodology improved the results reported in specialized literature for solving the problem studied. It should be recognized that the solver of GAMS failed to solve the problem when the solution space increased in size.

2 CONCLUSIONS

In this paper, it was proposed a master-slave methodology combined with the GA and PSO algorithms, with the aim to reduce the annual cost, operating and investment cost associated with active power losses and installation costs of D-STATCOMs, of an electrical distribution system by means of the optimal location and sizing of D-STATCOMs devices on the grid, by considering the variation in the power demand in a horizon time of 24 hours. For evaluating the effectiveness and robustness of the GA/PSO methodology, in this paper two electrical test systems of 33 and 69 nodes and three comparison methodologies based on commercial software and sequential programming were used. By analyzing the results obtained by the different solution methodologies in the small electrical system (33 bus test system), it was possible to observe that the GA/PSO presented the best results when compared with the commercial solvers of Matlab (COUENNE and BONMIn). Furthermore, the GA/PSO was second only to DCVSA with only a difference 0.01% with respect to the reduction of annual costs. For this reason, the proposed methodology is considered an adequate solution methodology for solving the problem of optimal integration of D-STATCOMs in small electrical distribution systems.

With the aim to verify the robustness of the different methodologies used in larger test systems, the 69 nodes test system was used. The results obtained demonstrated that the GA/PSO obtained the best results, with the DCVSA in second place. It is important to notice that it was not possible to evaluate the Matlab solvers on 69 bus test system, due to this solver failing the mathematical formulation that represented this electrical system. Based on the previous results, it is possible to conclude that the GA/PSO is the most suitable optimization method used for solving the problem of optimal integration of D-STATCOMs in distribution electrical systems for large size grid.

The location and sizing of D-STACOMs in electrical networks is a non-convex problem, due to the presence of binary variables associated with the location, and the nonlinearities existing within the global power balance constraint, which is the base of the power flow problem, necessary to evaluate the effect of each location and sizing of the D-STATCOMs within the network. MATLAB's solvers work well with continuous variable problems, guaranteeing the global optimum every time that these are executed. This occurs when this kind of optimization methods solve the power dispatch problem of distributed energy resources. However, when adding the problem of location to these technologies within the network, the nonlinearities associated with the binary variables means that the GAMS solvers are trapped in local optima. Based on the above, it is possible to conclude that the integration of binary variables into the mathematical model generates GAMS solvers that are not as efficient as metaheuristic optimization algorithms based on sequential programming such as GA/PSO.

In future work, it should be considered that the implementation of new solution methodologies that allow for improved results be reported in the literature, as well as by including other distributed energy resources inside the electrical grid as distributed generators and energy storage devices, with the aim to improve the technical and economic conditions of the grid.

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