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DESAFIOS DAS ENGENHARIAS:

ENGENHARIA ELÉTRICA 2

JOÃO DALLAMUTA
HENRIQUE AJUZ HOLZMANN
(ORGANIZADORES)

Atena
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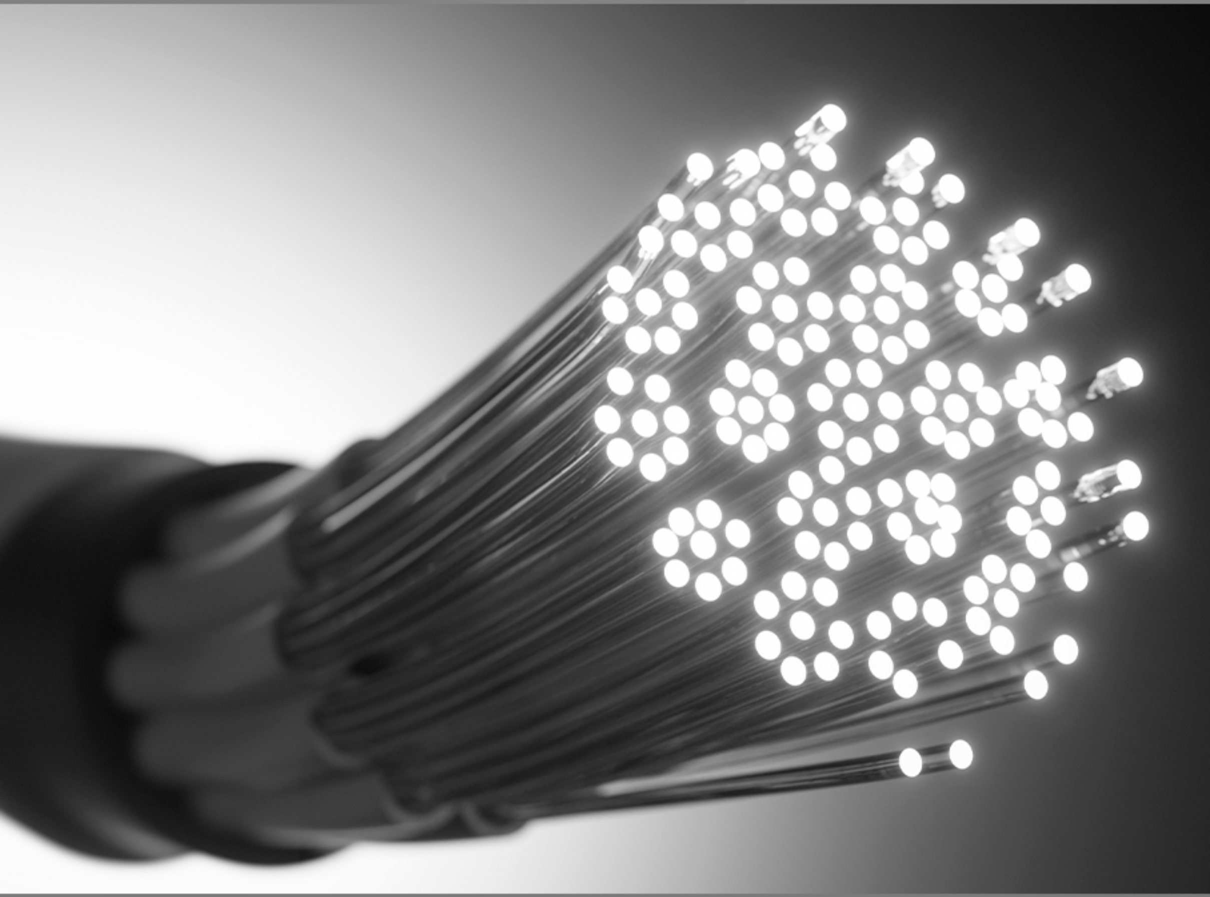

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Atena Editora
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Telefone: +55 (42) 3323-5493
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APRESENTAÇÃO

A engenharia elétrica tornou-se uma profissão há cerca de 130 anos, com o início da distribuição de eletricidade em caráter comercial e com a difusão acelerada do telégrafo em escala global no final do século XIX.

Na primeira metade do século XX a difusão da telefonia e da radiodifusão além do crescimento vigoroso dos sistemas elétricos de produção, transmissão e distribuição de eletricidade, deu os contornos definitivos para a carreira de engenheiro eletricista que na segunda metade do século, com a difusão dos semicondutores e da computação gerou variações de ênfase de formação como engenheiros eletrônicos, de telecomunicações, de controle e automação ou de computação.

Produzir conhecimento em engenharia elétrica é portando pesquisar em uma gama enorme de áreas, subáreas e abordagens de uma engenharia que é onipresente em praticamente todos os campos da ciência e tecnologia.

Neste livro temos uma diversidade de temas, níveis de profundidade e abordagens de pesquisa, envolvendo aspectos técnicos e científicos. Aos autores e editores, agradecemos pela confiança e espirito de parceria.

João Dallamuta
Henrique Ajuz Holzmann

SUMÁRIO

CAPÍTULO 9

CAPACITOR BANK ALLOCATION IN DISTRIBUTION SYSTEMS USING THE DISCRETE PSO ALGORITHM

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Luís Henrique Chouay Dall' Agnese
Faculdade União das Américas - UNIAMÉRICA
Foz do Iguaçu - PR
http://lattes.cnpq.br/1502220513099067

Carlos Roberto Mendonça da Rocha
Universidade Estadual do Oeste do Paraná
Foz do Iguaçu - PR
http://lattes.cnpq.br/4658529903411274
https://orcid.org/0000-0002-0711-2668

ABSTRACT: This chapter presents an article whose subject seeks to define the optimal allocation of capacitors for reactive power flow planning in distribution power system. The problem is based on a mathematical model that minimizes the operation and investment cost, where a sensitivity index and the lowest voltage are used to select the buses for allocation. A Particle Swarm Optimization (PSO) algorithm adapted to a discrete version is used to find the best quantity and location of the capacitor bank (CB). As a result, there was a reduction in power loss and an improvement in the voltage profile even with the addition of CB. The method is applied in the 10 and 34 bus system. The proposed algorithm presented a good solution compared to other optimization techniques presented in the literature.

KEYWORDS: Power systems, Power distribution, Reactive Power Planning.

ALOCAÇÃO DE BANCO DE CAPACITORES EM SISTEMAS DE DISTRIBUIÇÃO USANDO ALGORITMO DE PSO DISCRETO

RESUMO: Este capítulo apresenta um artigo cujo assunto procura por definir a alocação ótima de capacitores para o planejamento do fluxo de potência reativa no sistema de distribuição de energia. O problema é baseado em um modelo matemático que minimiza o custo de operação e investimento, onde um índice de sensibilidade e as barras de menor tensão são utilizados para selecionar as barras a serem alocadas. É utilizado um algoritmo de Otimização de Enxame de Partículas (PSO) adaptado para uma versão discreta para encontrar a melhor quantidade e localização do banco de capacitores (CB). Como resultado, houve uma redução na perda de potência e uma melhora no perfil de tensão mesmo com a adição do CB. O método é aplicado no sistema de 10 e 34 barras. O algoritmo proposto apresentou boa solução em comparação com outras técnicas de otimização apresentadas na literatura.

PALAVRAS-CHAVE: Sistemas de Potência, Sistemas de Distribuição, Planejamento de Potência Reativa.

1 I INTRODUCTION

The power grid is a set of equipment responsible for transporting electricity from one point to another, to ensure that consumers have access to electricity as pleased, and it is managed by electrical utility distribution. Besides continuous power supply, quality assurance is in the utility purview, meaning that the voltage levels shall be within limits established in technical standards for operating a distribution system (DS) (WILLIS, 2004).

During the years of operation, it is not possible to accurately predict the growth of the consumed load by the system, which leads to a reduction in the voltage profile of the grid and an increase in the power losses of electrical system (PEREIRA JUNIOR, 2009).

The DS is highly responsible for power losses in electrical power systems, and it has a low-voltage regulation. This issue is within the context of DS operation planning, which seeks to encounter a preferable operating scenario, aiming at minimizing costs. In this regard, several strategies are researched that reduces power loss in the grid, such as the use of distributed generation, the allocation of voltage regulators and the setup of capacitor banks (CB) (PRASAD REDDY P, 2014). The use of CB is a technique inserted within reactive power planning and usually employed to solve these problems (PRASAD REDDY P, 2014).

The allocation of CB is justified by the fact that these devices improve the grid voltage profile, leading to a more horizontal profile and thus improving the quality of the energy delivered to the consumer. Besides that, as they are inserting reactive power into the grid, they reduce the apparent power flow in the system, and this leads to lower electrical losses (TABARES, 2016). However, mistaken the CB insertion location as well as its quantity may worsen the system voltage profile and increase active power losses (DIXIT, 2016).

Thus, CB allocation can be handled as a combinatorial optimization problem, where there is a finite yet very large set of feasible solutions. For such problems, computer optimization algorithms are often employed, such as metaheuristics that do not guarantee a global solution to the problem, however, are efficient in finding high quality solutions without a high computational expense (DOS SANTOS PEREIRA, 2018).

For this problem, the literature shows a variety of algorithms that can be applied, such as Plant Growth Simulation Algorithm (RAO, 2008), Particle Swarm Optimization (DIXIT, 2016), Swarm robotics search & rescue algorithm, Genetic Algorithm (KALANTARI, 2011), Evolutionary Algorithms, Cuckoo Search Algorithm (PRASAD REDDY P, 2014), Gravitational Search Algorithm, Whale Optimization Algorithm (NEAGU, 2017), among others. The metaheuristic technique employed in this paper was the Particle Swarm Optimization (PSO), however, due to the nature of the problem, this algorithm has been adapted to work with discrete variables.

On the basis thereof, this paper presents an algorithm capable of reactive power planning of a power distribution system, through CB allocation. The algorithm is guided through an objective function that seeks to reduce the active power losses of the system, combined with a lower investment cost of CB setup.

The descriptions of mathematical model employed, the metaheuristic technique for objective function minimization, the adaptation of the technique to solve the problem, the results obtained, and the conclusion are described in the next sections.

2 | MATERIALS AND METHODS

This section describes in detail the mathematical model, aspects, formulation, adaptation of the meta- heuristic technique employed and a flowchart of the proposed algorithm. The mathematical formulation will be presented below.

The objective function evaluation that guides the PSO algorithm in search of the best location to insert CB is based on the following mathematical model.

$$\min Z = K_P P_T + \sum_{i=1}^{N_B} Kc_i Qc_i \tag{1}$$

$$-dp_i = \sum_{j-1}^{N} P_{i,j} + P_{j,i} \qquad i \in n \tag{2}$$

$$-dq_i + Nc_k * Q_B = \sum_{j=1}^{N} Q_{i,j} + Q_{j,i} \qquad i \in N, K \in N_B \tag{3}$$

$$P_{i,j} = V_i^2 g_{i,j} - V_i V_j g_{i,j} * \cos(\theta_i - \theta_j) - V_i V_j b_{i,j} * \mathrm{sen}(\theta_i - \theta_j) \tag{4}$$

$$Q_{i,j} = -V_i^2 b_{i,j} - V_i V_j g_{i,j} * \cos(\theta_i - \theta_j) + V_i V_j b_{i,j} * \mathrm{sen}(\theta_i - \theta_j) \tag{5}$$

$$S_{i,j} \le S_{MAX} \tag{6}$$

$$V_{MIN} \le V_i \le V_{MAX} \tag{7}$$

The first equation represents the function whose goal is to minimize two cost terms: the first of these is related to the system operation, which seeks to minimize the costs with active power losses, the second refers to investments in equipment where it looks for to minimize the cost of setting-up CB. In the equation, K_P (\$/kW) and $K_{C\text{i}}$ (\$/kvar) represents the cost for active power loss in the system and the cost of setting- up capacitor banks on bus *i*, P_T (kW) represents the total value of active power losses, Q_{Ci} (kvar) represents the reactive power of CB installed on bus *i*, and *NB* represents the set of system buses that has a CB connected to them.

The objective function is subject to a set of equality and inequality constraints. Within the equality constraints, (2) and (3) represents the system active and reactive power balance, where *dpi* and *dqi* represents the active and reactive power demands on bus *i*, respectively, $\mathcal{P}_{i,j}$ and $\mathcal{Q}_{i,j}$ represents the active and reactive power flow that flows from bus *i* to bus *j*, respectively, *N* refers to the set of system buses, N_{Ck} represents the number of CB installed on bus *k* and Q_B indicates the base power each bank can inject into the system.

Expressions (4) and (5) represents the equation of active and reactive power usage in line, respectively, V_i and Θ_i represents the magnitude and the angle of bus voltage *i* and, g_{ij} and b_{ij} represents the conductance and susceptance of line connecting bus *i* to bus *j*.

Regarding inequality constraints, (6) represents the apparent power limit on the line, which cannot exceed a maximum value, and (7) indicates the minimum and maximum voltage level limits on buses.

The optimization technique used is based on the particle cooperative movement within a swarm, like bird's flights, seeking the best solution for optimization problems (KENNEDY, 1995). The particles of PSO algorithm moves in three terms: the inertia term, which quantifies the particles tendency not to change direction, that is, keep its own movement, the cognitive term, which quantifies the particle tendency to follow the best path it has ever found, and the social learning term, which quantifies the particle tendency to follow the best path the entire swarm has already found, that is, the best position found.

Each particle carries two pieces of information: the number of CB to be installed and the candidate bus for receiving the devices, thereby defining the solution. Thus, at each iteration, the particles swarm moves within the solution space, seeking the best possible position. The position of each particle and the speed with which it moves are represented through expression (8).

$$V_p^{i+1} = wv_p^i + c1 * \left(p_p^{best} - p_p^i\right) + c2 * \left(g_{best} - p_p^i\right) \tag{8}$$

In (8), the first part refers to the inertia term, where v_p^i indicates the velocity of particle *p* in iteration *i* and *w* is the particle inertia index. The central expression indicates the cognitive learning term, where *c1* is the cognitive learning index, p_p^{best} is the best position where the particle *p* has ever been, p_p^i is the position of particle *p* in iteration *i*. And the last part shows the global learning term, where *c2* is the global learning index and g_{best} is the best position, any particle has ever been. The position of each particle represents the number of CB connected to bus *i*, where each CB is capable to provide a total of 150 kvar.

The PSO algorithm was designed to solve problems with continuous variables, however, the goal of this problem is to establish the number of CB that will be connected in each bus. Thus, the algorithm required adaptation so that it could work with discrete variables. The authors (KENNEDY, 1997) who initially developed PSO, also presents a way to discretize variables in PSO algorithms, which is based on the formulation presented below.

$$f = \frac{1}{1+e^{-v_p^{i+1}}} \tag{9}$$

$$p_p^{i+1} = \begin{cases} 1, & f \geq rand \\ 0, & f < rand \end{cases} \tag{10}$$

Equation (9) represents the Sigmoid Function which is responsible for establishing the particles velocity between 0 and 1, thus, equation (10) performs a draw to determine the logical level that represents that speed. The relation of this coding to the position vector of each particle is illustrated below.

$$p_p = [1 \quad 2 \quad 3 \quad 4 \quad 5] = \begin{bmatrix} 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix} \tag{11}$$

Equation (11) shows that each particle position is now represented by a binary vector, to use integer variables in discrete optimization problems. In addition, the position speed of each particle is also represented by a vector, so expressions (9) and (10) are used for each element of position matrix.

The definition of which system buses are candidates for insertion of CB is guided by two indicators presented below.

$$LSF_i = \frac{2Q_{i,j}r_{i,j}}{V_i^2} \tag{12}$$

$$Norm_i = \frac{V_i}{0.95} \tag{13}$$

Equation (12) indicates the Losses Sensitivity Factor on bus *i* (LSF_i), where $r_{i,j}$ represents the resistance of the line connecting bus to bus , and (13) represents a vector that normalizes voltage values on the buses. Both equations represent the criteria used to select the candidate buses for the CB installation. Firstly, the LSF is calculated and descending ordered, then are selected the buses whose corresponding normalization vector is greater than 1.01. The quantity definition and which are the candidate buses for CB allocation helps reduce the solving problem space (RAO, 2008).

A schematic diagram with the running steps of the algorithm is illustrated in Figure 1, which shows the execution process of the algorithm. The position of each particle is used to evaluate the objective function, so these values are compared to the best positions each particle has ever been, and with the best position the whole swarm has ever been. If these positions lead to a better value of the objective function, its stored. The best positions of each particle are used in equation (8) for updating the velocity of each particle.

3 I RESULTS AND DISCUSSIONS

The proposed algorithm was evaluated in test systems presents in literature, and the results compared with those obtained by other authors. For the algorithm execution, algebraic modeling software GAMS was used, with the CONOPT solver. In both cases, 10 particles, 50 iterations, K_P = 168 \$/kW, $w = c1 = c2 = 1$ were used, and the substation bus was chosen as a system voltage reference with value of $1\angle.0^{\circ}$ [p.u].

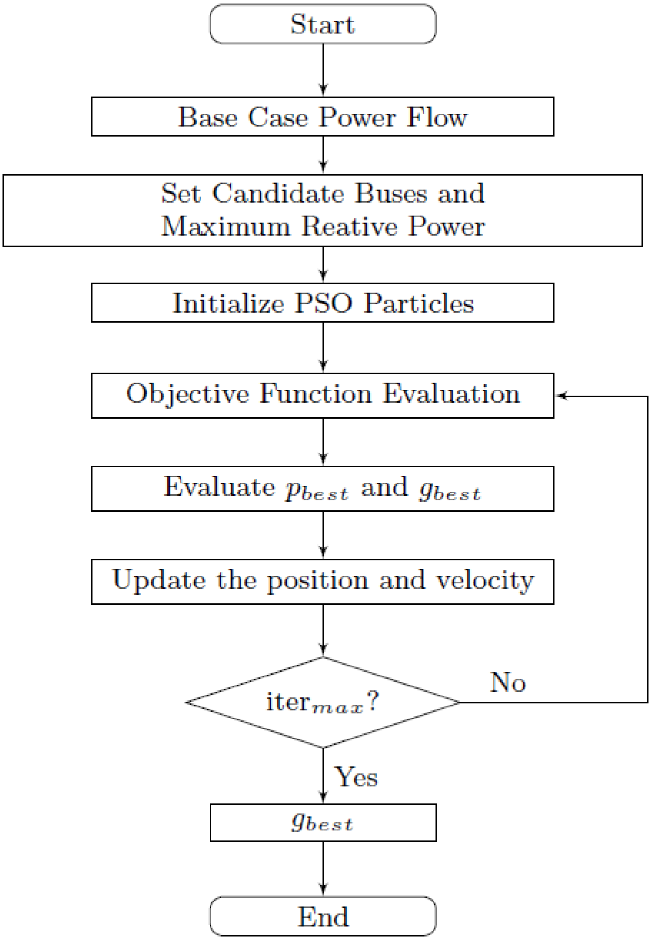

Figure 1 - Algorithm Flowchart.

Table 1 shows the available CBs that were considered in this test. The algorithm was written such manner that CBs with best cost-benefit ratio were used first, that is, the smallest values from the third column of Table 1.

Power (kvar)	Cost ($)	Ratio ($/kvar)
1200	2040	1.7
900	1650	1.833
600	1320	2.2
450	1140	2.533
300	975	3.25
150	750	5

Table 1 - Available Capacitor.

The 10-bus system operates at 23 kV and has a total load of 12368 kW and 4186 kvar. System data is available at (HAMADA, 2008). Figure 2 illustrates the system configuration. Table 2 indicates which system buses were considered in the optimization process, as well as the amount of CB to be installed. Table 3 shows a comparison between the base case where there is no CB installed, the results obtained by (DIXIT, 2016) and (HAMADA, 2008) and those found in this test. Figure 3 shows a comparison between system voltage levels before and after CB allocation.

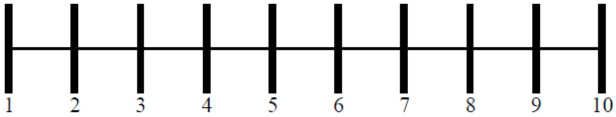

Figure 2 - 10-Bus System Configuration.

Results					
Candidate Buses	B04	B05	B06	B09	B10
Installed Banks	10	12	8	0	2

Table 2 - Installed Capacitors 10-Bus System.

	Base Case	(DIXIT, 2016)	(HAMADA, 2008)	Discrete PSO
Power Loss (kW)	783.78	703.97	684	681.57
Operation Cost ($)	131674.9	118226.96	114912	114503.76
Reactive Tot. (kvar)	0	2850	5400	4800
Installation Cost ($)	0	588	1199.4	939
Total Cost ($)	131674.9	118854.96	116111.4	115441.98
VMIN	0.838	0.873	0.9	0.878
VMAX	0.993	0.995	-	0.997

Table 3 Comparison of Obtained Results 10-Bus System.

According to Table 3 it is possible to notice that there was a 13% reduction in active power losses decreasing as at 102.21 kW. In addition, the total reactive power shows that a large amount of CB are not required, but this amount must be allied to the smart choice of installation buses.

The 34-bus system operates at 11 kV and has a total load of 4636.5 kW and 2873.5 kvar. System data is available at (HAMADA, 2008). Figure 4 illustrates the system configuration. Table 4 shows the CBs installed on the system buses, as well as the considered options.

Table 5 shows a comparison between the base case, where no CB is installed, the results obtained by (DIXIT, 2016) and (HAMADA, 2008) and those found in this paper. Figure 5 shows a comparison between system voltage levels before and after CB allocation.

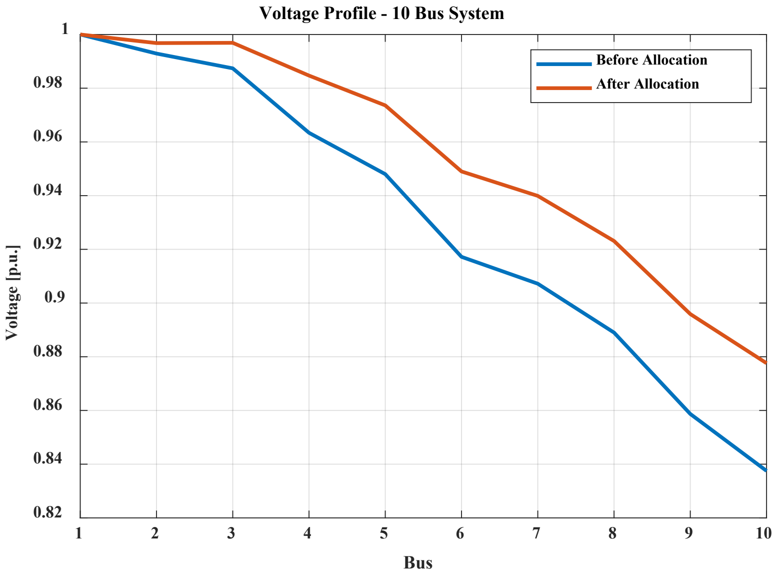

Figure 3 Voltage Profile 10-Bu s System.

Results					
Candidate Buses	B19	B20	B21	B22	B23
Installed Banks	6	0	4	1	0
Candidate Buses	B24	B25	B26	B27	-
Installed Banks	0	1	0	1	-

Table 4 - Installed Capacitors 34-Bus System.

	Base Case	(DIXIT, 2016)	(HAMADA, 2008)	Discrete PSO
Power Loss (kW)	221.71	168.37	158	166.94
Operation Cost ($)	37249.19	28286.16	26544	28045.36
Reactive Tot. (kvar)	0	1950	3000	2100
Installation Cost ($)	0	521.7	1365	544.5
Total Cost ($)	27249.19	28807.86	27909	28589.86
VMIN	0.9417	0.9502	0.951	0.9504
VMAX	0.9941	0.9950	-	0.9950

Table 5 - Comparison of Obtained Results 34-Bus System.

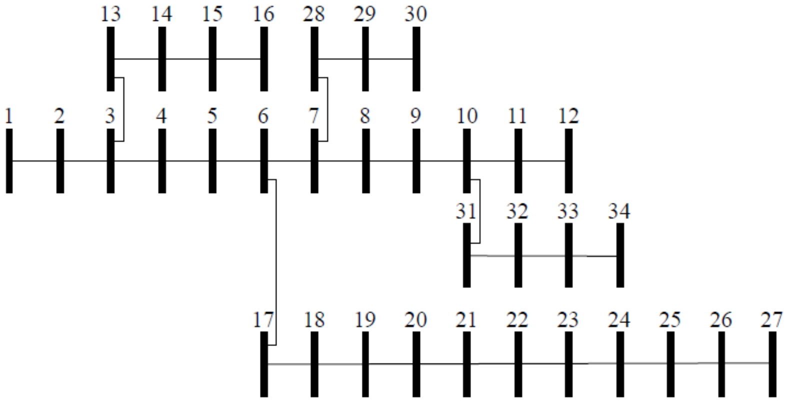

Figure 4 - 34-Bus System Configuration.

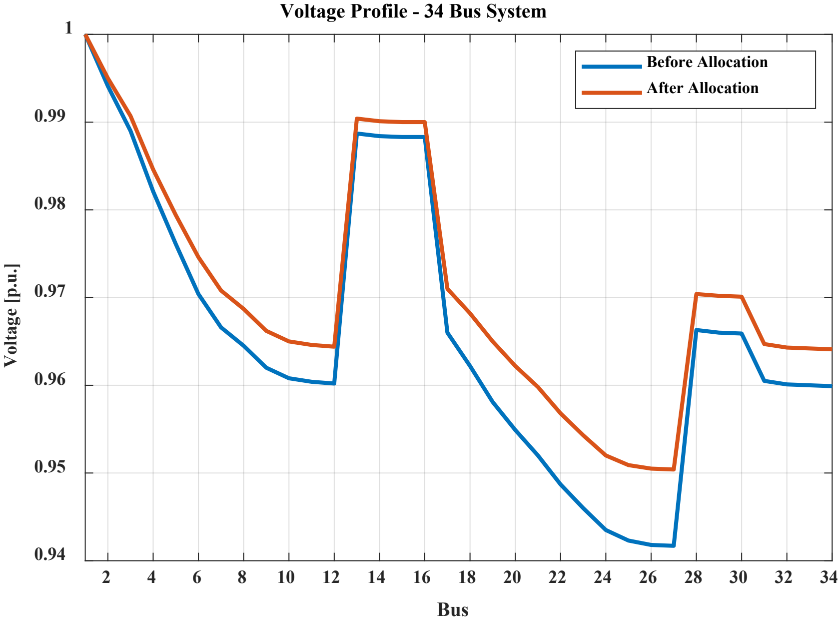

Figure 5 - Voltage Profile 34-Bus System.

Analyzing Table 5 it was observed that there was a reduction of 24.7%, that is, 54.78 kW in active power losses. In addition, the total determined reactive power shows, as well as the 10-bus system, that a large amount of CB is not required, but that amount must be consistent with the smart choice of installation buses.

Figure 5, as well as Figure 3, shows that CB allocation, furthermore, to reducing active power losses, leads to an improvement to grid voltage profile, which means a better operating point for the system.

4 I CONCLUSION

This chapter presents an article that presents the solution of a cost minimization problem of a DS for the optimal allocation of CB using adapted PSO metaheuristic technique for discrete variable problems. The algorithm used was evaluated in tests systems presents in literature and compared with other optimization techniques. In general, the discrete PSO algorithm showed itself robust, presenting excellent performance. Furthermore, it was efficient in determining the quantity and location of installation of the CB on the electrical grid, with low total costs, reducing operation and investment costs and minimizing active power losses.

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