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AN INTELIGENT SOLUTION FOR POWER LOSSES MINIMIZATION IN ELECTRIC DISTRIBUTION SYSTEMS

BY

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Abstract. The paper proposes a new approach to minimize the active power losses in distribution systems solving the capacitor allocation problem. Our approach splits the problem in two important tasks and solves them sequentially. The first task aims to identify the location of the capacitor, while the second task deals with the finding of the capacitor value. Both of them were solved using a metaheuristic approach, a modified Bat Algorithm. The objective functions are the voltage drop index and power losses minimization. The feasibility of the recommended method was tested using a real 20 buses distribution network and the results achieved in MATLAB environment were compared with a genetic algorithm.

Key words: power losses; distribution networks; capacitor.

1. Introduction

The expansion of electricity markets at regional levels requires joint operation of neighbouring transmission systems. In addition, the proliferation of small scale or “distributed” electricity sources changed the operation of local distribution systems, entities that traditionally were only consumers now injecting into the grid. These types of electrical systems require new optimization tools, which take into account multiple objectives. In engineering, the metaheuristics is well considered as one of the most effective methods that finds the optimal solutions even if there are lots of near-optimal solutions.

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Capacitor banks (CBs) are widely used in distribution system to achieve power loss reduction and to maintain the voltage profile with impermissible limits and to minimize the voltage flicker in power distribution networks. The extent of these benefits depends on the location, size, type and number of capacitors and the fast method of capacitor insertion (Mohamad *et al*., 2007).

Power losses minimization represents a subproblem of power flow through the real electricity distribution networks (EDN). In the last decades, in accordance with smart distribution networks, the frequently applied solution for grid structure uses a meshed configuration, with radial operation. The injection of the reactive power through CBs is a widely used method for decreasing the power losses or for energy savings, in distribution grids, with positive effects over the buses voltage profile. Voltage – VAR control (VVC) represents also a basic function necessity for all electricity grids. The main scope of VVC is to keep the acceptable voltages at all grids busses, for real steady states cases (Neagu *et al*., 2012).

In this paper, an original approach regarding the problem of power losses minimization in distribution grids is suggested. This approach presents two necessary sub-steps sequentially solved. The first step tries to find the optimal location for capacitors in all grid buses. The second step deals with the injection of reactive power using the so-called CBs allocation problem. Both steps are solved using the Bat Algorithm (BA) metaheuristic approach that uses as fitness functions a compromise between minimum power losses and voltage profile improvement.

The use of CBs can technically minimize the active power losses by balancing reactive power of the grid as well. Commonly, the CBs are coupled with parallel configuration to the grid using specific switches. Coupling these CBs allows the reactive power compensation with adaptable CBs with a good improvement of voltage variation at each connection point and the decrease of the power losses. For example, in Neagu *et al*., (2012) the power losses are minimized using both classical and genetic algorithm. Later on, for the studied problem, many metaheuristic algorithms were used, such as Hybrid Big Bang–Big Crunch and Fuzzy algorithm (Sedighizadeh *et al*., 2016), Flower Pollination (Abdelaziz *et al*., 2016), Cultural algorithm (Haldar *et al*., 2015), Harmony Search and Particle Artificial Bee Colony Algorithm (Muthukumar *et al*., 2017), Shark Smell Optimization (Gnanasekaran *et al*., 2016), Whale Optimization Algorithm (Neagu *et al*., 2017b), Particle Swarm Optimization (Ivanov *et al*., 2016), Moth-Flame Optimization (Ceylan *et al*., 2017) a.s.o.

Our research investigates a case study focused on the reactive power injection influences over the power losses minimization solution in real medium voltage (MV) distribution grids in a developing country (Romania). The proposed methodology will decrease both power losses and voltage drop by mounting a number of maximum CBs in the grid buses determined with a modified bat algorithm. The proposed approach was completed by taking into account the operating restrictions of the real EDN, *i.e.*: supplying end-users in safety conditions; the keeping in allowable operating limits of all voltages values for entire grid; the VAR injected by the CBs must not flow in the opposite direction to the supply point. In order to validate the utility of the proposed methodology, a Romanian radial distribution grid was tested and the results obtained in MATLAB environment were compared with the Genetic Algorithm (GA) (Neagu *et al.*, 2017a). The results confirm the efficiency and robustness of the BA, that have real performance for power losses reduction and voltage profile improvement, corroborated with the effective energy savings and power factor correction.

2. A Modified Bat Algorithm

The bat algorithm (BA) represents one of the latest metaheuristic technique and has its origin on the echolocation response of the micro-bats, characterized by a great feature through can evolve shortly or loudly noise pulsation. The echo is distinctly sent back from the proximate area by each bat, with the help of their massive auricle. The primary BA flowchart is briefly described in Fig. 1. In the proposed research, three essential approximated rules must be used (Yang *et al.*, 2010). Firstly, by knowing the difference from prey to obstacles, all bats use the echolocation process for assessing the distance between the two aforementioned terms.

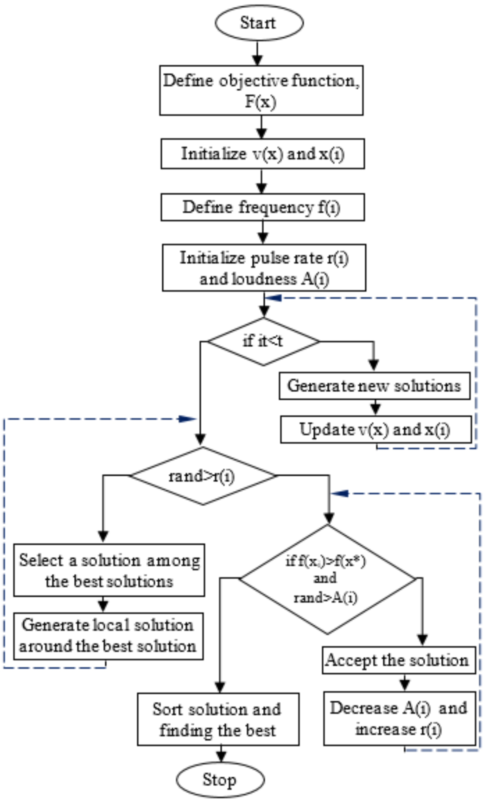
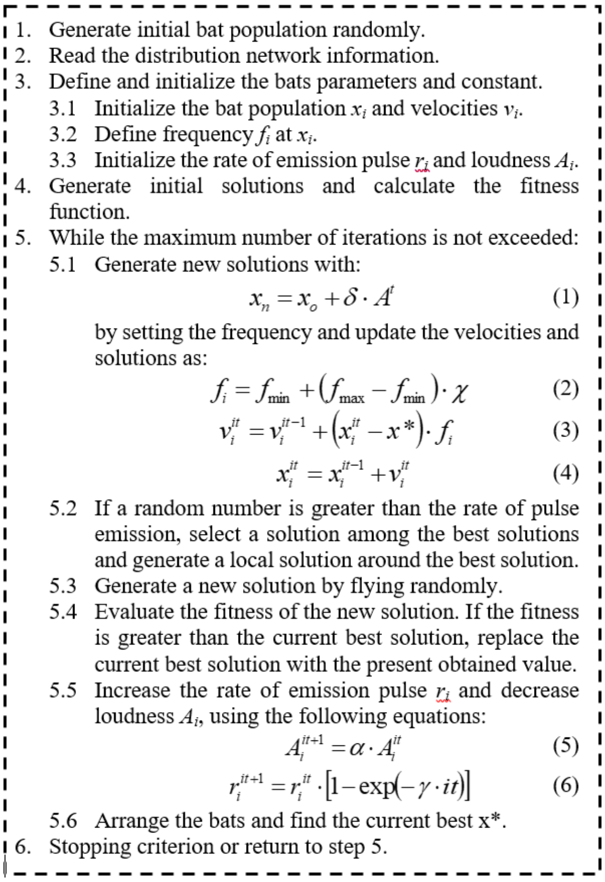


Fig. 1 − The flowchart of general Bat Algorithm.

Secondly, the bats fly randomly for finding the prey at an arbitrary location (x_i), with a velocity (v_i) at a smallest settable frequency ($f_{\min}$), for a wavelength (λ) and a loudness (A_0). Intuitively, the bat fluctuates the frequency of emanated vibrations. The pulse emission rate (r) rest with the signal nearness; it can be zero that means without pulses, and one for the maximum pulses. The third aspect is that the loudness may vary between a positive (A_0) value and a minimum constant imposed value ($A_{\min}$). The pseudocode with the indicator expression for the generally Bat method applied for CBs allocation is presented in Fig. 2.



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1. Generate initial bat population randomly.
2. Read the distribution network information.
3. Define and initialize the bats parameters and constant.
    3.1 Initialize the bat population $x_i$ and velocities $v_i$.
    3.2 Define frequency $f_i$ at $x_i$.
    3.3 Initialize the rate of emission pulse $r_i$ and loudness $A_i$.
4. Generate initial solutions and calculate the fitness function.
5. While the maximum number of iterations is not exceeded:
    5.1 Generate new solutions with:
            $x_n = x_o + \delta \cdot A^t$    (1)
        by setting the frequency and update the velocities and solutions as:
            $f_i = f_{\min} + (f_{\max} - f_{\min}) \cdot \chi$    (2)
            $v_i^{it} = v_i^{it-1} + (x_i^{it} - x^*) \cdot f_i$    (3)
            $x_i^{it} = x_i^{it-1} + v_i^{it}$    (4)
    5.2 If a random number is greater than the rate of pulse emission, select a solution among the best solutions and generate a local solution around the best solution.
    5.3 Generate a new solution by flying randomly.
    5.4 Evaluate the fitness of the new solution. If the fitness is greater than the current best solution, replace the current best solution with the present obtained value.
    5.5 Increase the rate of emission pulse $r_i$ and decrease loudness $A_i$, using the following equations:
            $A_i^{it+1} = \alpha \cdot A_i^{it}$    (5)
            $r_i^{it+1} = r_i^{it} \cdot [1 - \exp(-\gamma \cdot it)]$    (6)
    5.6 Arrange the bats and find the current best x*.
6. Stopping criterion or return to step 5.
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Fig. 2 − Basic steps of Bat Algorithm for our approach.

The unknown parameters from Fig. 2 are: χ is a vector with random values between [0, 1]; x^* represents the final solution in current iteration; $f_{\min}$ and f_{max} represent the smallest or the largest values of frequency; x_n is the current solution, x_o the past solution, and δ a random number with values between [–1, 1]. The cooling factors α and γ are two constant values ($0 < \alpha < 1$ and $\gamma > 0$), if it tends to ∞.

3. Problem formulation

By using CBs devices, the distribution network operators (DNOs) verify reactive power flow in the entire grid, which consequently leads to decreasing of active power losses corroborated with energy savings. Theoretically, the voltage control and the reactive power compensation have an interdependence, because the reactive power flows over an inductive electrical line with a specific voltage drop. The power losses minimization with reactive power injection problem proposed in the paper aims with the CBs allocation in a real EDN so that the fitness function became smallest. Having an established lot of CBs, the suggested approach finds a solution for the two main particular aspects. First, the CBs allocation using:

$$\min = \mathrm{d}V = \sum_{b=1}^{NN} \mathrm{abs}(V_b - V_{n,b}) . \tag{7}$$

Because the active losses (Joule-Lentz thermal effect) are:

$$\Delta P_{\mathrm{loss}} = \sum_{q=1} R_q \left| I_q \right|^2 , \tag{8}$$

the fitness function deals with the smallest value of the real power losses, considering all EDN branches:

$$\min(\Delta P_{\mathrm{loss}}^{\mathrm{EDN}}) = \min\left(\sum_{t=1}^{\mathrm{NT}} \Delta P_{\mathrm{loss},t} + \sum_{l=1}^{\mathrm{NL}} \Delta P_{\mathrm{loss},l} \right), \tag{9}$$

where: q represents the current branch, namely power transformers (t) and lines (l); R_q is the resistance, I_q the effective value of current, NT and NL are the number of power transformers and lines, $\Delta P_{\mathrm{loss},t}$ and $\Delta P_{\mathrm{loss},l}$ represent the Joule-Lentz losses through power transformer (t) and power lines (l).

The minimization power losses approach based on BA considers some technical restrictions, respectively:

- The branched current must be smaller than the allowable ampacity of the branch:

$$I_{br} <= I_{\max,br}, \;\; br = 1\ldots\mathrm{NBr}. \tag{10}$$

- All buss voltages must not exceed the limits:

$$U_{\min,b} <= U_{\mathrm{bus}} <= U_{\max,b}, \;\; b = 1\ldots\mathrm{NN}. \tag{11}$$

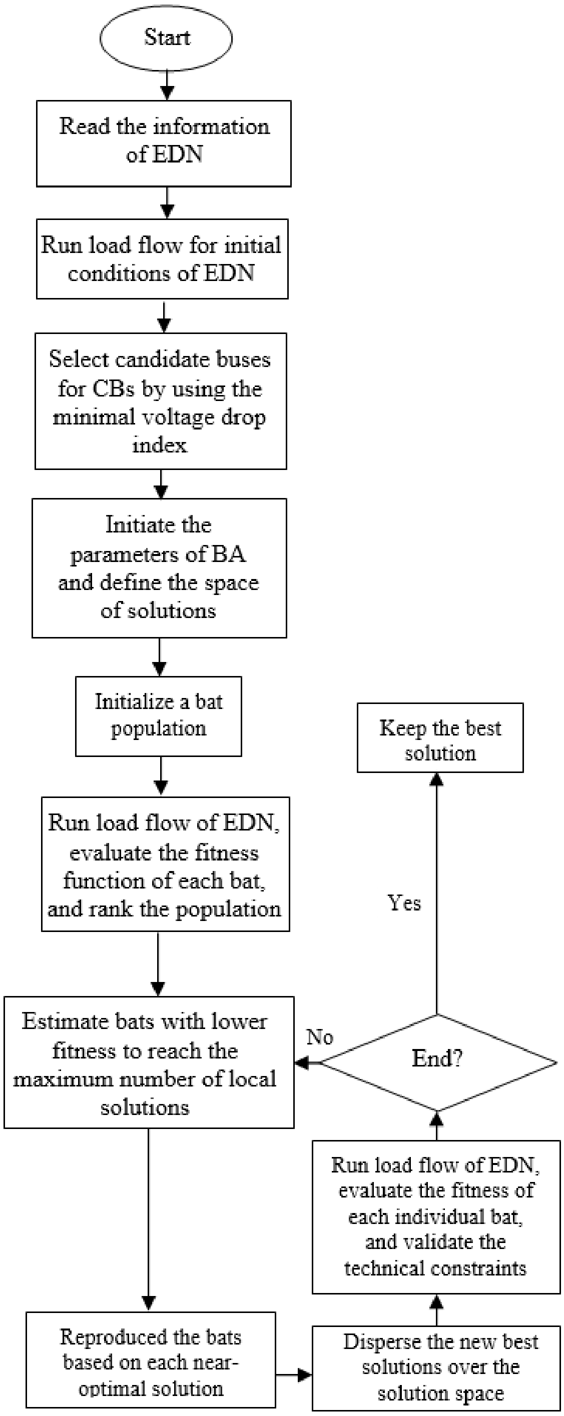

Fig. 3 − The proposed approach of BA for power losses minimization.

- The VAR injections are limited to a total demand of reactive power:

$$Q_{C,b} N_{c,b} \le Q_{d,b} N_{l,b}, \;\; b = 1 \ldots \mathrm{NN}. \tag{12}$$

- The flow of the reactive power in the opposite direction is not allowed:

$$\left(\min Q_{C,\mathrm{bus}} \right) \ge q_0 N_i, \; i \in \mathrm{NN}. \tag{13}$$

where: NN – the buses number; NBr – the branches number; I_{br} – the current branch value, $I_{max,br}$ – the ampacity branch value; $U_{\min,b}$, $U_{\max,b}$ – the inferior and superior voltage limit; q_0 – the reactive power injected by one CB; $Q_{C,b}$ – the injected reactive power, $Q_{D,b}$ – the reactive demand, N_l – the load buses, N_i – the number of placed CBs.

In our study, the voltages were considered in kV, powers in kW or kVAR and the currents in A. The flowchart for VVO problem using our particular methodology based on BA is presented in Fig. 3.

4. Case Study. Results and Discussion

A good management in reactive energy consumption brings important economic benefits. Generally, the power losses minimization is a problem of optimization because is possible to be more economically to compensate only a part, instead of the whole, of the reactive power. The DNOs must put into balance the CBs costs with the acquisition, installation, operation and maintenance, adding also the connection and control devices, the dielectric losses, a.s.o., and the end user's benefits in order to pay less money to the supplier for those delivered reactive power.

The compensation with CBs can be global (placement in a single place for the whole network), sectorial (compensation for each section), local (for each device) or a combination of the last two. To validate the robustness of the proposed VVC approach, a real EDN with 20-bus system was used. The one-line layout of the radial EDN configuration is synthetically presented in Fig. 4. Practically the proposed EDN supplies with electricity twenty substations (20/0.4 kV), at 400 or 630 kVA of apparent powers. In the analyzed case, the CBs were considered as mounted at low voltage (0.4 kV) bars.

The results, using combination of the population (25 and 50 for BA and GA), generations (70, 100 and 300) and specific parameters value of BA and GA are specified in Table 1. All results correspond to the global best objective function considering one hundred tries. We can observe that the best objective function was obtained by applying our particular BA. Only three cases have the fitness function as BA and only one for GA, otherwise it was higher than BA.

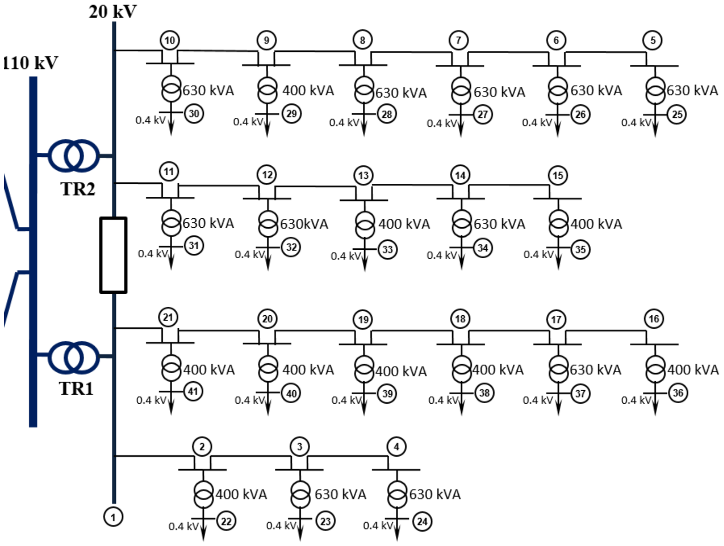

Fig. 4 – The real medium voltage (20 kV) EDN proposed for the study.

Table 1

The Best Global Fitness Function at Peak Load (kW)

Studied algorithm		Bat algorithm		Genetic algorithm	
Population		25	50	25	50
Generations	70	*28.661*	*28.661*	28.738	28.698
	100	*28.661*	*28.661*	*28.661*	28.685
	300	*28.661*	*28.661*	28.685	*28.661*

The results regarding voltage drop as a difference between nominal voltage and each real voltage and Joule losses (ΔP_{loss}) in the studied EDN both for real (before reactive power injection) and compensated operating state using those aforementioned algorithms (BA ang GA) are indicated in Table 2.

Table 2

Real Power Losses and Voltage Drop for the Analysed EDN with the Two Metaheuristics

Real state		Reactive power injection			
		BA		GA	
ΔU, [V]	ΔP_{loss}, [kW]	ΔU, [V]	ΔP_{loss}, [kW]	ΔU, [V]	ΔP_{loss}, [kW]
115.84	34.86	79.04	28.61	81.13	28.64

The allocation of the CBs at each EDN buses, taking into account the best global solution, as shown in Fig. 5 (for 100 generations, a maximum number of population) is given in Table 3.

Compared with the GA solutions, for the active power losses, in all examined circumstances, the BA gives better solutions (28.661) overall. The

GA gives also good solutions, but not better than the proposed method. In the real case the active power losses is 34.861. For comparison, the improvement of studied EDN bus voltage profile is exposed in Fig. 6. Is important to make a mention about the busses numeration, the 22 – 41 busses represent the LV bars (Fig. 4).

Table 3

The CBs Placement for the Low Voltage EDN Buses

LV bus number	Maximum number of SCBs (uncompensated)	Compensated state	
		BA	GA
22	6	6	6
23	4	4	4
24	11	11	11
25	3	3	3
26	9	9	9
27	5	5	5
28	3	3	3
29	4	4	3
30	2	2	2
31	5	5	5
32	4	4	4
33	3	3	3
34	5	5	5
35	5	5	4
36	6	6	6
37	2	2	2
38	1	1	1
39	3	3	3
40	2	2	2
41	7	7	7
Total	90	90	88

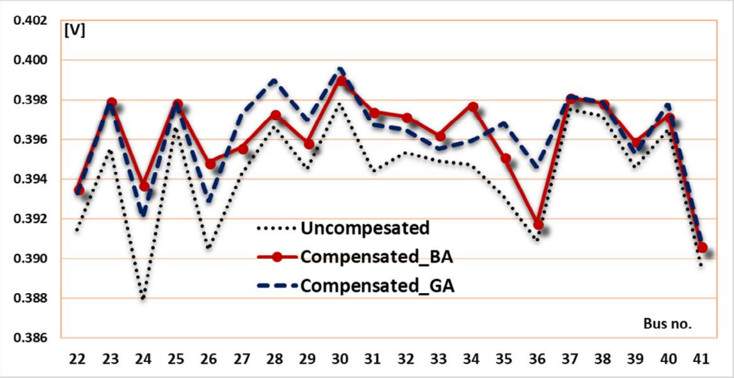

Fig. 5 – The improvent of voltage profile at low voltage buses level of the EDN.

The distribution of CBs on each LV bus is indicated in Fig. 6, taking into account the evolution of fitness function for all of the three algorithms.

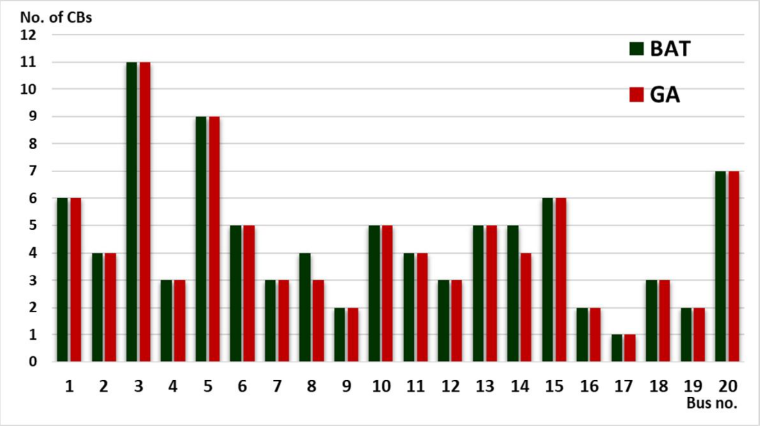

Fig. 6 – The distribution of CBs in LV substation bars,
using the two algorithms.

5. Conclusions

The paper exposes a particular approach to real power loss minimization by an improvement of the reactive power flow through the branches of radial EDN, solving the capacitor allocation problem using a newly nature inspired algorithm (BA). To justify the proposed approach efficiency the research was verified for a real Romanian MV grid and the objective functions were compared with those of genetic algorithm. The problem of power losses minimization through CBs allocation was computed taking into account two-real problems for DNOs, energy savings and voltage control through reactive power flow optimization. Also, the real power losses were minimized with 17.92% for BA (6.25 kW, $\Delta P_{\text{loss}} = 28.611$ kW), compared with 17.78% with GA (6.04 kW, $\Delta P_{\text{loss}} = 28.638$ kW) from (Neagu *et al.*, 2017a) and 13.37% ($\Delta P_{\text{loss}} =$ $= 30.204$ kW) with whale optimization algorithm (WOA), presented in (Neagu *et al.*, 2017b), when the real EDN power losses was only.

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O SOLUȚIE INTELIGENTĂ PENTRU MINIMIZAREA PIERDERILOR DE PUTERE ÎN SISTEMELE DE DISTRIBUȚIE A ENERGIEI ELECTRICE

(Rezumat)

Se propune o abordare nouă privind minimizarea pierderilor de putere activă care are la bază rezolvarea problemei privind amplasarea bateriilor de condensatoare în rețelele de distribuție. Abordarea noastră a împărțit această problemă în două etape, care vor fi rezolvate secvențial. Mai întâi se urmăreşte identificarea locațiilor bateriilor de condensatoare, iar apoi stabilirea necesarului de putere reactivă. Amândouă aceste subrobleme sunt rezolvate cu ajutorul unei metode metaeuristice, respectiv algoritmul liliacului. Funcția obiectiv concide cu minimizarea pierderilor de putere, respective scăderea cumulativă a căderilor de tensiune. Pentru a demonstra fezabilitatea metodei recomandate, o rețea reală de distribuție cu 20 de noduri a fost testată, iar rezultatele obținute în mediul de programare MATLAB sunt comparate cu cele provenite de la o metodă care are la bază Algoritmi Genetici.