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Optimal Placement and Sizing of Shunt Capacitors in Distorted Distribution Systems Using a Hybrid Algorithm

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Abstract: In this paper, a novel hybrid phasor particle swarm optimization and gravitational search algorithm, namely the hybrid PPSOGSA algorithm, is proposed to find the optimal size and location of shunt capacitors in distribution systems with non-linear loads. The performance of PPSOGSA are studied and evaluated using the IEEE 9- and 85-bus test systems with the objective of minimizing the total annual cost of the system. The procedure is conducted taking into account effects of harmonic distortion and discrete size of capacitors available in the market. Simulation results are compared with those obtained by other optimization techniques, and verified using the Electrical Transient Analysis Program (ETAP). It was established that that the hybrid PPSOGSA algorithm provides better solutions in terms of convergence and accuracy.

Keywords: Capacitor placement, Distribution system, Harmonic distortion, Hybrid algorithm.

1 Introduction

Determination of optimal placement and size of capacitor banks is a complex and up-to-date optimization problem that attracts the attention of researchers for decades [1]. A proper compensation of reactive power can significantly improve the voltage conditions in a system, reduce power losses, and therefore improve the transmission capabilities of the system. The traditional approach to solving this problem is based on the assumption that the loads are linear and includes only the fundamental frequency, ignoring the higher harmonic frequency components. However, the increasing presence of non-linear loads that generate harmonic currents in distribution power systems has imposed a need for developing new tools and techniques, as well as adapting existing ones, for the purpose of taking into account the influence of harmonics. Harmonic currents caused by non-linear loads pass through the impedance of the system and cause voltage distortions that may have a detrimental effect on the power system and equipment. Adverse

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effects of harmonics are manifested by increased power losses in lines, machines and transformers, dangerous resonance conditions, heating of cables, capacitors and equipment, vibrations and noise, interference on communication circuits, etc. [2, 3]. Researches show that most of the problems associated with the harmonic distortion in electric power systems result due to resonance. The use of shunt capacitors can cause resonant conditions which magnify the harmonic currents and create high harmonic voltage distortion levels. The presence of resonance in the electric power system is unacceptable and must be avoided. It is therefore very important to take the constraint on the harmonic distortion into account in the process of finding the optimal location and size of capacitor banks in systems with non-linear loads.

In the past few years, many population-based metaheuristic optimization algorithms, such as Particle Swarm Optimization (PSO) [4], Plant Growth Simulation Algorithm (PGSA) [5], Whale Optimization Algorithm (WOA) [6], Bacterial Foraging Optimization Algorithm (BFOA) [7], Fuzzy Genetic Algorithm (GA) [8], and Improved Harmony Algorithm (IHA) [9] have been successfully applied to find the optimal solution of the capacitor placement and sizing problem in distribution systems with different objective functions that reflect power losses minimization, voltage profile improvement, cost reduction, net saving maximization and system stability enhancement. In these papers, it is assumed that the loads are linear and the effects of harmonics are not taken in consideration. Particularly, the optimal solutions of the problem are found under the assumption of the sinusoidal condition and they may not be optimal due to the additional costs of losses or high harmonic levels caused by resonance. Accordingly, consideration of the harmonics effect is very essential in formulating the capacitor placement problem. In the scientific literature, there are few documents that considered the effect of harmonics on the optimal solution of the capacitor placement and sizing problem [10 − 17], such that the root-mean-square (RMS) voltages and total harmonic distortions of voltage (THD_V) are within permissible limits specified in the IEEE-519 standard [18].

This paper proposes a metaheuristic algorithm, called PPSOGSA, based on the phasor particle swarm optimization (PPSO) [19] and gravitational search algorithm (GSA) [20] for solving the optimization problem of capacitor placement and sizing in radial distribution systems with non-linear loads. The proposed algorithm is tested on the IEEE 9- and 85-bus test systems with the objective of minimizing the total annual cost of the system. The constraints of the problem include bus RMS voltages, THD_V levels and distribution line loading. The results are compared with those obtained by other metaheuristic methods like WOA [6], PPSO [19], GSA [20], PSOGSA [21, 22], Fuzzy Logic Technique [23], Hybrid FUZ-DP-GA [24], MINLP [25], and verified using the Load Flow Analysis and Harmonic Analysis modules of the Electrical Transient Analysis Program (ETAP) [26].

2 Problem Formulation

In this paper, the problem of optimal placement and sizing of fixed capacitors in distorted radial distribution systems is considered as a constrained non-linear and non-differentiable optimization planning problem with the objective of minimizing the annual operating cost of the system. The control variables of the problem are locations and sizes of fixed shunt capacitors, while the dependent variables contain RMS bus voltages (V_{RMS}), THD_V levels and distribution line loading (S_l).

2.1 Objective function

The objective cost function contains two parts. The first one is the cost of active power losses, and the second one is the cost of the reactive power provided by capacitors. It can be defined as [11]:

$$F = K_P P_{loss} + \sum_{i=1}^{N_C} K_{C,i} Q_{C,i}, \tag{1}$$

where:

- P_{loss} is total active power losses in the system [kW],
- K_p is the annual cost per unit of power losses [$/kW],
- $K_{C,i}$ is the capacitor annual cost [$/kVAr],
- $Q_{C,i}$ is the size of capacitor at bus *i* [kVAr]; and
- N_C is the total number of shunt capacitors.

2.2 Control variables

As aforementioned, the control variables of this problem are locations and sizes of fixed capacitors. Each bus in a network represents a potential location for placement of a capacitor. Only a capacitor can be connected in a bus. The commercially available capacitors are discrete and herein they are taken into account. Some of the commercially available capacitors with their corresponding costs are shown in **Table 1**.

As in [5, 6, 23 – 25], the bus reactive compensation power is limited to

$$Q_{C,i} \le \sum_{i=1}^{N_{bus}} Q_{L,i}, \tag{2}$$

where $Q_{L,i}$ is the reactive load power at bus *i*, and N_{bus} is the total number of buses in the system.

Table 1
Commercially available capacitors and their costs [6].

Q_C [kVAr]	K_C [$/kVAr]	Q_C [kVAr]	K_C [$/kVAr]	Q_C [kVAr]	K_C [$/kVAr]	Q_C [kVAr]	K_C [$/kVAr]
150	0.5	1200	0.17	2250	0.197	3300	0.174
300	0.35	1350	0.207	2400	0.17	3450	0.188
450	0.253	1500	0.201	2550	0.189	3600	0.17
600	0.22	1650	0.193	2700	0.187	3750	0.183
750	0.276	1800	0.187	2850	0.183	3900	0.182
900	0.183	1950	0.211	3000	0.18	4050	0.179
1050	0.228	2100	0.176	3150	0.195	-	-

2.3 Constraints

Equality constraints include power balancing at the fundamental frequency defined by (3) and (4), and constrains related to the harmonic power flow (HPF) represented by (5). On the other hand, inequality constraints are RMS bus voltage limits, branch loading limits and voltage distortion limits described by (6), (7) and (8), respectively.

$$P_{G,i} - P_{D,i} = \left|V_i^{(1)}\right| \sum_{j=1}^{N_{bus}} \left|V_j^{(1)}\right| \left|Y_{i,j}^{(1)}\right| \cos\left(\theta_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right), \tag{3}$$

$$Q_{G,i} - Q_{D,i} = \left|V_i^{(1)}\right| \sum_{j=1}^{N_{bus}} \left|V_j^{(1)}\right| \left|Y_{i,j}^{(1)}\right| \sin\left(\theta_{i,j}^{(1)} - \delta_i^{(1)} + \delta_j^{(1)}\right), \tag{4}$$

$$\boldsymbol{V}^{(h)} = \left[\boldsymbol{Y}_{\mathbf{BUS}}^{(h)}\right]^{-1} \boldsymbol{I}^{(h)}, \tag{5}$$

$$V_{RMS,i}^{\min} \le \sqrt{\sum_{h=1}^{h_{\max}} \left|V_i^{(h)}\right|^2} \le V_{RMS,i}^{\max}, \tag{6}$$

$$S_{l,i} \le S_{l,i}^{\max}, \tag{7}$$

$$THD_{V,i}(\%) = \frac{1}{\left|V_i^{(1)}\right|} \cdot \sqrt{\sum_{h \ne 1}^{h_{\max}} \left|V_i^{(h)}\right|^2} \times 100(\%) \le THD_{V,i}^{\max}. \tag{8}$$

In equations (3) – (8), the variables have the following meaning: $P_{G,i}$ and $Q_{G,i}$ are active and reactive power generations at bus *i*, respectively; $P_{D,i}$ and $Q_{D,i}$ are active and reactive load demands at bus *i*, respectively; $V_i^{(1)}$ and $V_j^{(1)}$ are voltages at buses *i* and *j*, respectively; $Y_{i,j}^{(1)}$ is the (*i*, *j*)-th element of the admittance matrix; $\theta_{i,j}^{(1)}$ is the angle of the (*i*, *j*)-th element of the admittance matrix; $\delta_i^{(1)}$ and $\delta_j^{(1)}$ are voltage angles at buses *i* and *j*, respectively; $\boldsymbol{V}^{(h)}$ is the bus voltage vector at the *h*-th harmonic; $\boldsymbol{Y}_{\mathbf{BUS}}^{(h)}$ is the bus admittance matrix at the *h*-th harmonic; $\boldsymbol{I}^{(h)}$ is the bus injected current vector at the *h*-th harmonic; $V_{RMS,i}^{\min}$ and $V_{RMS,i}^{\max}$ are the minimum and maximum bus voltage limits at bus *i*, respectively; $S_{l,i}^{\max}$ is the maximum power flow in line/branch *i*, and $THD_{V,i}^{\max}$ is the maximum acceptable level of the THD_V at any bus *i*.

To calculate the parameters of the considered distribution systems at the fundamental frequency, the Backward-Forward Sweep (BFS) method [27, 28] was used. On the other hand, the HPF solutions are obtained by using the Decoupled Harmonic Power Flow (DHPF) method [11, 12, 29].

2.4 Expanded objective function

The inequality constraints of the dependent variables such as RMS and THD for all bus voltages, as well as line flows, are added to the objective function as quadratic penalty terms, i.e.

$$F_e = F + \lambda_V \sum_{i=1}^{N_{bus}} \left(V_{RMS,i} - V_{RMS,i}^{\lim}\right)^2 + \lambda_{THD} \sum_{i=1}^{N_{bus}} \left(THD_{V,i} - THD_{V,i}^{\lim}\right)^2 + \\ + \lambda_S \sum_{i=1}^{N_L} \left(S_{l,i} - S_{l,i}^{\lim}\right)^2, \tag{9}$$

where:

- F_e is the expanded objective function;
- λ_V, λ_{THD} and λ_S are the corresponding penalty factors; and
- $x^{\lim}$ is the limit value of dependent variable x, which is given by:

$$x^{\lim} = x^{\max} \text{ if } x > x^{\max} \text{ and } x^{\lim} = x^{\min} \text{ if } x < x^{\min}.$$

In this study, the penalty factor of 10^6 is selected for all the inequality constraints.

3 Solution Method

In this section, the hybrid PPSOGSA algorithm is proposed to solve the problem of optimal placement and sizing of capacitors in distorted distribution systems.

The PPSOGSA approach consists of a combination of PPSO [19] and GSA [20]. The improvement of this algorithm in relation to the original PSOGSA [21, 22] is based on modelling the algorithm parameters with a phase angle (θ), which converts the standard PSO to a self-adaptive and parametric independent algorithm. Namely, the acceleration coefficients c_1 and c_1, which are the main control parameters of PSOGSA, are fixed during iteration process, and the PSOGSA's searching ability and efficiency depend largely on the values of these factors. Instead of using fixed values, in this paper the periodic nature of sine and cosine functions is used to represent control parameters through phase angles.

The velocity and position of particle *i* at iteration *t* are given by the equations:

$$\begin{aligned} \boldsymbol{V}_i(t+1) = r_1\boldsymbol{V}_i(t) + r_2\left|\cos\left(\theta_i(t)\right)\right|^{2\sin(\theta_i(t))}\boldsymbol{ac}_i(t) + \\ +r_3\left|\sin\left(\theta_i(t)\right)\right|^{2\cos(\theta_i(t))}\left(\boldsymbol{gbest}(t) - \boldsymbol{X}_i(t)\right), \end{aligned} \tag{10}$$

$$\boldsymbol{X}_i(t+1) = \boldsymbol{X}_i(t) + \boldsymbol{V}_i(t+1). \tag{11}$$

In equation (10), the phase angle of particle *i* (θ_i) is calculated as [19]:

$$\theta_i(t+1) = \theta_i(t) + \left|\cos\left(\theta_i(t)\right) + \sin\left(\theta_i(t)\right)\right|2\pi, \tag{12}$$

where:

– $\boldsymbol{V}_i(t)$ and $\boldsymbol{X}_i(t)$ are the velocity and the position of agent *i* at iteration *t,* respectively;

– r_1, r_2 and r_3 are random numbers between 0 and 1;

– $\boldsymbol{ac}_i(t)$ is the acceleration of agent *i* at iteration *t*, and

– $\boldsymbol{gbest}(t)$ is the best position of all particles in the group at iteration *t*.

The values of $\boldsymbol{ac}_i$ and $\boldsymbol{gbest}$ in equation (10) are obtained as in [21, 22].

3.1 PPSOGSA implementation

In this study, a potential solution can be presented by a vector consisting of a combination of locations and rated power of capacitors in these locations. The position of agent *i* can be defined as follows:

$$\boldsymbol{X}_i = \left[Bus_1^1, \ldots, Bus_{N_C}^d, Q_{C,1}^{d+1}, \ldots, Q_{C,N_C}^n\right], \tag{13}$$

where n indicates the number of control variables.

The flowchart of the PPSOGSA algorithm is presented in Fig. 1.

More details on PPSOGSA and its application in solving various problems in electrical engineering can be found in [30 − 33].

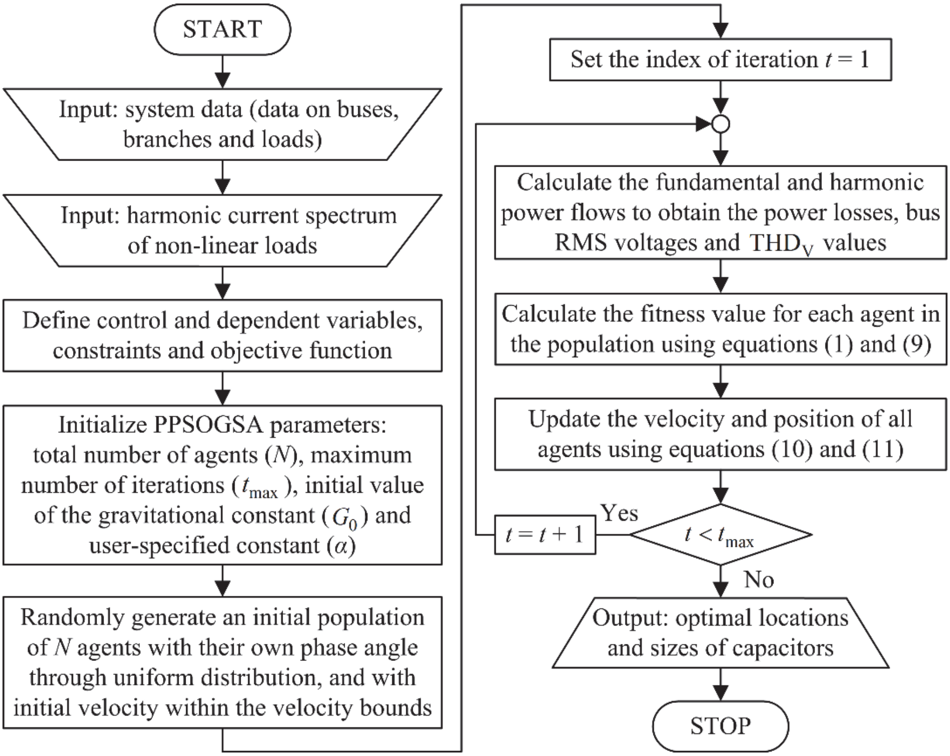


Fig. 1 – *Flowchart illustrating the PPSOGSA algorithm to optimize the locations and sizes of shunt capacitors in the presence of harmonics.*

4 Simulation Results

The proposed approach was implemented in MATLAB and tested on the IEEE 9- and IEEE 85-bus systems. For both test systems, the substation voltage is set to 1 p.u. In addition to this, it is assumed that the voltage at the utility connection point does not contain any harmonics. The equivalent impedance of the system was determined from short-circuit power of 1000 MVA and reactance-to-resistance ratio of 22.2.

Both sinusoidal and non-sinusoidal operating conditions were taken into account. In every bus, the loads of the systems comprise a linear part and a non-linear part. At the fundamental frequency (i.e., 50 Hz), all loads are represented by the constant power model, while capacitors are represented by the constant impedance model. At higher frequencies, linear passive loads are modelled using the parallel RL model [12], and non-linear loads are modelled as decoupled harmonic current sources.

The harmonic spectrum of currents injected from non-linear loads is presented in **Table 2.**

Table 2
The harmonic spectrum of non-linear loads.

Harmonic order	Magnitude [%]	Phase angle [degree]
1	100	0
5	60.82	-175
7	33.42	-172
11	3.84	166
13	7.74	-177
17	1.27	32
19	1.54	179
23	1.08	38
25	0.16	49

The harmonic spectrum has harmonic characteristics of a six-pulse converter of a pulse-width modulation (PWM) adjustable-speed drive (ASD) and only contains odd harmonics, except triplen harmonics.

For all test systems, the yearly cost of losses (K_p) is selected to be 168 $/kW [5], the maximum acceptable level of the THD_V is 5%, and the voltage limits are 0.9 p.u and 1.1 p.u., according to the limits specified by the IEEE-519 standard [18].

In order to prove the efficiency of the proposed algorithm, the same problem was solved using PPSO, GSA and PSOGSA and the results are compared with those obtained by other techniques from the literature [6, 23 − 25]. The setting parameters of PPSO, GSA, PSOGSA and PPSOGSA used in the calculation are provided in **Table 3**. The results presented herein are the best values obtained over twenty consecutive test runs.

Table 3
Parameter setting used in PPSO, GSA, PSOGSA and PPSOGSA.

Control parameters	PPSO	GSA	PSOGSA	PPSOGSA
Population size (N)	50	50	50	50
Maximum number of iterations (t_{max})	250	250	250	250
Acceleration constants (c_1, c_2)	-	-	2, 2	-
Initial value of the gravitational constant (G_0)	-	100	1	1
User-specified constant (α)	-	2	20	20

4.1 IEEE 9-bus test system

The algorithms are first tested on the IEEE 9-bus radial distribution system [12] with total active and reactive power loads of 12368 kW and 4186 kVAr, respectively. As in [23, 24], it was decided that the maximum capacitor size should not exceed the total reactive load (i.e., 4186 kVAr).

4.1.1 Sinusoidal condition

Under the sinusoidal operating condition all loads in the system are treated as linear and the calculation is performed at the fundamental frequency. The cost function and total active power losses in the initial case before compensation are 131676 $ and 783.787 kW, respectively. The simulation results obtained by different optimization techniques are shown in **Table 4**.

Table 4
Simulation results of the IEEE 9-bus system under the sinusoidal condition.

Bus number	Without capacitors	With capacitors					
		Ref. [23]	Ref. [24]	PPSO	GSA	PSOGSA	PPSOGSA
1	-	-	-	-	-	-	-
2	-	3600	3600	4050	3900	4050	4050
3	-	-	4050	4050	-	-	-
4	-	4050	450	-	3000	3450	3600
5	-	1650	1200	2100	1650	1650	-
6	-	-	-	-	-	-	1350
7	-	-	-	-	-	-	-
8	-	600	150	-	-	-	-
9	-	-	600	600	900	750	750
Minimum voltage [p.u.]	0.8375	0.9003	0.9001	0.9001	0.9001	0.9002	0.9001
Maximum voltage [p.u.]	1	1.007	1.007	1.0081	1.0052	1.0062	1.0059
Losses [kW]	783.787	686	681.28	681.31	682.03	680.55	680.75
Cost [$]	131676	117035	116317	116411	116313	116231	116189
Benefits [$]	-	14641	15359	15265	15363	15445	15487

As can be seen from **Table 4**, the minimum losses and cost of the system found by the PPSOGSA are, respectively, 680.748 kW and 116189 $, showing a reduction of 13.15% in power losses and 11.76% in cost of the system. Also, it can be observed that the cost of the system obtained with the proposed PPSOGSA method is less than that one obtained with other techniques.

From **Table 4**, it can be seen that the bus voltages after capacitor placement meet the defined limits.

To establish the accuracy of the BFS method, the power flow calculations were also performed using the Load Flow Analysis module of the Electrical Transient Analysis Program (ETAP). The results obtained by the ETAP software in the initial case and the case when the capacitors' parameters are generated by PPSOGSA are presented in Figs. 2 and 3, respectively.

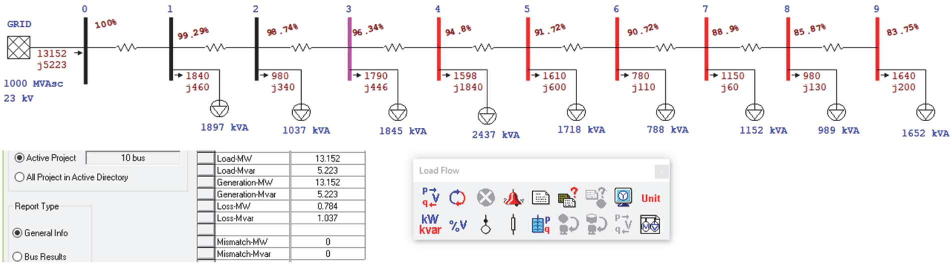


Fig. 2 – *Results obtained with ETAP program for the IEEE 9-bus test system in the case of the sinusoidal operation without capacitors.*

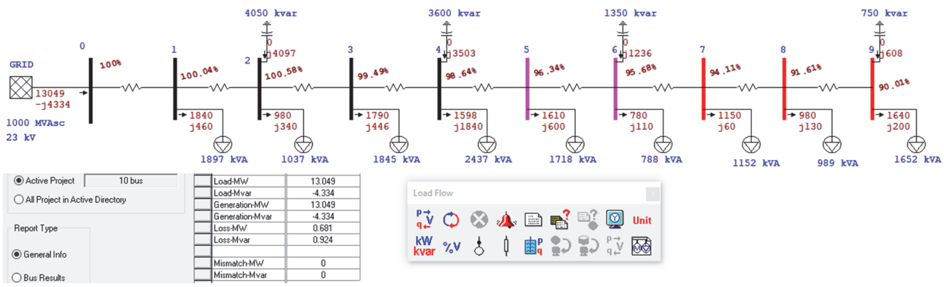


Fig. 3 – *Results obtained with ETAP program for the IEEE 9-bus test system in the case of the sinusoidal operation with capacitors.*

By comparing the results from Figs. 2 and 3 with the corresponding results from the second and eight columns of **Table 4**, it can be observed that the results calculated by the BFS method are almost equal to those obtained with ETAP program.

4.1.2 Non-sinusoidal condition

In order to demonstrate the performance of the hybrid PPSOGSA algorithm under non-sinusoidal conditions, the optimal capacitor placement and sizing problem is expanded for higher harmonic frequencies. In every bus, it is assumed that the loads of this test system comprise a linear part of 80% and a non-linear part of 20%. All non-linear loads have the same harmonic spectrum from **Table 2**. The optimal results are given in **Table 5**.

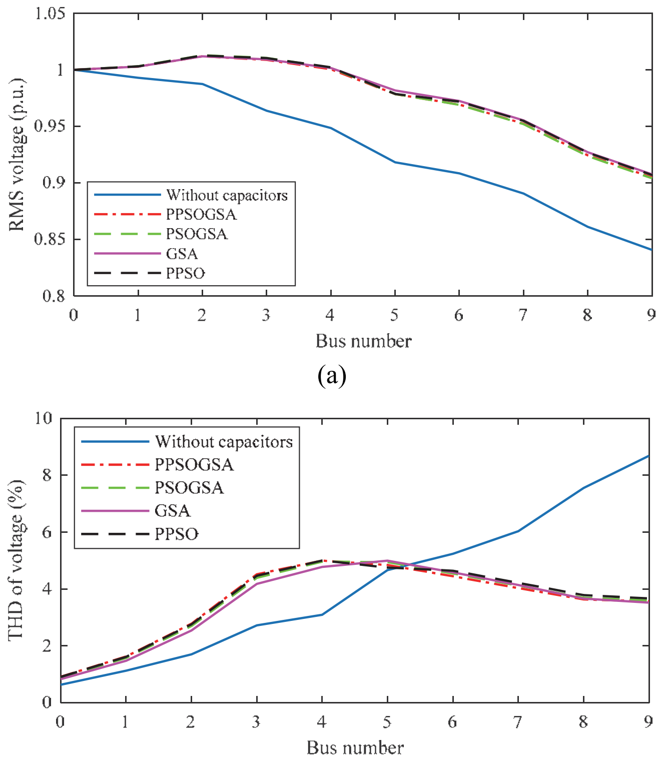
Table 5

Simulation results of the IEEE 9-bus system under the non-sinusoidal condition.

Bus number	Without capacitors	With capacitors			
		PPSO	GSA	PSOGSA	PPSOGSA
1	-	-	-	-	-
2	-	4050	3900	4050	4050
3	-	3600	3000	3300	4050
4	-	3600	3000	3300	3000
5	-	-	2700	2100	1800
6	-	1650	-	-	-
7	-	-	-	-	-
8	-	-	-	-	-
9	-	-	-	-	-
Min. V_{RMS} [p.u.]	0.8406	0.9065	0.9070	0.9050	0.9041
Max. V_{RMS} [p.u.]	1.0000	1.0128	1.0121	1.0125	1.0129
Max. THD_V [%]	8.685	5.000	4.998	4.966	4.998
Fund. freq. losses [kW]	783.787	702.733	706.639	702.392	701.773
Harmonic losses [kW]	6.860	8.567	8.579	8.8307	8.828
Total losses [kW]	790.647	711.3	715.218	711.223	710.601
Total cost [$]	132828	121765	122451	121728	121707
Benefits [$]	-	11063	10377	11100	11121

From the second column of **Table 5**, it can be seen that the total active power losses of the system are 790.647 kW, while the cost of the system is 132828 $. In addition, it is evident that the minimum RMS voltage and the maximum THD_V violate the permissible limits of 0.9 p.u. and 5%, respectively. The results from the last row of **Table 5** show that the proposed PPSOGSA algorithm is better than PPSO, GSA, PSOGSA algorithms in terms of achieving the benefits. Compared to the initial case, the best solution generated by PPSOGSA provides reductions of 10.12% and 8.37% in power losses and cost, respectively.

Figs. 4a and 4b respectively show the comparisons between RMS voltage profiles and THD_V levels in the IEEE 9-bus system for cases without and with capacitors. From **Table 5** and Fig. 4, after capacitor placement, it can be seen that the V_{RMS} voltages, as well as THD_V values meet limits specified in [18].



(a)

(b)

Fig. 4 – *Comparisons between:* (a) *voltage profiles;* (b) *THD_V levels of the IEEE 9-bus system.*

By comparing the power losses at the fundamental frequency from **Table 5** obtained after implementing the optimization procedure with those from **Table 4**, it can be seen that the losses from **Table 5** are higher by about 3%. To demonstrate the effect of the installation of shunt capacitors on the harmonic distortion voltage, the calculation of the HPF was performed. Fig. 5 illustrates the THD_V at each bus in the case when capacitors' parameters are obtained by PPSOGSA under the sinusoidal operation condition. It is clear that the THD_V at buses 3 to 9 reaches the level higher than 5%. In relation to the initial case from **Table 5**, the maximum value of THD_V increases 18.9% and reaches 10.33%. This increase in voltage distortion levels is due to harmonic resonant conditions caused by capacitors in combination with load and feeder reactance. From the results in Fig. 5, it is obvious that the optimal solution obtained in the case of the sinusoidal operation, lead to unacceptable THD_V levels at system buses. Based on that, it can be said that the optimal results from **Table 5** are more appropriate, because they take the harmonic constraint into consideration.

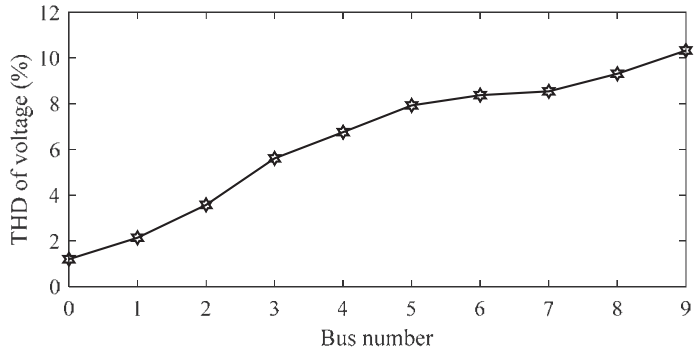


Fig. 5 – *THD_V levels of the IEEE 9-bus test system with capacitors' parameters obtained by PPSOGSA under the sinusoidal condition.*

The harmonic analysis was also performed using the ETAP software. The simulation results generated by the ETAP software for the initial case and the case when the capacitors' parameters are obtained by the PPSOGSA algorithm are presented in Figs. 6 and 7, respectively.

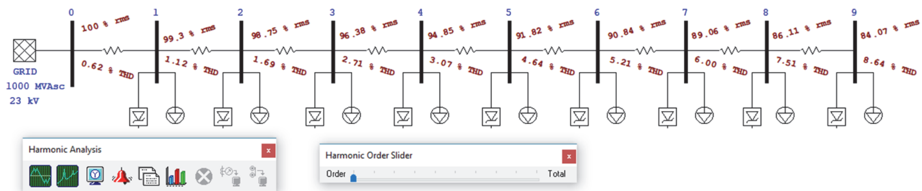


Fig. 6 –*Results obtained with ETAP program for the IEEE 9-bus system in the case of non-sinusoidal operation without capacitors.*

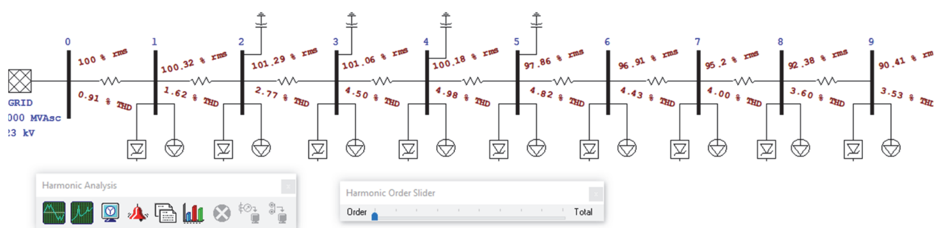


Fig. 7 – *Results obtained with ETAP program for the IEEE 9-bus test system in the case of non-sinusoidal operation with capacitors.*

Based on the comparisons of V_{RMS} and THD_V values from Figs. 6 and 7 with the corresponding results from Fig. 4, it can be observed that the results agree well.

4.2 IEEE 85-bus test system

The second test system that is used to demonstrate the performance of the proposed algorithm is the standard IEEE 85-bus system [6]. The total active and reactive powers of the system are 2570.3 kW and 2622.1 kVAr, respectively.

4.2.1 Sinusoidal condition

The simulation results of the IEEE 85-bus system under the sinusoidal condition are presented in **Table 6.**

Table 6

Simulation results of the IEEE 85-bus system under the sinusoidal condition.

Case	Method	Optimal location	Optimal size [kVAr]	Min. V_{fund} [p.u.]	Total losses [kW]	Total cost [$]	Benefits [$]
Without capacitors	-	-	-	0.8713	316.116	53107	-
With capacitors	PPSOGSA	12 25 48 67	450 900 600 600	0.9226	149.216	25610	27497
	PSOGSA	9 30 48 67	1050 450 450 600	0.9227	148.978	25627	27480
	PPSO	12 29 48 67	600 600 450 750	0.9206	149.341	25674	27433
	GSA	9 31 52 68	1200 600 300 450	0.9232	149.240	25627	27480
	Ref. [25]	7 8 29 58	300 700 900 500	0.9176	159.410	27354	25753
	Ref. [6]	25 34 67 80	490 709 566 417	0.9214	149.520	25652	27455

As can be seen in **Table 6**, the minimum voltage, total power losses and total cost of the system are 0.8713 p.u., 316.116 kW and 53107 $, respectively. By adjusting the control variables to the optimal values obtained using PPSOGSA, the minimum voltage is improved to 0.9226 p.u., while power losses and system cost are decreased to 149.216 kW and 25610 $, respectively. This apparently indicates that the proposed PPSOGSA algorithm can be successfully used for large-scale power systems.

From **Table 6**, it can be seen that the proposed approach outperforms PPSO, GSA, PSOGSA, WHO [6] and MINLP [25], because the results obtained using PPSOGSA are better than those obtained using other methods.

4.2.2 Non-sinusoidal operating condition

As well as in the previous test system, it is assumed that the loads comprise a linear part of 80% and a non-linear part of 20% in every bus. Also, all non-linear loads have the same harmonic spectrum from **Table 2**. The optimal results are given in **Table 7**.

Table 7
Simulation results of the IEEE 85-bus system under the non-sinusoidal operating condition.

Case	Method	Optimal location	Optimal size [kVAr]	Min. V_{RMS} [p.u.]	Max. THD_V [%]	Total losses [kW]	Total cost [$]	Benef. [$]
Without capacitors	-	-	-	0.8730	6.179	321.327	53982	-
With capacitors	PPSOGSA	13 25 31 64	750 300 1200 1200	0.9372	5.000	190.127	32661	21321
	PSOGSA	11 16 31 67	1350 300 1200 900	0.9371	4.971	190.937	32830	21152
	PPSO	13 20 30 68	900 150 1500 900	0.9365	4.995	191.422	32864	21118
	GSA	12 23 29 72	750 0 1650 1050	0.9366	4.929	196.911	33845	20137

The power losses of the system in the initial case are 321.327 kW of which 5.21 kW represents the harmonic power losses. The annual cost of the system, minimum RMS voltage and maximum THD_V level are 53982 \$, 0.873 p.u. and 6.179%, respectively. After applying the optimization procedure, it appears from **Table 7** that the power losses, and therefore the annual cost of the system, are significantly reduced in comparison to the initial case. In addition, voltage profile and power quality are improved.

Based on the comparison of the results from **Table 7**, it can be noted that the hybrid PPSOGSA approach outperforms PPSO, GSA and PSOGSA providing the highest benefits.

Figs. 8a and 8b, respectively, illustrate the comparisons between RMS voltage profiles and between THD_V levels in the IEEE 85-bus system for cases without and with capacitors.

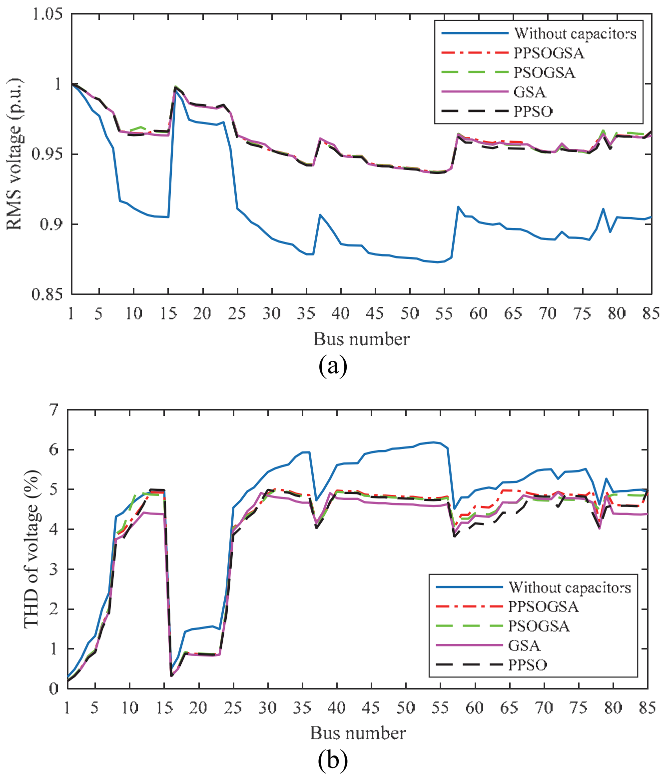


Fig. 8 – *Comparisons between:* (a) *voltage profiles;*
(b) *THD_V levels of the IEEE 85-bus system.*

The system parameters computed by BFS and DHPF methods, including voltages, power losses and harmonic levels, were also verified using the Load Flow Analysis and Harmonic Analysis modules of the ETAP software, but these results are not displayed due to the limited space. It was also found that there is a high degree of compatibility between them.

4.3 Statistical parameters and convergence profiles

The statistical parameters of the results obtained by PPSO, GSA, PSOGSA and PPSOGSA over twenty independent runs for the IEEE 9- and 85-bus test systems are presented in **Tables 8** and **9**, respectively.

Table 8

Statistical parameters of different algorithms for the IEEE 9-bus system.

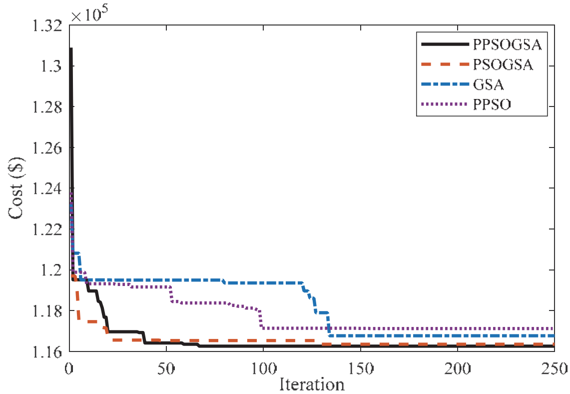
Operating condition	Method	Minimum solution [$]	Maximum solution [$]	Average solution [$]	Standard deviation [$]
Sinusoidal	PPSO	116410	117141	116575	465
	GSA	116313	117650	117030	582
	PSOGSA	116231	116982	116645	361
	PPSOGSA	116189	116845	116420	265
Non-sinusoidal	PPSO	121765	129340	123762	1570
	GSA	122451	129847	126196	2051
	PSOGSA	121728	129715	123851	1805
	PPSOGSA	121707	125601	123283	1118

Table 9

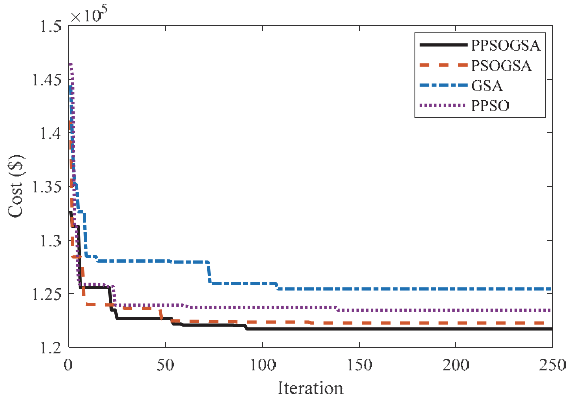
Statistical parameters of different algorithms for the IEEE 85-bus system.

Operating condition	Method	Minimum solution [$]	Maximum solution [$]	Average solution [$]	Standard deviation [$]
Sinusoidal	PPSO	25674	29171	25845	808
	GSA	25627	27068	26301	560
	PSOGSA	25627	26512	26283	251
	PPSOGSA	25610	26144	25864	226
Non-sinusoidal	PPSO	32864	38229	34177	2171
	GSA	33845	37665	35927	1571
	PSOGSA	32830	35898	34094	1027
	PPSOGSA	32661	35668	33936	821

The results from **Tables 8** and **9** show that the proposed algorithm has better performance in comparison to PPSO, GSA and PSOGSA. The convergence profiles of all algorithms are shown in Figs. 9 and 10. The figures indicate that the proposed algorithm can converge to its optimal solutions in lower iterations compared to the other algorithms. The authors have also performed several test runs and it was found that the proposed PPSOGSA in most cases converges to a solution after 50-100 iterations.



(a)



(b)

Fig. 9 – *Convergence profiles for the IEEE 9-bus system under:*
(a) *sinusoidal condition;* (b) *non-sinusoidal condition.*

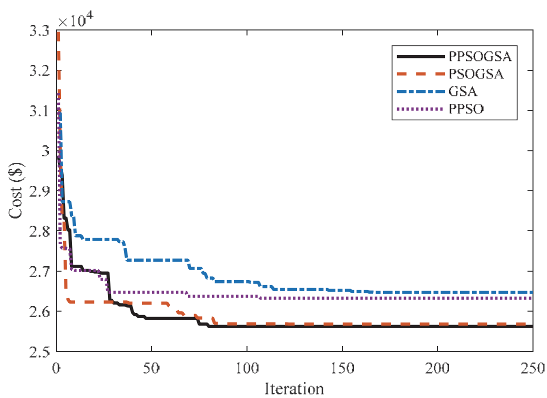
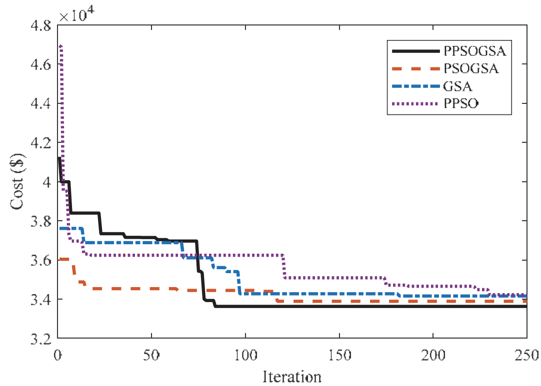


Fig. 10a – *Convergence profiles for the IEEE 85-bus system under sinusoidal condition.*



(b)

Fig. 10b – *Convergence profiles for the IEEE 85-bus system under non-sinusoidal condition.*

5 Conclusion

In this paper, a new hybrid and efficient metaheuristic algorithm is proposed to find optimal sizing and placement of shunt capacitors with the objective of minimizing the annual operating cost of the system. The proposed algorithm is tested on the IEEE 9- and 85-bus systems with non-linear loads. The solutions obtained by the proposed algorithm are compared with those obtained with other optimization techniques. Simulation results are shown that the hybrid PPSOGSA algorithm provides efficient, robust and high-quality solutions. Furthermore, by comparing the optimal values of the results, standard deviations and convergence profiles, it is found that the hybrid PPSOGSA algorithm gives better results than the other methods applied to solve this problem.

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7 References

[1] M. M. Aman, G. B. Jasmon, A. H. A. Bakar, H. Mokhlis, M. Karimi: Optimum Shunt Capacitor Placement in Distribution System - A Review and Comparative Study, Renewable and Sustainable Energy Reviews, Vol. 30, February 2014, pp. 429 – 439.

[2] E. F. Fuchs, M. A. S. Masoum: Power Quality in Power Systems and Electrical Machines, 1st Edition, Academic Press, Amsterdam, Boston, New York, London, 2008.

[3] J. Arrillaga, N. R. Watson: Power System Harmonics, 2nd Edition, John Wiley & Sons, Christchurch, 2003.

[4] K. Prakash, M. Sydulu: Particle Swarm Optimization Based Capacitor Placement on Radial Distribution Systems, Proceedings of the IEEE Power Engineering Society General Meeting, Tampa, FL, USA, June 2007, pp. 1 – 5.

[5] R. Srinivasas Rao, S. V. L. Narasimham, M. Ramalingaraju: Optimal Capacitor Placement in a Radial Distribution System Using Plant Growth Simulation Algorithm, International Journal of Electrical Power & Energy Systems, Vol. 33, No. 5, June 2011, pp. 1133 – 1139.

[6] D. B. Prakash, C. Lakshminarayana: Optimal Siting of Capacitors in Radial Distribution Network Using Whale Optimization Algorithm, Alexandria Engineering Journal, Vol. 56, No. 4, December 2017, pp. 499 – 509.

[7] K. R. Devabalaji, K. Ravi, D. P. Kothari: Optimal Location and Sizing of Capacitor Placement in Radial Distribution System Using Bacterial Foraging Optimization Algorithm, International Journal of Electrical Power & Energy Systems, Vol. 71, October 2015, pp. 383 – 390.

[8] D. Das: Optimal Placement of Capacitors in Radial Distribution System Using a Fuzzy-GA Method, International Journal of Electrical Power & Energy Systems, Vol. 30, No. 6-7, July-September 2008, pp. 361 – 367.

[9] E. S. Ali, S. M. Abd Elazim, A. Y. Abdelaziz: Improved Harmony Algorithm and Power Loss Index for Optimal Locations and Sizing of Capacitors in Radial Distribution Systems, International Journal of Electrical Power & Energy Systems, Vol. 80, September 2016, pp. 252 – 263.

[10] X.- M. Yu, X.- Y. Xiong, Y.- W. Wu: A PSO-Based Approach to Optimal Capacitor Placement with Harmonic Distortion Consideration, Electric Power Systems Research, Vol. 71, No. 1, September 2004, pp. 27 – 33.

[11] C. S. Chen, Y. H. Yan: Optimal Capacitor Placement for Power Systems with Nonlinear Loads, International Journal of Electrical Power & Energy Systems, Vol. 14, No. 6, December 1992, pp. 387 – 392.

[12] Y. Baghzouz: Effects of Nonlinear Loads on Optimal Capacitor Placement in Radial Feeders, IEEE Transactions on Power Delivery, Vol. 6, No. 1, January 1991, pp. 245 – 251.

[13] M. A. S. Masoum, A. Jafarian, M. Ladjevardi, E. F. Fuchs, W. M. Grady: Fuzzy Approach for Optimal Placement and Sizing of Capacitor Banks in the Presence of Harmonics, IEEE Transactions on Power Delivery, Vol. 19, No. 2, April 2004, pp. 822 – 829.

[14] M. Ladjavardi, M. A. S. Masoum: Genetically Optimized Fuzzy Placement and Sizing of Capacitor Banks in Distorted Distribution Networks, IEEE Transactions on Power Delivery, Vol. 23, No. 1, January 2008, pp. 449 – 456.

[15] S. A. Taher, M. Hasani, A. Karimian: A Novel Method for Optimal Capacitor Placement and Sizing in Distribution Systems with Nonlinear Loads and DG Using GA, Communications in Nonlinear Science and Numerical Simulation, Vol. 16, No. 2, February 2011, pp. 851 – 862.

[16] J. Vuletić, M. Todorovski: Optimal Capacitor Placement in Distorted Distribution Networks with Different Load Models Using Penalty Free Genetic Algorithm, International Journal of Electrical Power & Energy Systems, Vol. 78, June 2016, pp. 174 – 182.

[17] M. Ayoubi, R.- A. Hooshmand, M. T. Esfahani: Optimal Capacitor Placement in Distorted Distribution Systems Considering Resonance Constraint Using Multi-Swarm Particle Swarm Optimisation Algorithm, IET Generation, Transmission & Distribution, Vol. 11, No. 13, September 2017, pp. 3210 – 3221.

[18] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, IEEE Std 519-1992, IEEE, New York, 1993.

[19] M. Ghasemi, E. Akbari, A. Rahimnejad, S. E. Razavi, S. Ghavidel, L. Li: Phasor Particle Swarm Optimization: A Simple and Efficient Variant of PSO, Soft Computing, Vol. 23, No. 19, October 2019, pp. 9701 – 9718.

[20] E. Rashedi, H. Nezamabadi-pour, S. Saryazdi: GSA: A Gravitational Search Algorithm, Information Sciences, Vol. 179, No. 13, June 2009, pp. 2232 – 2248.

[21] S. Mirjalili, S. Z. Mohd Hashim: A New Hybrid PSOGSA Algorithm for Function Optimization, Proceedings of the International Conference on Computer and Information Application, Tianjin, China, December 2010, pp. 374 – 377.

[22] J. Radosavljević, D. Klimenta, M. Jevtić, N. Arsić: Optimal Power Flow Using a Hybrid Optimization Algorithm of Particle Swarm Optimization and Gravitational Search Algorithm, Electric Power Components and Systems, Vol. 43, No. 17, August 2015, pp. 1958 – 1970.

[23] S. F. Mekhamer, S. A. Soliman, M. A. Moustafa, M. E. El-Hawary: Application of Fuzzy Logic for Reactive-Power Compensation of Radial Distribution Feeders, IEEE Transactions on Power Systems, Vol. 18, No. 1, February 2003, pp. 206 – 213.

[24] A. R. Seifi: A New Hybrid Optimization Method for Optimum Distribution Capacitor Planning, Modern Applied Science, Vol. 3, No. 4, April 2009, pp. 196 – 202.

[25] S. Nojavan, M. Jalali, K. Zare: Optimal Allocation of Capacitors in Radial/Mesh Distribution Systems Using Mixed Integer Nonlinear Programming Approach, Electric Power Systems Research, Vol. 107, February 2014, pp. 119 – 124.

[26] ETAP 12.6 User Guide, Operation Technology, Inc., Irvine, CA, 2014.

[27] C. S. Cheng, D. Shirmohammadi: A Three-Phase Power Flow Method for Real-Time Distribution System Analysis, IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995, pp. 671 – 679.

[28] M. Milovanović, J. Radosavljević, B. Perović: A Backward/Forward Sweep Power Flow Method for Harmonic Polluted Radial Distribution Systems with Distributed Generation Units, International Transactions on Electrical Energy Systems, Vol. 30, No. 5, May 2020, pp. 1 – 17.

[29] M. Milovanović, J. Radosavljević, D. Klimenta, B. Perović: GA-Based Approach for Optimal Placement and Sizing of Passive Power Filters to Reduce Harmonics in Distorted Radial Distribution Systems, Electrical Engineering, Vol. 101, No. 3, September 2019, pp. 787 – 803.

[30] J. Radosavljević, N. Arsić, M. Milovanović, A. Ktena: Optimal Placement and Sizing of Renewable Distributed Generation Using Hybrid Metaheuristic Algorithm, Journal of Modern Power Systems and Clean Energy, Vol. 8, No. 3, May 2020, pp. 499 – 510.

[31] M. Milovanović, D. Tasić, J. Radosavljević, B. Perović: Optimal Placement and Sizing of Inverter-Based Distributed Generation Units and Shunt Capacitors in Distorted Distribution Systems Using a Hybrid Phasor Particle Swarm Optimization and Gravitational Search Algorithm, Electric Power Components and Systems, Vol. 48, No. 6-7, August 2020, pp. 543 – 557.

[32] M. Milovanović, J. Radosavljević: A Hybrid PPSOGSA Algorithm for Optimal Volt/VAr/THDv Control in Distorted Radial Distribution Systems, Applied Artificial Intelligence, Vol. 35, No 3, 2021, pp. 227 – 246.

[33] Z. Ullah, S. Wang, J. Radosavljević, J. Lai: A Solution to the Optimal Power Flow Problem Considering WT and PV Generation, IEEE Access, Vol. 7, 2019, pp. 46763 – 46772.