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Particle swarm optimization algorithm for capacitor allocation problem in distribution systems with wind turbine generators

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ABSTRACT

This paper aims at adopting the Particle Swarm Optimization (PSO) technique to find the near-optimal solutions for the capacitor allocation problem in distribution systems for the modified IEEE 16-bus distribution system connected to wind energy generation based on a cost function. The proper allocation and the optimized number of capacitors have led to adequate power losses reduction and voltage profile enhancement. Because of the wind power generation variations due to the nature of wind speed intermittency and the lack of reactive power compensation, the problem under study have been presented involving a nonlinear fitness function. In order to solve it, the corresponding mathematical tools have to be used. The formulated fitness cost function has consisted of four terms: cost of real power loss, capacitor installation cost, voltage constraint penalty, and capacitor constraint penalty. PSO technique has been used to obtain the near-optimum solution to the proposed problem. Simulation results demonstrate the efficiency of the proposed fitness cost function when applied to the system under study. Furthermore, the application of PSO to the modified IEEE 16-bus system has shown better results in terms of power losses cost and voltage profile enhancement compared to Genetic Algorithm (GA). In order to verify the successful adaptation of PSO toward attaining adequate near-optimal capacitor allocations in distribution systems, this metaheuristic technique has been employed to the large-scale IEEE 30-bus system. The proposed PSO technique has provided adequate results while modifying the objective function and constraints to include the power factor and transmission line capacities for normal and contingency (N-1) operating conditions.

Introduction

Distribution systems, typically passive radial networks with unidirectional power flow, have a high R/X ratio and significant voltage drop that may cause significant undesirable power losses. Distribution systems capture about 13% of the overall power generation [1–3]. From the utility point of view, the system efficiency is directly influenced by real power losses. However, the reactive power flow should be accounted for in order to maintain voltage within acceptable limits and to release the transmission capacity especially for system reliability and stability purposes [4]. In order to reveal the estimated minimized power loss in distribution networks, capacitor placement, feeder reconfiguration, and Distributed Generation (DG) allocation have been used [1].

Capacitors provision in power systems are mainly for voltage profile management, power factor correction, power flow control, system stability improvement and reactive power compensation. Due to capacitor installations, a part of the reactive currents will be cancelled that results in a considerable decrease in the overall supplied current [2]. Reactive power loss minimization and voltage profile improvement are successfully accomplished through either/both DG sources or/and capacitors banks in distribution systems. In order to reduce the system losses and enhance its performance, the most convenient installation location and the related capacity of these components should be identified. This considerable identification will keep the power generation/consumption coincidence which leads to minimum power losses [5]. An economical momentum can be harnessed through power losses minimization delivered by capacitor banks investment [6]. Therefore,

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perceptible challenges dealt with near-optimal capacitor placement for both voltage control and loss minimization have been proposed [6]. For attaining this goal, selecting the most appropriate number of capacitor units, their locations and sizing have to be determined. Therefore, power loss reduction, voltage profile regulation, and power flow control could be realized.

Many optimization techniques have been developed to find the best capacitor placement and sizing in distribution systems. These techniques can be classified into four categories: analytical methods, numerical programming approaches, heuristic methods and Artificial Intelligent (AI) based techniques [7,8]. To successfully reach the most convenient solution, advanced stochastic techniques can replace the time-consuming analytical optimization approaches particularly for complex problems. Therefore different optimization techniques such as dynamic programming, evolutionary programming, tabu search, genetic algorithm, simulated annealing, particle swarm optimization (PSO), ant colony system, fuzzy based optimization approaches, honey bee mating optimization and shuffled frog leaping algorithm have been investigated [3,9,10]. Despite of the fact that heuristic methods do not assure a global optimal solution, reasonable near-optimal ones with an admissible computation time have been demonstrated [10]. For more favorable optimization results, hybrid approaches can be considered [10–17].

The main contribution of this paper deals with proposing PSO technique, in favor its simplicity and relative short convergence time, to determine the near-optimum capacitor locations and their relevant sizes to improve the performance of the modified IEEE 16-bus, three feeder systems with one wind generator. The objective function, employed by PSO, has included the annual net saving and the cost of power losses resulting from the reduction of peak power losses while accounting for the total cost of the capacitor [18–22]. To verify the adequacy of the PSO technique for the determination of the near-optimum capacitor location/size in the modified IEEE 16-bus, the simulation results are compared to those reached from using the GA approach. Furthermore, the PSO is applied to the IEEE 30-bus system to confirm the effectiveness of such metaheuristic technique toward estimating the near-optimum solutions of capacitor placement/size in the system. For all simulation studies, the insertion of the capacitor penalty cost is considered as a constraint in the objective function. Precisely, if the allocated capacitor size required for fitness function minimization is not one of the available capacitor standards, a defined penalty is added in the objective function to reject such capacitive candidate and to search for another capacitor that satisfies both the cost function minimization and the given constraints [18–22].

The rest of the paper is organized as follows: a comprehensive literature review has been presented in section 'Literature review'. In section 'System under study and problem formulation', the IEEE modified 16-bus system under study has been presented. Moreover, an overview of the problem formulation besides the construction of the fitness function and system constraints has been illustrated. Section 'Solution approach based on PSO' has briefly demonstrated the PSO technique. Simulation results have been explicitly discussed in section 'Simulation results' for exhibiting the PSO technique performance and its effectiveness compared to the base case (before using the proposed optimization method). In addition, the PSO technique has been compared to the GA when applied to the modified IEEE 16-bus system. In section 'PSO method validation', the verification of the proposed PSO technique has been considered. The capability of the proposed PSO technique in enhancing the voltage profile of the IEEE 30-bus system and minimizing its relevant power losses cost has been demonstrated. Then, validity of the PSO methodology has been verified through a modified objective functions with new constraints such as the power factor and the line capacities when applied to the original IEEE 16-bus system. Finally, the conclusions and the forthcoming research perspectives have been drawn in section 'Conclusions'.

Literature review

Since 2010, abundant researches have highlighted the importance of optimal placement and sizing of capacitor for real power loss reduction and voltage profile regulation in distribution systems. Segura et al. have proposed an efficient heuristic algorithm for optimal capacitor allocations in radial distribution systems [23]. De Oliveira et al. have used the Mixed Integer Non-Linear Programming (MINLP) technique for optimal reconfiguration and capacitor allocation solutions for energy loss minimization of radial distribution networks considering different load levels [24]. Eajal et al. have developed an efficient hybrid PSO algorithm to find a convenient solution for optimal allocation and sizing of the capacitors while satisfying operating and power quality constraints [25]. Guimaraes et al. have sought for optimal capacitor placement and reconfiguration solutions via GA in distribution systems [26]. Carpinelli et al. have applied GA in order to find the optimal allocation and sizing of capacitors in unbalanced multi-converter distribution systems [27]. Tabatabaei et al. have suggested the bacterial foraging solution with a fuzzy logic decision for optimal capacitor allocation in radial distribution system [28]. Szuvovivski et al. have studied both GA algorithms and optimal power flow for allocating simultaneously capacitors and voltage regulators at distribution networks [29]. Singh et al. have used the PSO approach to determine the optimal capacitor placement for cost savings' maximization [30]. Kansal et al. have presented the optimal allocation of different DG using PSO technique for active and reactive power compensation to minimize the real power losses in the primary distribution networks [31,32].

Nojavan et al. have presented the optimization approach based on MINLP approach for optimal capacitor placement in radial/mesh distribution systems. The superiority of the considered optimization technique compared to others in terms of both power loss and investment costs reduction has been demonstrated [33]. Ramadan et al. have considered fuzzy set optimization approach for optimal capacitor allocation solution in radial distribution system. Different membership functions for voltage profile constraint, active power losses and total power losses constraints have been proposed in the optimization process [2]. Furthermore, Karimyan et al. have presented a worthy bibliographical survey in which a comprehensive literature review concerning the common techniques and the related optimization approaches used for distribution systems' loss minimization have been illustrated [1].

Gholami et al. have developed a GA-based approach for the optimal sizing and placement of either fixed or switchable capacitors both to guarantee the benefits of capacitor installation at different load levels and to minimize the investment cost of capacitors [34]. Augugliaro et al. have presented the GA to solve optimization problems with many discrete variables such as the best allocation/sizing of DG systems or the relevant optimal compensation [35]. Injeti et al. have proposed the Bio-Inspired Optimization (BIO) algorithm for the optimal capacitors placement/sizing in radial distribution systems in order to minimize the power loss and maximize the network savings [36].

Devabalaji et al. have studied the optimal allocation of capacitor bank in radial distribution systems in order to minimize the power loss based on the loss sensitivity factor and voltage stability index [37]. For this purpose, the Bacterial Foraging Optimization (BFO) approach has been considered for the optimal sizing/allocation for the capacitors in such distribution system. Duque et al. have presented the Monkey Search Optimization (MSO) technique for the allocation of fixed capacitors banks in order to optimize the distribution network operation through reducing the system loss and minimizing the investment cost in capacitors [38]. Muthukumar and Jayalalitha have applied a hybrid optimization algorithm based on the Harmony Search Algorithm (HSA) and Artificial Bee Colony (ABC) algorithm in radial distribution networks to minimize the power loss [39]. To overcome the drawback of the premature and the slow convergence of using HSA approach alone, the hybrid method has been used for enhancing the harmony memory vector and therefore better results can be expected [39].

In this paper, the PSO is proposed for the capacitor allocation problem as it is mainly based on the intelligence that permits such optimization technique to be conveniently applied into both scientific research and engineering use. Unlike most of other optimization techniques, the PSO has no overlapping and mutation calculation. The particle speed can carry out the search. Within multi-generation development, only the most optimist particle can transmit information onto the other particles, and the speed of the researching is very fast. The PSO is characterized by its relatively simplicity, ease, and better optimization ability. However compared to other metaheuristic optimization algorithms, the PSO suffers from limited disadvantages. It may result in partial optimism and may not properly deal with the problems of scattering and/or non-coordinate systems. The latter can be avoided through the appropriate system re-structuring. The restructuring of the both systems under study is already considered in the load flow analysis and system impedance matrix building.

To cope with the expected complexity in distribution networks resulted from both the insertion of the wind energy generation and the fast load's dynamic behavior variations, the use of adaptive AI based optimization approaches becomes more important.

System under study and problem formulation

The system under study consists of 16 buses of three feeders' distribution system as shown at Fig. 1. One of them has been connected to Wind Turbine Generator (WTG) at bus 2 and defined as PV bus while the other two feeders have been attached to conventional generators. The system's data are given in Table 1 [40].

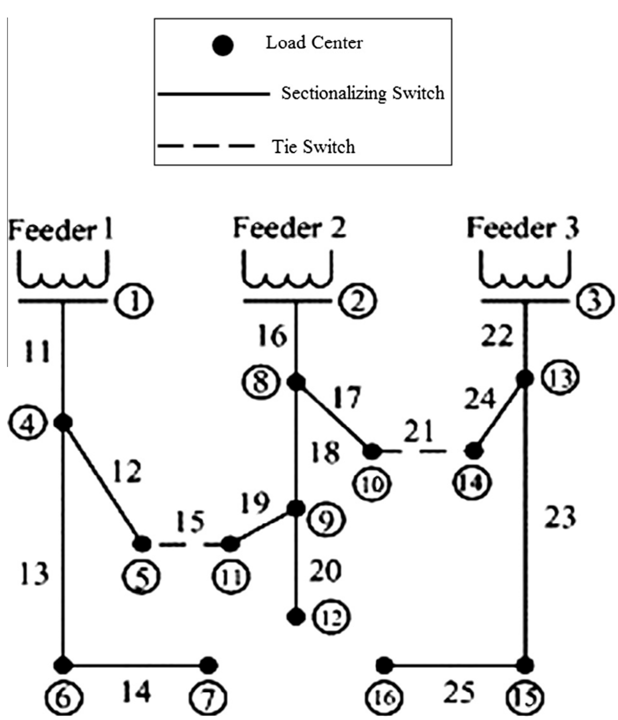

Fig. 1. Modified IEEE 16 bus, three feeders system, bus 2 connected to WTG.

Table 1
Three feeder system data (base 100 MVA, 23 kV).

T.L.	R[a]	X[a]	P[b]	Q[c]	T.L.	R[a]	X[a]	P[b]	Q[c]
1–4	0.075	0.100	7.50	6.00	9–12	0.080	0.110	9.00	3.00
4–5	0.080	0.110	12.0	6.00	3–13	0.110	0.110	4.44	4.00
4–6	0.090	0.180	12.0	3.20	13–14	0.090	0.120	5.70	4.00
6–7	0.040	0.040	6.25	5.00	13–15	0.080	0.110	4.44	4.00
2–8	0.110	0.110	12.0	8.10	15–16	0.040	0.040	8.00	4.00
8–9	0.080	0.110	10.5	6.00	10–14	0.040	0.040	–	–
8–10	0.110	0.110	4.44	4.00	5–11	0.04	0.04	–	–
9–11	0.110	0.110	3.00	5.00	The shunt capacitors Cap (MVAR) are initially zero				

[a] R and X are the transmission line (T.L.) resistance and reactance in p.u.
[b] P is MW at the end bus.
[c] Q is in MVAR at the end bus.

The cost fitness function, which has to be minimized, has been considered while developing the network. Therefore, the performance of this network for different proposed capacitor locations and rating can be analyzed [41]. Using MATLAB™ program, the network modeling has been performed. The main objective of the overall model has been to evaluate the voltage profile and capacitor rating at the specified location besides the total power losses cost after using PSO.

The analytical optimization algorithms, used for finding the near-optimal capacitors' placement solutions, have been recommended when powerful computing resources are available especially for complex networks [42]. In such methods, the use of calculus to determine the maximum saving cost function, which relates to the minimum cost of power losses, has been involved [42]. For the system under study, the following constraints have to be considered:

A. Voltage constraints

The voltage magnitude at each bus must be maintained within specified limits as follows:

$$V_{\min} \leqslant V_j \leqslant V_{\max} \quad j \in \{1, \ldots, 16\} \tag{1}$$

where V_j is the voltage magnitude of the bus j, $V_{\min}$ and $V_{\max}$ are the bus minimum and maximum voltage limits, respectively.

B. Capacitors' placement constraints

The distribution of different capacitor bank locations and ratings depend upon the network configuration and actual load values have been proposed. The capacitor sizes and locations have been placed assuming the following constraints [43–45]:

- Capacitors inserted on those circuits are of heavy kVAR load.
- Capacitor sizes do not exceed the record kVAR of each feeder.

Finally, the fitness function can be described as follows:

$$F = \text{Minimize}\left(H_{\text{loss}}P_{\text{loss}} + K_c\sum_{i=1}^{16}Q_c(i) + V_{\text{pen}} + C_{\text{pen}}\right) \tag{2}$$

where H_{loss} is the annual cost of real power loss equal to 168 $/kW [12], P_{loss} is the total power loss, K_c is the cost of kVAR for capacitor i, $i \in \{1, \ldots, 16\}$, and $Q_c(i)$ is the size in kVAR of the available standard capacitor i. V_{pen} is the voltage constraints penalty. It penalizes (increases) the cost value if the chosen capacitor is failed in adjusting the voltage value within the limits in Eq. (1). C_{pen} is the capacitor constraints penalty if the required capacitor is outside the available standard ranges. Therefore, the annual saving will be estimated using PSO technique and compared to the base case (without using PSO approach).

Solution approach based on PSO

PSO has been employed to find the values of the voltage at each bus. PSO is a stochastic population-based metaheuristic designed by Eberhart and Kennedy [46,47] to solve continuous optimization problems. The idea of this metaheuristic came from the observation of behavior of natural organisms to find food. PSO works with a swarm of particles. Each particle is a solution to a problem in the decision space and has two characteristic: its own position and velocity. The position represents the current values in the solution, the velocity defines the direction and the distance to optimize the position at next iteration. For each particle i its own past best position p_i^{best} and the entire swarm's best overall position G are remembered. In basic PSO the velocity and position of each particle are updated in the following way [53,54]:

$$v_i(k+1) = wv_i(k) + \rho_1 c_1(p_i^{best} - x_i(k)) + \rho_2 c_2(Gx_i(k)) \quad (3)$$

$$x_i(k+1) = x_i(k) + v_i(k+1) \quad (4)$$

where i is a particle index, k is an iteration number, $v_i(k)$ is velocity, $x_i(k)$ is the position of particle i at iteration k; p_i^{best} is the best position found by particle i (personal best), G is the best position found by the swarm (global best, best of personal bests), w is an inertia coefficient, (ρ_1, ρ_2) are random numbers in [0,1] interval, c_1, c_2 are positive constants representing the factors of particle's attraction toward its own best position or toward the swarm's best position.

The flowchart of PSO is depicted in Fig. 2 [48]. Over other optimization techniques, PSO has distinct advantages. It is simple in concept, ease in implementation, and efficient in computation in terms of both memory requirements and speed [47–52]. For capacitor allocation problem each particle i corresponds to a capacitor, the position $x_i(k)$ is a vector with components $x_{ij}(k)$ corresponded to a voltage magnitude at bus j and capacitor i. The values of all the parameters such as the size of a swarm, inertia coefficient, factors of attraction have been defined by default in toolbox of MATLAB™.

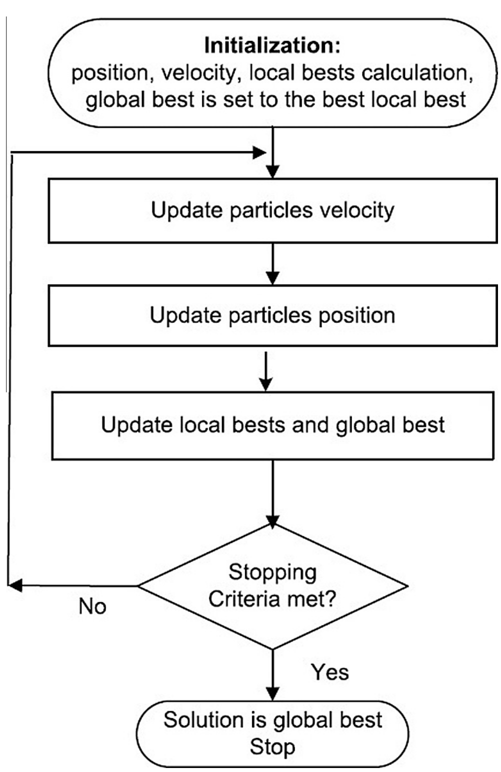

Fig. 2. Flowchart for PSO algorithm [52–55].

As demonstrated in Fig. 2, PSO algorithm mainly comprised five steps: initialization, update particle velocity, update particle position, and stopping criteria [53–55]. Each step is defined as:

- *Initialization:* n position vectors are randomly initialized. The elements are uniformly distributed within appropriate limits. In parallel, n velocity vectors are randomly initialized and then uniformly distributed between maximum and minimum limits. An objective function is assigned to evaluate the fitness of each particle. Therefore, the local best of each particle is initialized to its initial position, the global best to the best fitness among the best locals. The inertia weight ranges can be initially adapted if necessary.
- *Update particle velocity:* this can be done through two terms. The first is the inertia component which is concerned with maintaining the same direction for particle movement as in the previous iteration. The second, named cognitive component, deals with returning the particle to its local best it has encountered so far. Therefore, it acts as the particles' memory.
- *Update particle position:* the particle position should be updated accounting the new updated velocity.
- *Update local bests and global best:* these bests are updated in case of the updated particle positions which lead to better objective function values compared to other previous one.
- *Stopping criteria:* the algorithm is terminated if either the number of iterations reaches the maximum allowable number or the desired value of the objective function is reached.

Simulation results

To observe the efficiency of the PSO algorithm, simulation studies of the distribution system shown in Fig. 1 have been executed by MATLAB™ both with and without shunt capacitor placement. The following values of the PSO parameters have been used:

PSO stopping criteria, the algorithm stops either after 2000 iterations or the fitness value has not been improved more than $1e^{-9}$ during 50 running iterations; swarm's size $n = 20$, the factors of particle's attraction $c_1 = c_2 = 2$, the inertia coefficient w is varied from 0.9 to 0.2 (after 1500 iterations). The following two cases have been studied:

Base case (Case A)

The base case has been concerned with studying the modified IEEE system of 16 buses without applying the PSO (no shunt capacitor insertion has been considered). Then, the voltage profile at all buses of the network has been illustrated in Fig. 3. Clearly, the values of the voltage at some buses are out of the permissible limits as shown in Table 2. In addition, the estimated annual losses cost is about 1.151 M$.

Optimal cases (Case B)

In this case, PSO approach has been employed to the base case while using shunt capacitors. The near-optimal capacitor location and sizing will be searched for taken into account both voltage and capacitor constraints. Table 3 demonstrates the available three phase capacitor size Q_c and their corresponding cost K_c [4–8]. Table 4 has depicted that the voltage profile at all buses has been greatly improved compared to the base case after PSO technique

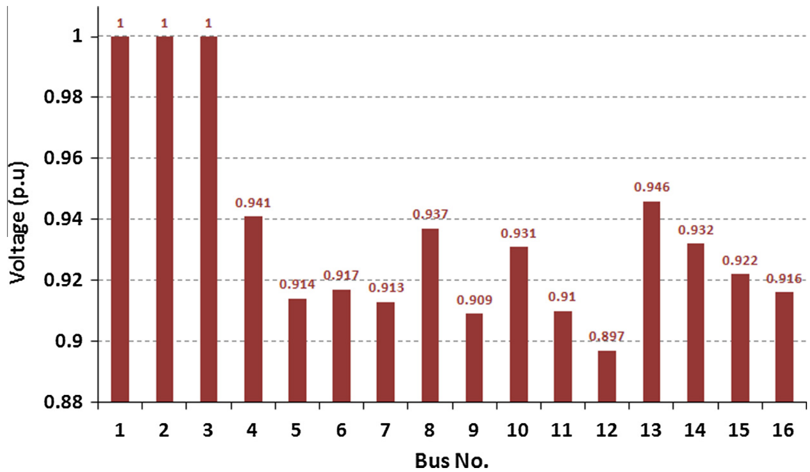

Fig. 3. Voltage profile of the modified IEEE16-bus three feeder (base case).

Table 2
Base case data.

Bus No.	V_{bus} (p.u)	Bus No.	V_{bus} (p.u)
1	1.000	9	0.909
2	1.000	10	0.931
3	1.000	11	0.910
4	0.941	12	0.897
5	0.914	13	0.946
6	0.917	14	0.932
7	0.913	15	0.922
8	0.937	16	0.916
Annual power losses cost = 1.151 M$.			

Table 3
Available three phase capacitor sizes and their corresponding cost.

Q_c [a]	K_c [b]	Q_c [a]	K_c [b]
5	0.800	2250	0.197
15	0.750	2400	0.170
30	0.700	2550	0.189
50	0.650	2700	0.187
100	0.600	2850	0.183
150	0.500	3000	0.180
300	0.350	3150	0.195
450	0.253	3300	0.174
600	0.220	3450	0.188
750	0.276	3600	0.170
900	0.183	3750	0.183
1050	0.228	3900	0.182
1200	0.170	4050	0.179
1350	0.207	5000	0.170
1500	0.201	5500	0.178
1650	0.193	6000	0.168
1800	0.187	7000	0.167
1950	0.211	8000	0.165
2100	0.176		

[a] Capacitor size (kVAR).
[b] Capacitor cost ($/kVAR).

Table 4
Cost and voltage profile comparison.

Bus No.	Case A [a]		Case B.1 [b]		Case B.2 [c]	
	Q_c	V_{bus}	Q_c	V_{bus}	Q_c	V_{bus}
1	0	1.000	0	1.000	0	1.000
2	0	1.000	0	1.000	0	1.000
3	0	1.000	0	1.000	0	1.000
4	0	0.941	8	0.970	7	0.968
5	0	0.913	4	0.957	6	0.954
6	0	0.916	0	0.955	4	0.954
7	0	0.913	8	0.955	0	0.952
8	0	0.936	8	0.965	8	0.964
9	0	0.908	7	0.954	8	0.950
10	0	0.930	0	0.961	0	0.964
11	0	0.909	8	0.956	5	0.952
12	0	0.897	0	0.949	0	0.940
13	0	0.946	5	0.971	6	0.972
14	0	0.931	7	0.964	4	0.965
15	0	0.922	4	0.961	0	0.959
16	0	0.916	0	0.957	4	0.956
Annual power losses cost = 1.151 M$			0.782 M$		0.818 M$	
Annual net saving			0.369 M$ (32%)		0.333 M$ (28%)	

[a] *Case A:* No capacitor insertion in the distribution system.
[b] *Case B.1:* Near-optimal capacitor placement and sizing via PSO (WTG delivers 35 MW at bus 2).
[c] *Case B.2:* Near-optimal capacitor placement and sizing via PSO (WTG delivers 40 MW at bus 2).

consideration. In addition, the cost of power losses have been decreased by 32% and 28% in comparison with the base case if the wind power generated at bus 2 are 35 MW (Case B.1) and 40 MW (Case B.2) respectively. Therefore, the PSO approach has significantly provided annual net savings for both cases.

From Table 4, the net saving for Case B.1 has been estimated as:

$$\text{Annual net saving} = \text{Annual Cost}_{(\text{Case A})} - \text{Annual Cost}_{(\text{Case B.1})}$$
$$= 1.151 - 0.782 = 0.369\ \text{M\$}$$

Therefore, the proper capacitor installation in the distribution network has leaded to a desired reduction in power losses cost by 0.369 M$/year (32% reduction) which reflects the importance of these capacitors. On the other hand, the voltage profile in favor of a near-optimal capacitor insertion has been enhanced compared to the base case.

The net saving for Case B.2 was equal to:

$$\text{Annual net saving} = \text{Annual Cost}_{(\text{Case A})} - \text{Annual Cost}_{(\text{Case B.2})}$$
$$= 1.151 - 0.818 = 0.333\ \text{M\$}$$

Indeed, the capacitor installation in the distribution network has resulted in reduction of power losses cost by 0.333 M$/year (28% reduction). This net saving has been less favorable than that revealed in Case B.1.

Fig. 4 has displayed the voltage profile after compensation when the wind turbine at bus 2 delivered 35 MW and 40 MW respectively. Owing to the proposed PSO technique, an explicit voltage profile enhancement has been reached at all buses partic-

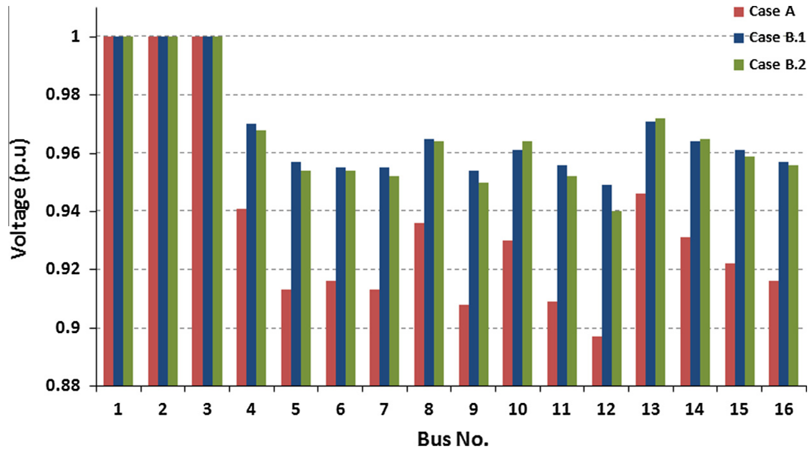

Fig. 4. The voltage profile while using near-optimal capacitor for WTG of 35 MW and 40 MW power output.

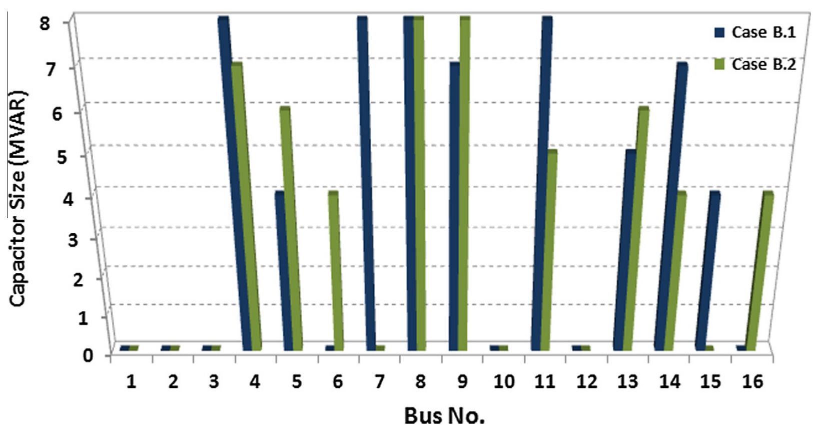

Fig. 5. The requested near-optimal capacitor sizing at different buses in the distribution system.

ularly for those suffering from out-of-limit voltages in the base case.

As introduced in Fig. 5, nine shunt capacitors of different near-optimal sizing have been requested at the buses. Moreover, there is no need of shunt capacitor on the generator buses for Case B.1 and Case B.2 respectively. However, making use of the capacitor bank group of Case B.1 has provided more profitable solution compared to Case B.2. Obviously, the voltage profile at the buses has been more enhanced and maximum net saving has been attained.

Fig. 6 has illustrated the variation of fitness function with number of generation (named Epochs) when the WTG outputs are 35 MW and 40 MW respectively. It has demonstrated how the PSO technique has successfully forced the fitness function value to decrease with epoch rise. Obviously, the proposed optimization approach can be used effectively used toward both enhancing the voltage profile and minimizing the power losses cost.

In favor of the GA advantages such as its adequate quality solutions and its less convergence time compared to other conventional optimization approaches, GA is considered an alternative optimization technique. Without adding WTG, the same study has been performed for the optimal capacitor allocation in the modified IEEE 16-bus system. The voltage profile of the different buses is depicted in Table 5. Obviously, an improved voltage profile of most of the buses of the IEEE 16-bus is reached compared to the base case. From the simulation results, the active power losses cost is reduced to 0.8145 M$. This losses is higher than that reached in Case B.1 which equals to 0.782 M$. Therefore, the PSO provides better solution than both the GA and the base case study. Hereby, the proposed PSO method can be considered an acceptable simple, fast, efficient and more promising technique for the optimal placement/sizing of capacitors in distribution systems.

Fig. 7 displays the Fitness Function (FF) variation and the losses cost respectively against the number of generation. Indeed, more iteration number is noticed compared to that of the PSO technique shown in Fig. 6.

From the comparative study between the application of both PSO and GA to the modified IEEE 16-bus system, it is obvious that the PSO has properly dealt with providing an adequate capacitor allocation solution. Furthermore, the PSO has been proven as a considerable optimization technique in terms of convergence time and iteration number compared to GA. The use of the meta-heuristic PSO technique has led to a significant near-optimal capacitor placement/size solution for both minimizing the modified IEEE 16-bus power losses cost and enhancing the system's voltage profile.

PSO method validation

Toward verifying the effectiveness of the proposed PSO technique for the identification of the near-optimal capacitor allocation, further simulations using MATLAB™ have been performed on the IEEE 30-bus test system depicted in Fig. 8 (6 generators, 20 loads, 41 lines) extensively introduced in [56]. Similarly, the objective function is to reduce the active power losses cost besides enhancing the buses voltage profile. Simulation results investigate the capability of the proposed PSO approach in reducing the overall

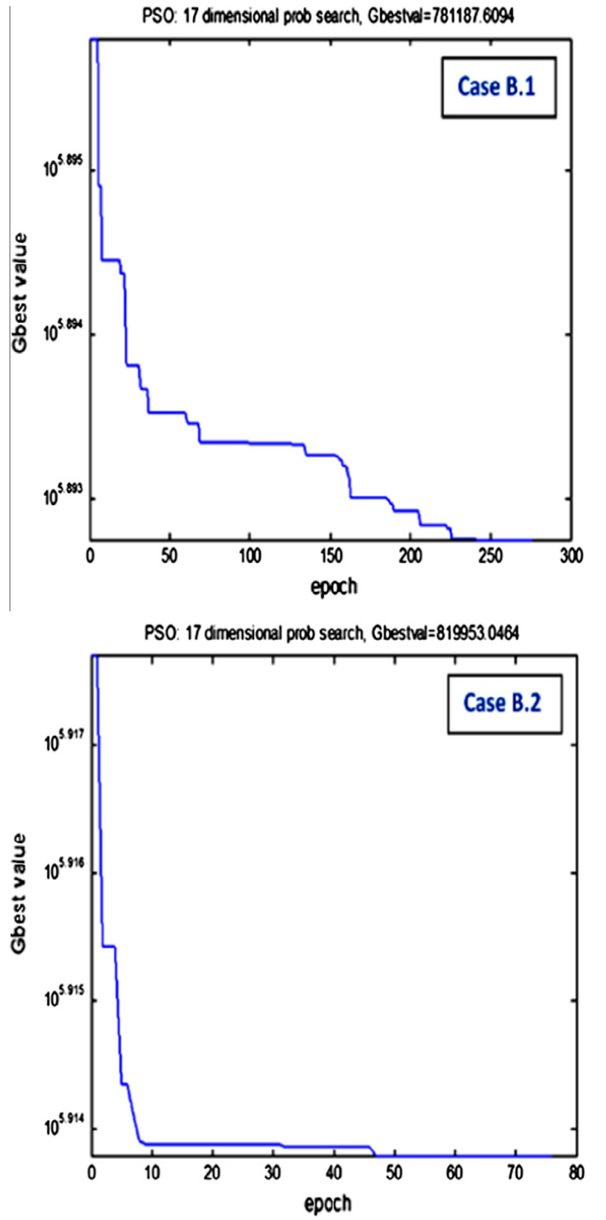

Fig. 6. Variation of fitness function with number of generation for PSO technique.

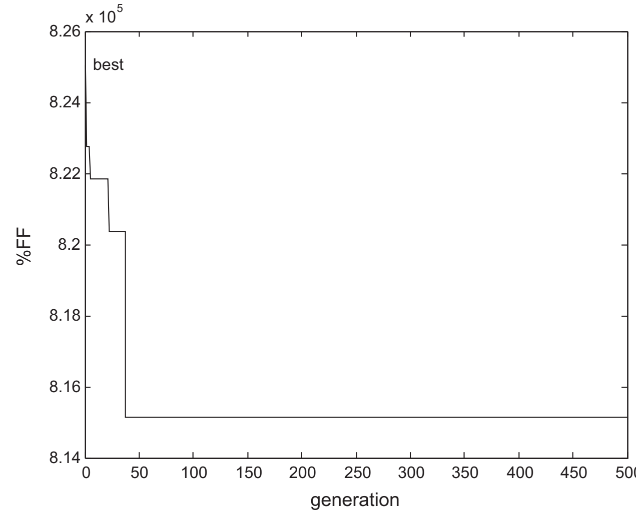

Fig. 7. Fitness function variation against number of generation in GA.

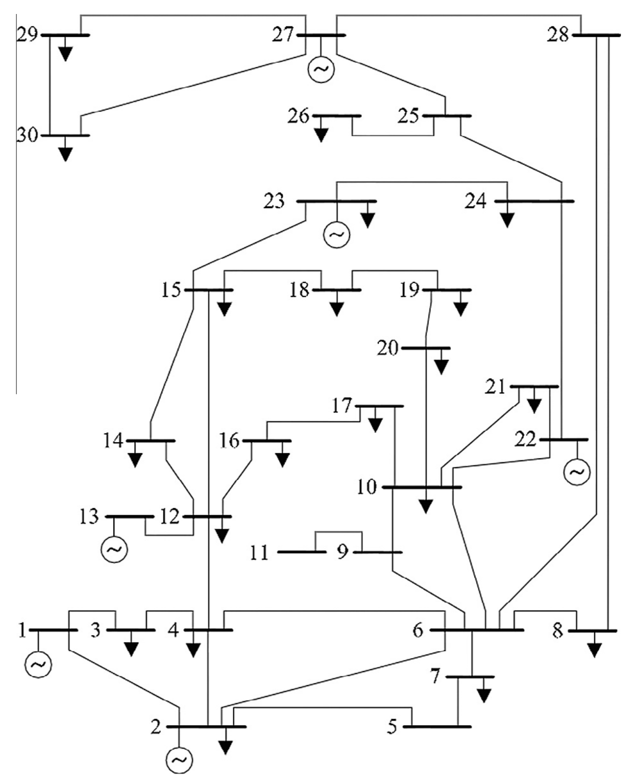

Fig. 8. IEEE 30-bus test system [56].

Table 5
Voltage profile using GA for IEEE 16-bus test system.

Bus #	Q_c (MVAR)	V_{bus}	Bus #	Q_c (MVAR)	V_{bus}
1	0	1	9	5	0.919
2	0	1	10	4.5	0.944
3	0	1	11	4.5	0.923
4	5	0.978	12	6	0.905
5	6	0.967	13	3.75	0.986
6	6	0.970	14	3.75	0.983
7	1.5	0.967	15	0	0.980
8	5.5	0.945	16	4	0.978

power losses cost by approximately 22% and improving the voltage profile at most of system buses taken into account the constraint boundaries (such as: min/max active power, available capacitor size and voltage constraint). As illustrated in Table 6, the voltage profile of almost all buses have been enhanced according to the reactive power compensation of the capacitor optimally allocated using the PSO technique. In addition, the active power losses have been reduced from 22 MW to 18 MW (about 22% reduction).

Therefore, the PSO has been employed on both the modified IEEE 16-bus and the IEEE 30-bus test systems. The first is used for clarifying the superiority of the PSO rather than the GA in identifying the near-optimal capacitor placement/size. Compared to the previous research performed, the proposed capacitor allocation solution takes into consideration the standard capacitor-bank availability besides the voltage limits and the min/max active power constraints. Therefore, the near-optimal solution is treated as a multi-objective function for enhancing the system bus voltage profile and reducing its relevant active power losses cost. The mod-

Table 6
Voltage profile enhancement using PSO for IEEE 30-bus test system.

Bus #	Q_c (MVAR)	V_{bus}[a]	V_{bus}[b]	Bus #	Q_c (MVAR)	V_{bus}[a]	V_{bus}[b]
1	0	1.000	1.000	16	18.373	0.937	1.045
2	0	1.000	1.000	17	0	0.937	1.036
3	0	0.944	0.970	18	13.660	0.908	1.018
4	0	0.941	0.972	19	0	0.905	1.011
5	0	0.967	0.985	20	0	0.911	1.015
6	12.168	0.936	0.974	21	33.761	0.965	1.041
7	0	0.938	0.969	22	0	0.975	1.040
8	0	0.923	0.961	23	22.663	0.955	1.010
9	0	0.945	1.040	24	24.164	0.933	1.012
10	40.339	0.951	1.044	25	9.780	0.957	1.001
11	32.102	0.945	1.102	26	0	0.902	0.948
12	0	0.957	1.030	27	0	1.000	1.000
13	53.252	1.000	1.050	28	0	0.936	0.971
14	9.880	0.930	1.022	29	11.185	0.918	0.961
15	12.694	0.931	1.018	30	2.022	0.922	0.952
Total active power losses in MW						22	18

[a] Without PSO.
[b] With PSO.

ified IEEE 30-bus system is used for ensuring the effectiveness of the proposed PSO technique in fulfilling the desired objectives.

To validate the significance results of the proposed PSO technique, further analysis has been discussed considering both normal and severe contingency (N-1) operating conditions. For the modified IEEE 16-bus system depicted in Fig. 1, the objective function is readjusted to account for both the power factor (pf) and the line loading in both operating conditions. Lower and upper limits have been set for the bus pf. If this desired condition has not been reached, an additional penalty should be added and a new capacitor allocation should be searched for. In contingency (N-1) cases, the effect of line outage on the optimal placement/sizing of the capacitors has been studied. Some bus voltages have been influenced by this case particularly those nearest to the disconnected line. The power flow through the system has been accordingly changed. The active/reactive power flow through the other lines have been modified to compensate the outage of the contingency (N-1) line.

The modified fitness function can be described as follows:

$$F = \text{Minimize}\left(H_{loss}P_{loss} + K_c\sum_{i=1}^{16}Q_c(i) + V_{pen} + C_{pen} + PF_{pen} + CON_{pen}\right) \tag{5}$$

PF_{pen} is the pf constraints penalty. It penalizes (increases) the cost value if the chosen capacitor is failed in adjusting the voltage value within the limits in Eq. (2). CON_{pen} is the line constraints penalty related to the expected line loading variation caused by the contingency (N-1) case. If the required capacitor is outside the available standard ranges, such penalty part will be charged in the cost. Hence, the relevant annual saving or annual charge will be estimated using PSO technique and compared to the corresponding normal case as shown in Table 7.

To perform the contingency (N-1) study, the following assumptions are considered: (i) the bus voltages are maintained constant (an equality constraint in the objective function); (ii) the capacitor locations are kept at the same buses; (iii) two different objective functions are considered to verify the capability of PSO in determining the optimal size of capacitors (Eqs. (2) and (5)). Thus, the study becomes seeking for the optimal resizing of the capacitor without its replacement that fulfills the overall proposed constraints.

Considering the objective function defined in Eq. (2), the contingency analysis has been studied upon the outage of line 8–9 and line 5–11 respectively. The PSO technique has successfully resized the capacitors in both cases at the same buses. However, an additional annual charge of (28.72%) and (34.72%) are requested to fulfill the desired objectives and constraints. In case of using the new objective function of Eq. (5), the power factor term and line capacity have been included. Although the same objectives are required, the new power factor and line capacity constraints should be accounted for. The contingency (N-1) condition analysis has been studied upon the outage of the same lines (i.e., 8–9 and 5–11 respectively). The new optimal resized capacitors have necessitated additional annual charge of (31.54%) and (44.41%) respectively to attain the desired objectives in presence of the different definite constraints.

Still the issues of optimally allocating the capacitors and reconfiguring the network in distribution systems have widespread

Table 7
Voltage profile and relevant Capacitors using PSO for IEEE 16-bus test system: base and contingency (N-1) case studies.

	With conventional objective function (Eq. (2))						With modified objective function (Eq. (5))					
	Normal case		Contingency (N-1) case				Normal case		Contingency (N-1) case			
			Line 8–9		Line 5–11				Line 8–9		Line 5–11	
Bus #	V_{bus}	Q_c	V_{bus}	Q_c	V_{bus}	Q_c	V_{bus}	Q_c	V_{bus}	Q_c	V_{bus}	Q_c
1	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0
2	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0
3	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0	1.000	0
4	0.968	7	0.968	7	0.968	12	0.968	7	0.968	8	0.968	15
5	0.954	6	0.954	6	0.954	10	0.954	7	0.954	7	0.954	15
6	0.954	4	0.954	4	0.954	4	0.954	6	0.954	6	0.954	4
7	0.952	0	0.952	0	0.952	0	0.952	0	0.952	0	0.952	0
8	0.964	8	0.964	12	0.964	8	0.964	8	0.964	15	0.964	8
9	0.950	8	0.950	15	0.950	10	0.950	10	0.950	20	0.950	12
10	0.964	0	0.964	0	0.964	0	0.964	0	0.964	0	0.964	0
11	0.952	5	0.952	7	0.952	7	0.952	6	0.952	8	0.952	10
12	0.940	0	0.940	0	0.940	0	0.940	0	0.940	0	0.940	0
13	0.972	6	0.972	6	0.972	6	0.972	6	0.972	6	0.972	6
14	0.965	4	0.965	4	0.965	4	0.965	6	0.965	7	0.965	4
15	0.959	0	0.959	0	0.959	0	0.959	0	0.959	0	0.959	0
16	0.956	4	0.956	4	0.956	4	0.956	5	0.956	6	0.956	4
Cost	0.818 M$		1.053 M$		1.102 M$		0.894 M$		1.176 M$		1.291 M$	
Annual charge			0.235 M$		0.284 M$		Annual charge		0.282 M$		0.397 M$	
Rise (%)			(28.72%)		(34.72%)		Rise (%)		(31.54%)		(44.41%)	

interest and attention particularly in presence of parameter variations and severe penetrations [57–63].

Conclusions

This paper has presented an application of PSO for determining the location, the size and the number of capacitors for the modified IEEE 16 bus, distribution system connected to wind turbine generators. Simulation results have shown that the PSO approach can be successfully applied to find near-optimum solution to the proposed problem when compared to the GA technique. When the PSO approach is employed to both modified IEEE 16-bus and IEEE 30-bus systems, maximum net saving and significant voltage profile enhancement compared to the original base case have been reached. The technical and economic benefits of adopting the PSO technique are:

- Improving the voltage profile across the system and reducing the voltage gradient, in addition to the revenue due to voltage quality improvement.
- Determining the near-optimum wind generation (35 MW) for such a distribution network from economical point of view that leads to annual loss cost reduction.
- The reduction in the cost of power losses particularly in peak load condition. Therefore, additional investments for using high rating equipment are prevented.

The PSO technique effectiveness is verified for the IEEE 16-bus system using a modified objective function while considering the power factor and line capacity constraints in both normal and contingency (N-1) operating conditions. The optimal resizing problem of the capacitor has been successfully treated using the proposed PSO approach.

In the future work, the PSO technique will be used for finding near-optimal solutions of DG-capacitor banks-energy storage systems coordination problems considering abnormal operation conditions.

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