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OPTIMAL CAPACITOR PLACEMENT IN 13-BUS URDS USING PARTICLE SWARM OPTIMIZATION

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Abstract

Shunt capacitors installation in distribution systems requires optimal placement and sizing. Distortion of sinusoidal voltage and current waveforms caused by harmonics is one of the major power quality concerns in electric power industry. The efforts have been made in recent years to improve the management of harmonic distortions in power systems. Standards for harmonic control have been established. Instruments for harmonic measurements are widely available. The area of power system harmonic analysis has also experienced significant advancement. More harmonics are being injected into distribution systems. Adding shunt capacitors may lead to high distortion levels. The capacitor placement and sizing problem is a nonlinear integer optimization problem, with locations and ratings of shunt capacitors being discrete values. The goal is to minimize the overall cost of the total real power loss and that of shunt capacitors while satisfying operating and power quality constraints.

This paper proposes to solve the problem using particle swarm optimization (PSO). A discrete version of PSO is combined with a radial distribution power flow algorithm (RDPF) to form a hybrid PSO algorithm (HPSO). The former is employed as a global optimizer to find the global optimal solution, while the latter is used to calculate the objective function and to verify bus voltage limits. To include the presence of harmonics, the developed HPSO was integrated with a harmonic power flow algorithm (HPF). The proposed (HPSO-HPF)-based approach is tested on an IEEE 13-bus radial distribution system (13-Bus-RDS). The findings clearly demonstrate the necessity of including harmonics in optimal capacitor placement and sizing to avoid any possible problems associated with harmonics.

Index terms: *Harmonics, Particle Swarm, Shunt Capacitors.*

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1. INTRODUCTION

Shunt capacitors are commonly used in distribution systems to reduce power losses, improve voltage profile, and release system capacity. The achievement of such benefits among other benefits depends greatly on how optimally these shunt capacitors are installed. Studies have indicated that approximately 13% of generated power is consumed as loss at the distribution level. In addition, with the application of loads, the voltage profile tends to drop along distribution feeders below acceptable operating limits. Along with power losses and voltage drops, the increasing growth in electricity demand requires upgrading the infrastructure of distribution systems. Shunt capacitors can be of great help in enhancing the performance of distribution systems. Distribution systems are inherently unbalanced for several reasons. First, distribution systems supply single and three-phase loads through distribution transformers. Second, the phases of transmission lines are unequally loaded. Third, unlike those in transmission systems overhead lines in distribution systems are not transposed.

Due to the widespread use of harmonic-producing equipment in distribution systems, harmonics are propagated throughout those systems. Harmonics are undesirable and cause equipment overheating due to the excessive losses and potential malfunctioning of electric equipment. Inclusion of shunt capacitors without considering the presence of harmonic sources in the system may lead to an increase in harmonic distortion levels due to resonance between capacitors and the various inductive elements in the system

Baghzouz developed a local variations-based heuristic approach to find the global optimal ratings of shunt capacitors such that the cost of total real power loss and that of shunt capacitors were minimized. The optimal capacitor sizing problem was formulated as a nonlinear integer programming problem with inequality constraints. The constraints considered were the rms values of bus voltages and total harmonic distortions. The only harmonic source assumed was the utility substation. A heuristic algorithm based on local variations was proposed to overcome the prohibitive computational time associated with considering every single potential capacitor size at a given iteration. Yan accounted for the presence of harmonic-producing loads in distribution systems. A hybrid differential evolution algorithm was developed to optimally locate and rate shunt capacitors in distorted distribution systems.

A sensitivity test was done prior to the optimization process to determine the candidate buses for reactive power compensation. The objective was to minimize the cost of real power losses and that of shunt capacitors while satisfying some practical constraints. The results indicated that neglecting the presence of harmonic sources could cause a severe harmonic distortion problem. Carpinelli et al. solved the capacitor placement and sizing problem in a way that the overall cost was minimized. The cost function involved the cost of real power losses, shunt capacitors, and harmonic distortions. An approximate power flow method and a linear harmonic power flow method were used to calculate the cost function at the fundamental and various harmonic frequencies. Another optimization technique used to solve the optimal capacitor placement and sizing problem is genetic algorithms (GA). Abou-Ghazala proposed a GA to find the best combination of locations and ratings of shunt capacitors such that the total net savings were maximized.

Loss reduction was achieved through the proper installation of shunt capacitors while rms values of bus voltages and total harmonic distortions being kept within allowable limits. Nikham et al. also used a genetic algorithm to solve the optimal capacitor allocation and sizing problem taking the presence of harmonic sources into account. The objective function consisted of the cost of real power losses and that of shunt capacitors to be installed. The cost associated with the reactive power injection was fixed for all possible capacitor sizes. In other words, the cost of the reactive power injected was assumed to be constant independent of the capacitor size. Masoum et al. developed a hybrid tool based on maximum sensitivity selection (MSS) and local variations (LV) to solve the optimal capacitor placement and sizing problem. The former was used to enhance the convergence speed by narrowing down the search space, while the latter was employed to find the global optimal solution. Three harmonic distortion levels were considered for the system investigated. The system under investigation involved only one harmonic source and that was a six-plus converter. The results of the hybrid MSS-LV algorithm were compared with those of the MSS-based algorithm. In later work, Masoum et al. applied a fuzzy logic-based algorithm to solve the same problem. Both the objective function and the constraints were fuzzified. Alpha cuts were used to direct the search process and to ensure that the objective function improved each time. The candidate buses were determined according to the objective function, constraints and reactive power compensation sensitivities.

Two harmonic distortion levels were considered this time to compare the results obtained with those obtained by the MSS-based algorithm. A conclusion was drawn that the appropriate locations and ratings of shunt capacitors would not only improve voltage profiles but also would reduce harmonic distortion levels. Masousm et al. took advantage of the capability of genetic algorithms (GAs) to escape local optima. Improvements in voltage profiles and power quality were achieved through the proper installation of fixed shunt capacitors in distorted distribution systems. The applicability of GA-based approach was proven to yield to better results compared to the previous work done by the same authors. Another method based on particle swarm optimization (PSO) was offered to solve the capacitor placement and sizing problem considering harmonics.

The problem was mathematically modeled as a nonconvex optimization problem. The objective function was augmented by quadratic penalty functions to account for inequality constraints. That is, the objective function was penalized whenever the inequality constraints were violated. The proposed PSO algorithm did not account for unbalanced operating conditions. Khalil et al. proposed a binary PSO algorithm to find the best locations and ratings of fixed shunt capacitors in balanced distribution systems. The only harmonic source considered was the substation voltage. Their objective was to properly place and size shunt capacitors while keeping the cost of real power losses and that of shunt capacitors at a minimum. The objective function was subject to equality and inequality constraints.

2. PROBLEM FORMULATION

The optimal capacitor placement and sizing problem is formulated as a constrained nonlinear integer optimization problem with both locations and sizes of shunt capacitors being discrete. The objective function encompasses the total cost of the total real power loss and that of shunt capacitors. The objective function is restricted by equality and inequality constraints.

Objective Function: The goal is to minimize the cost of the total real power loss and that of the shunt capacitor installation.

The cost function is given by

$$F = K_p Ploss + \sum_{i=1}^{nc} K_{ci} Q_{ci} \quad (\$) \text{ -(1)}$$

K_{ci} annual cost per unit of the reactive power injected;

K_p annual cost per unit of real power loss ($/kW/year);

Q_{ci} reactive power injection at bus I (KVAR);

nc total number of shunt capacitors to be installed;

$Ploss$ total real power loss (KW);

The total real power loss is defined by

$$Ploss = \sum_{i=1}^{nb} Ploss_i^{(1)} + \sum_{i=1}^{nb} \sum_{h=h_0}^{h_{max}} Ploss_i^{(h)} (kW) \quad (2)$$

Where

nb number of branches;

h_0 smallest harmonic order of interest;

h_{max} highest harmonic order of intrest;

The fundamental component of the total real power loss is calculated using a three phase power flow algorithm (RDPF). The harmonic component of the total real power loss is computed by a harmonic power flow algorithm (HPF). Note that the harmonic component of the total real power los is small compared with the fundamental one. However, this portion of the total real power loss increases as harmonic-producing loads continue to increase in RDS. Consequently, the undesirable presence of harmonics will cause more equipment overheating, stress on equipment insulation, and equipment failure. Not to mention of course the interference with communication networks. It should be pointed out that the cost of the real power loss per unit is fixed.

However, the cost of the reactive power injection per unit varies from one capacitor size to another. Generally, the larger the capacitor size is, the cheaper it becomes.

Constraints: Along with the objective function, there is another significant part of the optimization model that needs to be defined and that is the constraints. In real applications, there are always limits on the choices of control variables. The constraints considered in this research are of two types: equality and inequality.

A. Equality Constraints

The equality constraints are those associated with the nonlinear power flow equations. It is noted in many published papers that the power flow equations are the real and reactive power mismatch equations. The reason for this is that modified versions of conventional power flow programs such as Newton- Raphson method and Gauss Siedel method are widely used. In this work, the power flow representation is based on bus current injections and thus the equality constraints are the bus current mismatch equations. The equality constraints are expressed in a vector form as follows:

$$H(x,u) = 0 \quad (3)$$

x Vector of state (dependent) variables;

u Vector of control (independent) variables;

B. Inequality Constraints

The inequality constraints are those associated with the bus voltages, total harmonic distortion levels, and shunt capacitors to be installed.

1). Bus Voltage Limits*:* The bus voltage magnitudes are to be kept within acceptable operating limits throughout the optimization process

$$V_{min} \le |V_i| \le V_{max} \quad (4)$$

V_{min} lower bound of bus voltage limits;

V_{max} upper bound of bus voltage limits;

$|V_i|$ rms value of the i th bus voltage and defined by

$$|V_i| = \sqrt{|V_i^{(1)}|^2 + \sum_{h=h_0}^{h_{max}} |V_i^{(h)}|^2}, i = 1,2,3,\ldots\ldots..n \quad (5)$$

Where n number of buses;

2) Total Harmonic Distortion Limits: The total harmonic distortion at each bus is to be kept less or equal to the maximum allowable harmonic distortion level as shown

$$THD_i(\%) = THD_{max} \quad (6)$$

Where

$THD_{\max}$ maximum allowable harmonic distortion level at each bus.

3) Number and Sizes of Shunt Capacitors*:* There are constraints associated with the shunt capacitors themselves. Capacitors that are commercially available come in discrete sizes. That is, the shunt capacitors to be dealt with are multiple integers of the smallest capacitor size available

$$Q_{ci} \leq LQ_0, L = 1,2,3,.......nc. \quad (7)$$

Where

Q_0 smallest capacitor size available

$$\sum_{i=1}^{nc} Q_{ci} \leq Q_T \quad (8)$$

Q_T total reactive power demand

3. PARTICLE SWARM OPTIMIZATION

PSO is a metaheuristic optimization technique developed in 1995 byKennedy and Eberhart. The fundamental idea behind the PSO algorithm is that a population called a swarm is randomly generated. The swarm consists of individuals called particles. Each particle in the swarm represents a potential solution of the optimization problem. Each particle moves through a D-dimensional search space at a random velocity. Each particle updates its velocity and position according to the following equations:

4. SOLUTION METHOD

As one of this research objectives, a hybrid particle swam optimization algorithm (HPSO) was developed to find the best combination of the locations and sizes of single phase shunt capacitors in unbalanced radial distribution systems (unbalanced- RDS). The HPSO algorithm combines a discrete version of PSO with a three phase power flow algorithm (RDPF).

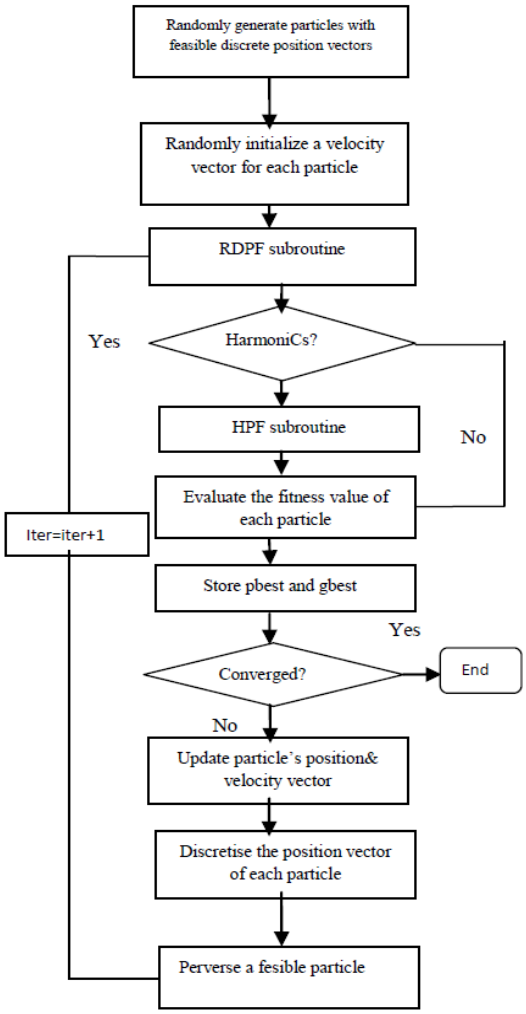

Fig 1: flow chart of the HPSO-HP based algorithm

The former is employed as a global optimizer to optimally locate and rate shunt capacitors, while the latter is utilized to minimize the bus current mismatch equations (i.e., the power flowequations). The developed HPSO algorithm starts with generating a swarm of particles randomly in the feasible region of the search space. The feasible swarm is passed to the RDPF subroutine as initial guess to minimize bus current injection mismatch equations. Each particle recalls its best position associated with the best fitness value (i.e., the total cost). Each particle records the best position achieved by the entire swarm.

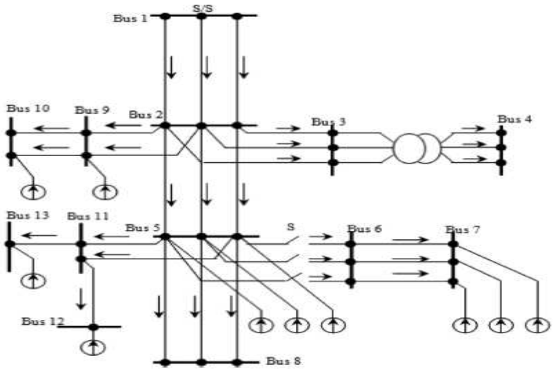

Fig 2: Unbalnced 13-Bus radial distribution system.

The update process of particles' positions results in continuous values of particles' positions. Thus, discretization of particles' position vectors is made. Once the updated particles' positions are discretized, the particles go through feasibility check to ensure that no particle flies outside the feasible region. When the presence of harmonics is considered, the total harmonic distortion limit at each bus is included as constraints in the optimization problem to ensure that the harmonic distortion levels at all busses are within the allowable limits.

A Harmonic power flow (HPF) subroutine is incorporated with the HPSO algorithm to calculate the harmonic bus voltages, harmonic real power losses, and total harmonic distortions. The flowchart of Fig. 1 illustrates the HPSOHPF-based algorithm that combines the HPF algorithm with the HPSO algorithm.

5. RESULTS AND DISCUSSION

The three algorithms in this work, namely, RDPF, HPF, and PSO, were implemented in MATLAB computing environment on a Dell Laptop with Intel Pentium M processor of 1.86 GHz and RAM of 1 GB. The developed algorithms were tested on an unbalanced-13-bus radial distribution system (unbalanced-13-bus-RDS) whose single line diagram shown in Fig. 2. The unbalanced-13-bus-RDS consists of single, double, and three phase lines and loads. The total real and reactive power demand are 3464.1 kW and 1568.9 kVAR respectively. The system loads are of two types, distributed loads and spot loads.

The only supply source in the system is the substation at bus 1. Bus 1 is treated as a slack bus with a constant voltage on each phase of its three phases. The other buses (2–13) are mod led as PQ constant buses The MVA base value is 10 and the line to line base voltage is the same as the feeder nominal voltage 4.16kV. The bus voltages are to be kept within 10% of the nominal voltage throughout the optimization process. Table1 lists some commercially available capacitor sizes with their corresponding costs .

The number of shunt capacitors to be installed is not to exceed10 banks of a discrete size of 150 k VAR each. That is to say, the total reactive power injection of these capacitors is not to exceed the total reactive power demand (1586.9 k VAR).

To include the presence of harmonics, the developed HPSO was integrated with a harmonic power flow algorithm (HPF). The proposed (HPSO-HPF) based approach is tested on the same test system (13-Bus-RDS). For the distorted voltage-13-Bus-RDS shown in Fig. 2, harmonic-producing loads, namely fluorescent lighting, adjustable speed drives (ASD), and nonspeci c sources such as PCs, TVs, and etc, are considered. The typical harmonic spectrum of these nonlinear loads All loads are treated as constant PQ spot loads for harmonic studies. Load composition in terms of harmonic sources The developed HPSO-HPF-based approach is applied to nd the optimal locations and sizes of shunt capacitors in an unbalanced-IEEE-13-bus radial distribution system (13-Bus-RDS)while taking harmonics into account. The total harmonic distortion levels are to be maintained within 5% of the voltage value as recommended by the IEEE standard 519-1992. In the presence of harmonics, three different cases are considered to investigate the impact of shunt capacitor installation on the voltage pro les, total harmonic distortions, total real power loss, and net savings.

Case 1 represents the system with harmonics consideration before capacitor installation.
Case 2 represents the system without harmonics consideration after capacitor installation.
Case 3 represents the system with harmonics consideration after capacitor installation.

The PSO parameters were tuned to enhance the performance of the proposed algorithm. For one shunt capacitor to be installed, 20 independent runs were carried out for each PSO parameter. The number of iterations was taken as 50 for the tuning process of each parameter. It was found that the PSO algorithm was less sensitive to its parameters for small problem dimension (the problem dimension was the shunt capacitor location and size). However, the larger the problem dimension is, the more sensitive the PSO algorithm becomes. A swarm size of 20 particles, acceleration constants of 2, and a particle's maximum velocity of 4 were selected. installing a shunt capacitor of 600 kVAR at phase c of bus 6 in case 2 will reduce the total real power losses from 192.7494 kW to 179.1373 kW andpro t the utility 2,099.694 U.S.$/year. The capacitor size required to bring the violated bus voltages back

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within the maximum and minimum bus voltage limits are the same for cases 2 and 3, while the PSO-based algorithm selected phase c of bus 5 to be the optimal location of the shunt capacitor in case 3. Before capacitor installation (case 1), the cost of real power losses is 32,326.694 U.S.$/year. In case 2 (after capacitor installation without harmonics consideration), the cost of real power losses is reduced to 30,227 U.S.$/year, while in case 3 (after capacitor installation with harmonics consideration), the cost of real power losses is reduced to 30,271 U.S.$/year. The net savings in case 2 (when harmonics are neglected) are slightly better than those obtained in case 3 (when harmonics are considered). However, the maximum total harmonic distortion level of case 2 is much higher than that of case 3.

The total harmonic distortion reduction in case 3 with respect to case1 is

THD reduction in case 3 with respect to case1 is

$$= \frac{THD_{\max}^{case1} - THD_{\max}^{case3}}{THD_{\max}^{case1}} \times 100$$

$$= \frac{4.4590 - 3.1986}{4.4590} \times 100 = 30.587\%$$

The total harmonic distortion reduction in case 3 with respect to case2 is

THD reduction in case 3 with respect to case2 is

$$= \frac{THD_{\max}^{case2} - THD_{\max}^{case3}}{THD_{\max}^{case2}} \times 100$$

$$= \frac{34.8937 - 3.1986}{34.8937} \times 100 = 90.833\%$$

The reduction in the maximum total harmonic distortion level in case 3 with respect to cases 1 and 2 justi es the inclusion of harmonics in the optimal capacitor placement and sizing problem.

MATLAB OUTPUTS

ONE CAPACITOR

CASE1

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000
2	0.96760	2.30760	0.98150	2.13190	0.95070	2.33290
3	0.96470	2.32020	0.97950	2.14100	0.94800	2.33840
4	0.94140	2.40640	0.96040	2.21550	0.92910	2.40030
5	0.95090	4.42140	0.98520	3.66740	0.90090	4.69210
6	0.95090	4.42140	0.98520	3.66740	0.90090	4.69210
7	0.94360	4.49400	0.98630	3.65410	0.89740	4.71890
8	0.95090	4.42140	0.98520	3.66740	0.90090	4.69210
9	0.97020	2.38470	0.97020	2.38470	0.95420	2.37870
10	0.96630	2.33510	0.96630	2.33510	0.95810	2.35510
11	0.94950	4.50420	0.94950	4.50420	0.89810	4.78350
12	0.94420	4.57180	0.94420	4.57180	0.94420	4.57180
13	0.89540	4.85900	0.89540	4.85900	0.89540	4.85900

In order to do more testing on the proposed HPSO-HPF based algorithm, the capacitor placement and sizing problem is extended to multiple capacitors. Three single phase capacitors are considered instead of one capacitor. The maximum reactive power injection of these capacitors is not to exceed the total reactive demand of the system. As in the case of one shunt capacitor, the PSO parameters have to be properly adjusted. Taking the total real power loss without harmonic components as an objective, 20 independent runs were conducted to find the best settings of the PSO parameters. 100 iterations were taken as the maximum number of iterations to adjust each of these parameters. A swarm size of 25 particles, acceleration factors of 2 each, and a maximum particle's velocity of 3 were selected. The developed PSO-based algorithm was able to find the optimal locations and ratings of three shunt capacitors such that the overall cost was minimized.

It can be observed that the reactive power injections required to minimize the total cost in case 2 (when harmonics are neglected) are equal to the reactive power injections in case 3 (when harmonics are considered). Moreover, the total real power loss in case 3 is higher than that in case 2. As a result, the net savings obtained in case 2 is better than that in case3. However, the optimal solution in case 3 yields a 61.27% reduction in total harmonic distortion with respect to case 1 and 90.927% reduction in total harmonic distortion with respect to Case 2. Consequently, the net savings obtained in case 2 can be justifiably sacrificed to avoid any possible damage to the electric equipment of both the utility and the customers.

Below tabels demonstrates that the proper installation of three shunt capacitors in the 13-Bus-RDS leads to voltage profile improvement. The harmonic distortion levels at some load buses in case 2, however, exceed the IEEE standard 519-1992 due to neglecting the presence of harmonic sources in the system). In contrast, taking harmonics into account (case 3) maintained the harmonic distortion levels at load buses within the allowable limits, the convergence characteristics of the developed HPSO-HPF-based approach for cases 2 and 3 in the optimal placement and sizing of three shunt capacitors problem with the total cost being the objective are depicted in Figs.

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.08392	0.05638	0.11293
2	0.04386	9.42153	23.87378
3	0.06773	0.11558	0.06460
4	0.03664	6.02572	0.07205
5	0.07816	0.06789	0.15547
6	0.06273	0.08066	0.06277
7	0.05139	0.10202	0.07016
8	0.08316	0.04915	0.12698
9	0.08872	-0.01904	0.07995
10	10.50438	0.10730	0.12687
11	115.95816	0.03903	0.06242
12	0.03251	24.55387	0.11255
13	0.02606	0.06362	0.04546
total	127.11742	40.66373	24.96598

g_best =

3.232669424845786e+004

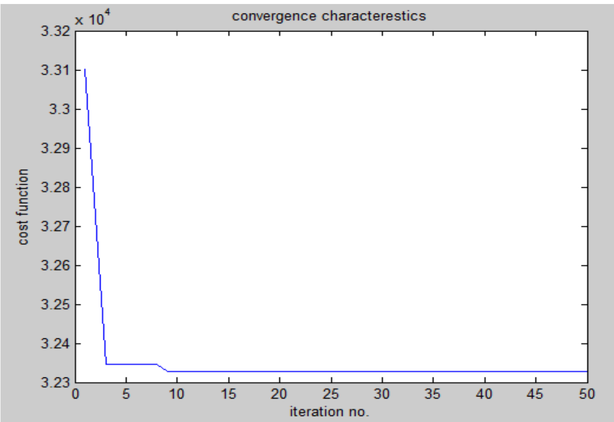

FIG: Convergence characteristics

CASE2

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000
2	0.96380	13.54540	0.96880	11.69540	0.99190	25.26730
3	0.96090	13.58900	0.96680	11.72100	0.98920	25.32450
4	0.93730	13.97610	0.94790	11.96720	0.97030	25.82140
5	0.94130	20.91880	0.95980	16.96220	0.98370	34.07440
6	0.94130	20.91880	0.95980	16.96220	0.98370	34.07440
7	0.93390	21.20730	0.96100	16.94630	0.98010	34.29730
8	0.94130	20.91880	0.95980	16.96220	0.98370	34.07440
9	0.95760	12.26560	0.95760	12.26560	0.99530	25.28760
10	0.95370	12.20380	0.95370	12.20380	0.99930	25.16050
11	0.93980	21.17080	0.93980	21.17080	0.98080	34.50390
12	0.93450	21.38860	0.93450	21.38860	0.93450	21.38860
13	0.97820	34.89370	0.97820	34.89370	0.97820	34.89370

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.07799	0.05240	0.10495
2	0.04076	8.75607	22.18753
3	0.06295	0.10741	0.06004
4	0.03405	5.60011	0.06696
5	0.07264	0.06310	0.14449
6	0.05830	0.07496	0.05834
7	0.04776	0.09481	0.06520
8	0.07729	0.04568	0.11801
9	0.08245	-0.01769	0.07430
10	9.76244	0.09972	0.11791
11	107.76781	0.03628	0.05801
12	0.03021	22.81958	0.10460
13	0.02422	0.05913	0.04225
total	118.13887	37.79157	23.20258

g_best =

3.022705474250000e+004

optimalplacement =

11

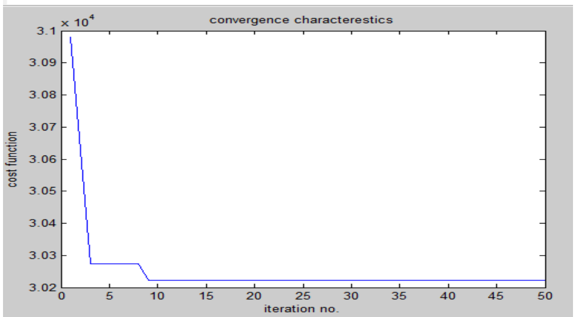

FIG: Convergence characteristics

CASE 3:

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000
2	0.96390	1.48760	0.96890	1.59400	0.99190	0.68510
3	0.96100	1.49700	0.96700	1.60060	0.98920	0.68640
4	0.93740	1.55990	0.94800	1.65960	0.97040	0.70250
5	0.94170	2.78610	0.96020	2.63850	0.98380	1.21070
6	0.94170	3.06950	0.96020	2.88480	0.98380	1.90740
7	0.93430	3.12140	0.96140	2.87170	0.98030	1.89780
8	0.94170	3.06950	0.96020	2.88480	0.98390	1.90740
9	0.95770	1.84680	0.95770	1.84680	0.99530	0.74350
10	0.95390	1.79340	0.95390	1.79340	0.99930	0.72490
11	0.94030	3.14200	0.98100	3.14200	0.98100	1.94910
12	0.93500	3.19860	0.93500	3.19860	0.93500	3.19860
13	0.97840	1.97590	0.97840	1.97590	0.97840	1.97590

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.07811	0.05248	0.10511
2	0.04082	8.76911	22.22057
3	0.06304	0.10757	0.06013
4	0.03411	5.60845	0.06706
5	0.07275	0.06319	0.14471
6	0.05839	0.07507	0.05842
7	0.04783	0.09495	0.06530
8	0.07740	0.04575	0.11818
9	0.08258	-0.01772	0.07441
10	9.77697	0.09987	0.11808
11	107.92830	0.03633	0.05810
12	0.03026	22.85356	0.10476
13	0.02425	0.05922	0.04231
total	118.31480	37.84785	23.23714

g_best =

3.027124585544600e+004

optimalplacement =

11

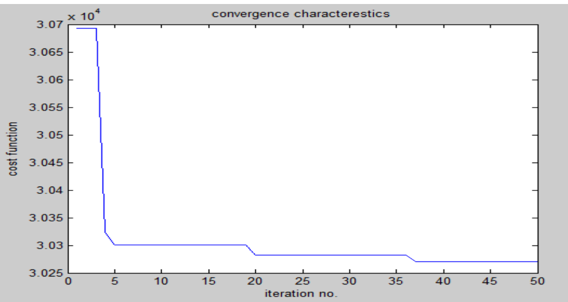

FIG: Convergence characteristics

THREE SHUNT CAPACITORS

CASE1

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.95070
2	0.96760	2.30760	0.98150	2.13190	1.00000	0.95070
3	0.96470	2.32020	0.97950	2.14100	1.00000	0.95070
4	0.94140	2.40640	0.96040	2.21550	1.00000	0.95070
5	0.95090	4.42140	0.98520	3.66740	1.00000	0.95070
6	0.95090	4.42140	0.98520	3.66740	1.00000	0.95070
7	0.94360	4.49400	0.98630	3.65410	1.00000	0.95070
8	0.95090	4.42140	0.98520	3.66740	1.00000	0.95070
9	0.97020	2.38470	0.97020	2.38470	1.00000	0.95070
10	0.96630	2.33510	0.96630	2.33510	1.00000	0.95070
11	0.94950	4.50420	0.94950	4.50420	1.00000	0.95070
12	0.94420	4.57180	0.94420	4.57180	1.00000	0.95070
13	0.89540	4.85900	0.89540	4.85900	1.00000	0.95070

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.08392	0.05638	0.11293
2	0.04386	9.42153	23.87378
3	0.06773	0.11558	0.06460
4	0.03664	6.02572	0.07205
5	0.07816	0.06789	0.15547
6	0.06273	0.08066	0.06277
7	0.05139	0.10202	0.07016
8	0.08316	0.04915	0.12698
9	0.08872	-0.01904	0.07995
10	10.50438	0.10730	0.12687
11	115.95816	0.03903	0.06242
12	0.03251	24.55387	0.11255
13	0.02606	0.06362	0.04546
total	127.11742	40.66373	24.96598

g_best =

3.232669424845786e+004

optimalplacement =

11

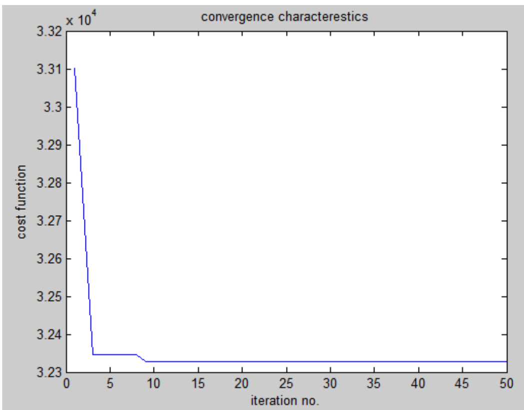

FIG: CONVERGE CHARACTERISTICS

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CASE2

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.98040
2	0.98690	1.61920	0.98570	8.63090	1.00000	0.98040
3	0.98390	1.62820	0.98370	8.65380	1.00000	0.98040
4	0.96060	1.66810	0.96470	8.85240	1.00000	0.98040
5	0.98870	6.00310	0.99340	19.03350	1.00000	0.98040
6	0.98870	2.21490	0.99340	9.42520	1.00000	0.98040
7	0.98140	2.24800	0.99450	9.42320	1.00000	0.98040
8	0.98870	2.21490	0.99340	9.42520	1.00000	0.98040
9	0.97440	9.15360	0.97440	9.15360	1.00000	0.98040
10	0.97050	9.08090	0.97050	9.08090	1.00000	0.98040
11	0.98730	2.23680	0.98730	2.23680	1.00000	0.98040
12	0.98200	2.26680	0.98200	2.26680	1.00000	0.98040
13	0.95550	11.70210	0.95550	11.70210	1.00000	0.98040

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.07183	0.04826	0.09666
2	0.03754	8.06431	20.43463
3	0.05798	0.09893	0.05529
4	0.03136	5.15768	0.06167
5	0.06690	0.05811	0.13308
6	0.05370	0.06904	0.05373
7	0.04399	0.08732	0.06005
8	0.07118	0.04207	0.10868
9	0.07594	-0.01629	0.06843
10	8.99117	0.09185	0.10859
11	99.25376	0.03341	0.05343
12	0.02782	21.01675	0.09634
13	0.02230	0.05446	0.03891
total	108.80546	34.80590	21.36949

```
g_best =

    2.806902442454550e+004


optimalplacement =

    11
```

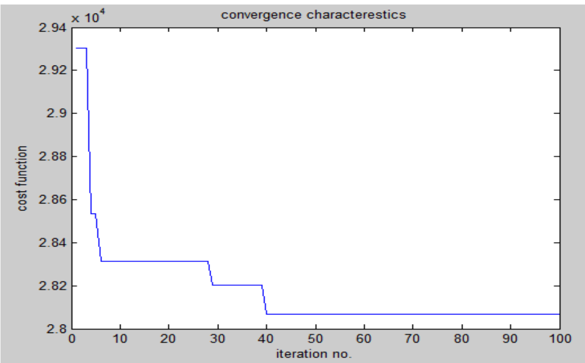

FIG:CONVERGE CHARACTERISTICS

CASE3

Voltage profile for IEEE 13 bus URDS

No	Va	THD a	Vb	THD b	Vc	THD c
1	1.00000	0.00000	1.00000	0.00000	1.00000	0.00000
2	0.98690	0.57550	0.98570	0.68200	0.98050	0.40810
3	0.98390	0.57840	0.98370	0.68320	0.97770	0.40850
4	0.96060	0.60460	0.96470	0.69860	0.95890	0.41640
5	0.98880	1.43220	0.99350	1.46310	0.96100	0.79200
6	0.98890	1.64000	0.99350	1.67290	0.96110	1.29420
7	0.98160	1.66650	0.99470	1.65830	0.95750	1.27010
8	0.98890	1.64000	0.99350	1.67290	0.96110	1.29420
9	0.97440	0.88550	0.97440	0.88550	0.98390	0.42890
10	0.97050	0.83630	0.97050	0.83630	0.98780	0.42060
11	0.98740	1.69720	0.98740	1.69720	0.95820	1.32240
12	0.98220	1.72700	0.98220	1.72700	0.98220	1.72700
13	0.95560	1.33980	0.95560	1.33980	0.95560	1.33980

Active losses for IEEE 13 bus URDS

No	A	B	C
1	0.07194	0.04833	0.09680
2	0.03760	8.07618	20.46470
3	0.05806	0.09907	0.05538
4	0.03141	5.16527	0.06176
5	0.06700	0.05820	0.13327
6	0.05378	0.06914	0.05381
7	0.04405	0.08745	0.06014
8	0.07128	0.04213	0.10884
9	0.07605	-0.01632	0.06853
10	9.00440	0.09198	0.10875
11	99.39980	0.03346	0.05351
12	0.02786	21.04767	0.09648
13	0.02234	0.05454	0.03897
total	108.96556	34.85711	21.40094

```
g_best =

    2.810721442245141e+004


optimalplacement =

    11
```

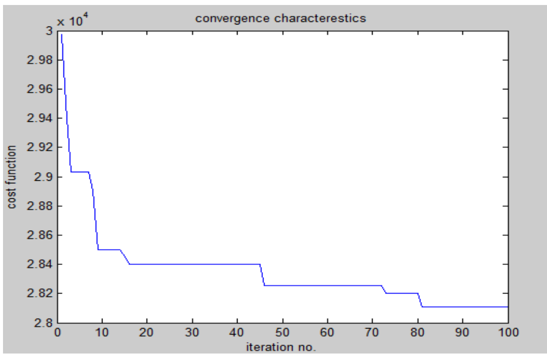

FIG: CONVERGE CHARACTERISTICS

CONCLUSION

In this paper, the developed HPSO-HPF-based algorithm was tested on an unbalanced 13-bus test system to find the optimal locations and sizes of shunt capacitors taking harmonics into account. The objective was to minimize the total cost of the system real power loss and the shunt capacitors to be installed. The objective function was subject to some operating constraints and power quality constraints. The outcome of this research is that neglecting the presence of harmonics in the system may lead to undesirable harmonic disto tion levels causing more damage to the electric equipment of both the electric utility and customers.

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