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A MULTI OBJECTIVE GENETIC ALGORITHM FOR CAPACITOR PLACEMENT IN UNBALANCED AND HARMONIC DISTORTED DISTRIBUTION SYSTEMS

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Abstract- This paper tries to solve a multi objective optimal capacitor placement problem, considering system unbalancing as well as the harmonic distorted nature of distribution systems using Non-dominated Sorting Genetic Algorithm (NSGA). By using NSGA, relationship between various components of objective functions, such as total installed capacitors, system unbalancing index and total harmonic distortion level can be obtained clearly. This would result in helpful information that can be utilized to make a reasonable decision on the best tradeoffs between capacitor placement cost, system unbalancing and harmonic distortion level of system. The proposed (NSGA)-based approach is tested on an IEEE 37-bus radial distribution system. The findings clearly demonstrate the necessity of including harmonics in optimal capacitor placement to avoid any possible problems associated with harmonics.

Keywords: Capacitor Placement, Harmonic Distortion, Genetic Algorithm, Multi Objective Optimization, Unbalanced, Distribution Systems.

I. INTRODUCTION

Shunt capacitors are greatly utilized in distribution systems to reduce power losses, adjust power factor, improve voltage profile and release system capacity. The realization of such benefits depends greatly on how optimally these capacitors are installed [1]. The capacitor placement problem (determining capacitor sizes and locations) is a nonlinear, mixed integer, non-differentiable and is a large scale combinatorial problem with many local minimum solutions. Also, the difficulty and complexity of the problem increases with the size of the distribution system. Optimal capacitor placement has been introduced under observation since the 60’s [2]. Many of papers refer to balanced and/or harmonic free distribution systems. Generally, distribution systems are obviously unbalanced for several reasons such as:

- Distribution systems supply single phase loads,
- Dissimilar to transmission systems, overhead lines in distribution systems are not transposed.

Due to the widespread use of harmonic-producing equipment such as power electronic converters in distribution systems, harmonics are generated throughout those systems. Generated harmonics are unpleasant and cause equipments overheating due to the excessive losses and may fail the proper operation of electric equipments [3]. Capacitor placement without paying attention to the presence of harmonic sources can increase harmonic distortion levels because of probable resonance between capacitors and the various inductive elements in the system [1]. Eajal [1] proposed a Particle Swarm Optimization (PSO) algorithm to find optimal locations and sizes of capacitors taking harmonics into account in unbalanced distribution systems without paying attention to relationship between harmonic distortion and unbalancing in systems. In reference [2], the capacitor placement problem was solved by using an extended Tabu Search (TS) approach. Authors didn’t take into account the unbalancing of distribution systems. A multi-objective optimization algorithm which includes cost investment, operating efficiency, system security and service quality were represented in [4].

The paper paid attention to neither unbalancing of system nor the harmonic distortion. Wang [5] considered the harmonic distorted and balanced distribution systems. Ruiz-Rodriguez [6] considered a balanced and undistorted distribution system, both of them also considered the probabilistic characteristics of system. Reference [7] proposed a multi objective optimization algorithm for capacitor placement based on non-dominated sorting genetic algorithm. The paper didn’t consider the system unbalancing. Reference [8] represented a simultaneous procedure for capacitor placement and reconfiguration in a balanced and undistorted distribution system. Mohammadian [9] discussed the selection of optimal conductor size and capacitor placement in balanced and harmonic free radial distribution network with increasing rate of loads. Chopade [10] covered the optimal capacitor placement in a balanced system using ETAP software, and it also considered harmonic distortion in distribution systems.

Murthy [11] was similar to efforts mentioned and compared conventional and evolutionary based algorithms. In addition, a simultaneous procedure for capacitor placement and reconfiguration in an undistorted distortion system was proposed [12]. Masoum [13] discussed optimal placement, replacement and sizing of capacitor banks in distorted distribution networks although it wasn't considered the unbalancing of distribution system.

Reference [14] represented a heuristic constructive algorithm for capacitor placement in a balanced and undistorted distribution system. In this way [15] proposed an Ant Colony based algorithm for reconfiguration and capacitor placement in balanced and undistorted distribution systems.

Reference [16] proposed a GA based method for capacitor allocation in a balanced system which could evaluate uncertainty of loads. Detail of genetic algorithm was proposed in [17]. In [18] elite based simplex GA hybrid approach combined with multi population GA to determine the location, size, and number of capacitors in unbalanced distribution systems is proposed, although the harmonic distorted systems weren't considered in this study.

Also some papers considered to the unbalancing of system and the harmonic distortion of distribution systems in capacitor placement problem, simultaneously. None of the papers mentioned have considered the unbalancing of system and harmonic distorted nature of the distribution systems, in a multi objective frame. It is very important, in the capacitor placement problem to know the exact relationship between system unbalancing and harmonic distortion parameters of systems. This would result in illuminating information that can be utilized to make a reasonable decision on the best tradeoffs between capacitor placement cost, system unbalancing improvement and harmonic distortion reduction of systems.

Recently, a Matlab based multi objective genetic algorithm program (NSGA_II) is taken into account by many researchers [19]. Superior ability of this algorithm in finding global optimum solutions has been proved to be useful in many papers [20-22]. The main objective of this paper is to solve capacitor placement problem considering the system unbalancing as well as the harmonic distorted nature of distribution systems.

II. RADIAL DISTRIBUTION SYSTEMS POWER FLOW

In distribution systems, with decreasing ratio of lines reactance to resistance, convergence speed of conventional methods such as Quasi-Seydel decreases severely. The iterative backward-forward load flow algorithm developed for solving radial distribution systems [23]. This method consists of three steps at each iteration as follows:

- Nodal currents calculation,
- Section current calculation,
- Voltage of nodes updating.

Assuming the initial voltages of all buses as 1 p.u., node currents can be computed with respect to nodal apparent power. Starting from the nodes at the end of the feeder and moving towards the root node (distribution feeder is connected to sub transmission network), backward sweep is used to sum up line section current, using KCL rule. For voltage update, forward sweep is applied from root node moving towards the end of feeder using KVL rule.

III. HARMONIC INCLUDED POWER FLOW

In this paper, three phase representations of system components and a harmonic power flow (HPF) algorithm were used. In this method, nonlinear loads (harmonic producing loads), which inject harmonics into distribution systems, are modeled as harmonic current sources [24, 25].

IV. MULTI OBJECTIVE OPTIMIZATION

Generally, multi objective optimization problems can be represented as Equation (1).

$$\text{minimize } f(u) = \{ f_1(u), f_2(u), ..., f_k(u)\} \tag{1}$$

The constraints are as follow:

$$g(u) = \{g_1(u), g_2(u), ..., g_k(u)\} \le 0 \tag{2}$$

$$h(u) = \{h_1(u), h_2(u), ..., h_k(u)\} = 0 \tag{3}$$

where, u is the vector of control variables. The solution of (1) is usually not unique. The concept of Pareto optimality may be explained in terms of a dominance relation [17]. For a multi objective problem having k objective functions, a solution u_1 is said to dominate the other solution u_2 if u_1 is better than u_2 for at least one objective f_i and is not worse for any other f_j, where $j = 1, 2, ..., k$ and $j \ne i$ as Equation (4).

$$\left.\begin{array}{l} f_i(u_1) < f_i(u_2) \\ \text{and} \\ f_j(u_1) \le f_j(u_2) \end{array}\right\} \Rightarrow u_1 \succ u_2 \tag{4}$$

where, the symbol $\succ$ denotes domination operator. The above concept is used to find a set of non-dominated solutions in search space in such a manner that none of them is dominated by any other solution. These solutions are equally optimal when all objectives are obtained. The solutions that are non-dominated regarding the entire search space are called Pareto optimal solutions. The hyper surface connecting those defines the Pareto optimal front [26]. Moeini [27] proposed the detail of multi objective optimization and Pareto optimal.

V. PROBLEM FORMULATION

Loss reduction, voltage profile improvement, unbalancing improvement and *THD* level decreasing by minimum cost of capacitor placement, is formulated as a mixed integer and non-linear optimization problem as follows:

A. Objective Function

The objective function has various components as:

$$\sum_{i=1}^{n_{bus}}\sum_{j\in i}\sum_{p=abc} r_{ij}^{p}\cdot\left|\frac{V_i^{p,1}-V_j^{p,1}}{Z_{ij}^{p,1}}\right|^2 + \sum_{h=5}^{H}\sum_{i=1}^{n_{bus}}\sum_{j\in i}\sum_{p=abc} r_{ij}^{p}\cdot\left|\frac{V_i^{p,h}-V_j^{p,h}}{Z_{ij}^{p,h}}\right|^2 \tag{5}$$

$$\sum_{i=1}^{n_{bus}}\sum_{p=abc}\left|V_i^{p}-1\right| \tag{6}$$

$$\sum_{i=1}^{n_{bus}}\left|V_i^{a}-V_i^{b}\right|+\left|V_i^{a}-V_i^{c}\right|+\left|V_i^{b}-V_i^{c}\right| \tag{7}$$

$$THD=\sum_{i=1}^{n_{bus}}\sum_{p=abc}\frac{1}{\left|V_i^{p,1}\right|}\sqrt{\sum_{h=5}^{H}\left|V_i^{p,h}\right|^2} \tag{8}$$

$$\sum_{p=abc}\sum_{i\in L_p} Q_i \tag{9}$$

$$V_i^{p}=\sqrt{\left(V_i^{p,1}\right)^2+\sum_{h=5}^{H}\left|V_i^{p,h}\right|^2} \tag{10}$$

where,
P indicates the system phase,
h indicates the harmonic level,
n_{bus} is the number of busses,
$j \in i$ means set of busses connected to ith bus,
$V_i^{p,h}$ is the ith bus voltage at pth phase and at hth harmonic level,
L_p is the set of buses in pth phase, that their load isn't zero.
$Z_{ij}^{p,h}$ is the impedance of line between buses i and j at pth phase and at hth harmonic level,
r_{ij}^{p} is the resistance of line between buses i and j at pth phase.

The Equation (5) represents total active power system losses. The Equation (6) represents criteria for system voltage profile deviation from nominal value. The Equation (7) indicates criteria for system voltages unbalancing, the Equation (8) represented the total harmonic distortion in all buses at three phases and the Equation (9) represents the total capacitor installed in various phases of all system. This equation also is related to total cost of capacitor placement.

B. Constraints

The equality constraints include active and reactive power balance at fundamental frequency as following:

$$P_{Gi}^{p,1}-P_{Di}^{p,1}-\sum_{j\in i}P_{ij}^{p,1}=0 \tag{11}$$

$$Q_{Gi}^{p,1}+Q_i^{p,1}-Q_{Di}^{p,1}-\sum_{j\in i}Q_{ij}^{p,1}=0 \tag{12}$$

$P_{Gi}^{p,1}$ and $Q_{Gi}^{p,1}$ are the generated active and reactive power at ith node at pth phase (if there is any generation at ith node),
$P_{Di}^{p,1}$ and $Q_{Di}^{p,1}$ are the consumed active and reactive power in ith node at pth phase,
$P_{ij}^{p,1}$ and $Q_{ij}^{p,1}$ are the transferred active and reactive power from ith bus to jth bus at pth phase,
$Q_i^{p,1}$ is the injected reactive power to ith bus at pth phase due to capacitor placement.

$$\left[I^{(p=a,b,c),h}\right]=\left[Y_{bus}^{(p=a,b,c),h}\right].\left[V^{(p=a,b,c),h}\right] \tag{13}$$

where,
$\left[I^{(p=a,b,c),h}\right]$ is the vector of three phase injected currents to nodes due to presence of non-linear loads at hth harmonic frequency,
$\left[Y_{bus}^{(p=a,b,c),h}\right]$ is the admittance matrix of system considering coupling of three phases at hth harmonic frequency,
$\left[V^{(p=a,b,c),h}\right]$ is the three phase voltages of nodes at hth harmonic frequency.

The inequality constraints are as:

$$V_{\min}\le V_i^{p}\le V_{\max} \tag{14}$$

$$THD\le THD_{\max} \tag{15}$$

where, $THD_{\max}$ is the maximum permissible harmonic distortion level.
Also the constraint on the control variable is given as:

$$Q_i^{p}\le Q_{\max} \tag{16}$$

$$\sum_{p=abc}\sum_{i\in L_p}Q_i^{p}\le\sum_{i=1}^{n_{bus}}\sum_{p=abc}Q_{Di}^{p} \tag{17}$$

Inequality (17) represents that the sum of total installed capacitors must not be greater than the total reactive power demand of system.

VI. SOLUTION METHOD

Multi-objective optimization is a suitable tool for managing various incommensurable objectives with agreeing/disagreeing relations or also not having any mathematical relation with each other [21]. Methods for solving multi-objective optimization problems can be separated into two essential types: mathematical based and evolutionary based. First type represents some difficulties such as follows:

- Convergence to an optimal solution depends greatly on initially chosen solution,
- Most algorithms tend to become trapped at sub-optimal solution,
- These algorithms can't be applied for some non-convex multi-objective problems [28].

Evolutionary algorithms have many advantages in comparison to conventional ones. These algorithms use a population of solutions and can get away from getting trapped in a local optimal solution. NSGA_II is an evolutionary based multi objective optimization tool which has great advantages in comparison to other evolutionary algorithms. The steps of NSGA_II developed to find a set of the best tradeoffs between the objectives in the proposed capacitor placement problem and discussed in more detail as follows:

Each individual represents a set of control variables and indicates a feasible solution in search space. First, the population is initialized, randomly. Then, the population in previous step is sorted based on non-domination concept into each front. The first front is absolutely non-dominant set in the current population and the second front is dominated by the first front only and so on. Each individual in each front are assigned rank values based on front they belong to. Individuals in first front are assigned a rank value of 1 and individuals in second are assigned rank value as 2 and so on. In addition to rank value, another parameter which is called crowding distance is calculated for each individual. The crowding distance is a measure of how near an individual is to its neighbors.

Great average crowding distance is equal to better diversity in the population. Then, parents are selected from the population by using binary tournament selection based on the rank and crowding distance. An individual is selected which its rank is lesser than the other or its crowding distance is greater than the other. Then, the selected population generates off-springs from crossover and mutation operators. The population with the current population and current off-springs is sorted based on non-domination, again. Finally, only the best *N* individuals are selected, where *N* is the population size. The selection is based on the rank and crowding distance. These procedures are repeated till the maximum iteration number is reached. Detailed description of NSGA_II is represented in [29]. Figure 1 summarizes the basic steps of the NSGA_II applied to proposed problem.

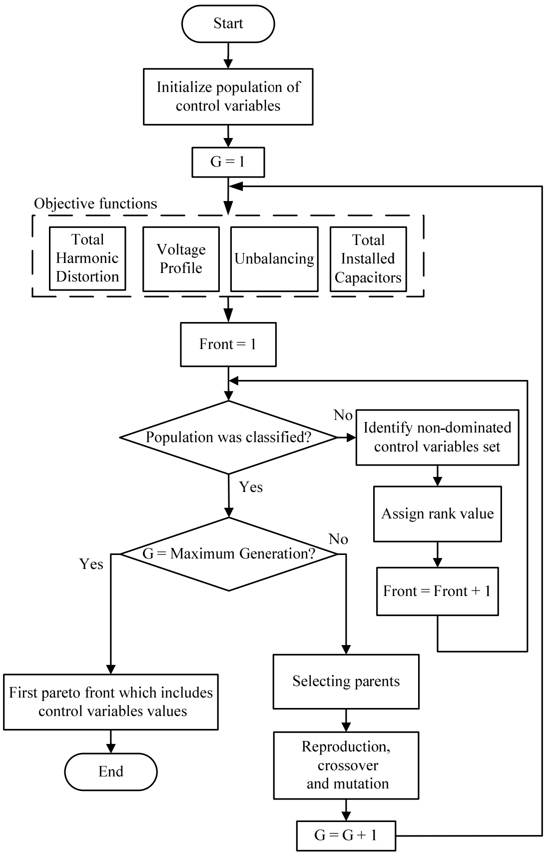

Figure 1. Basic steps of the NSGA_II applied to proposed capacitor placement problem

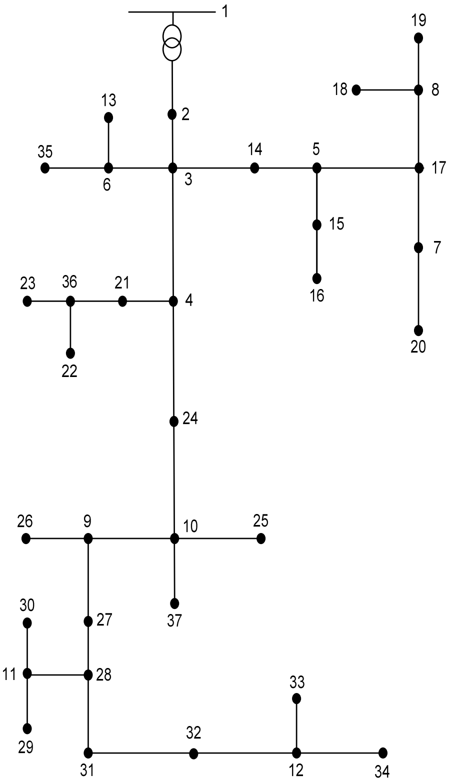

Figure 2. One line diagram of IEEE 37 nodes test system

VII. CASE STUDY

The test system studied in this study is IEEE 37 nodes test feeder. One line diagram of this system has been shown in Figure 2. This system is an actual feeder located in California. Some characteristics of the feeder are as follows:

- Three wire delta operating at a nominal voltage of 4.8kV,
- All line segments are underground,
- All loads are “spot” loads and consist of constant PQ, constant current and constant impedance,
- The loads are very unbalanced [30].

VIII. RESULTS

In this section the proposed algorithm is applied to test system. The relation between the various components of objective function is obtained and discussed.

The parameters of the NSGA_II algorithm applied to the test system are as follows:

- The population is initialized based on the control variable ranges as usual,
- The population is sorted based on non domination concept,
- Crowding distance is assigned front wise,
- Selection of parents is based on binary tournament with crowding comparison operator,
- Simulated binary crossover is used for crossover operator,
- Polynomial mutation is used for mutation operator,

- Population size are equal to 25,
- Number of generations is equal to 1000.

It is assumed that non linear loads are located at nodes 2, 15, 22 with the weight factor of 0.5 as well as the node 35 with the weight factor of 0.25. Weight factor of non-linear loads at a particular node means the ratio of non-linear loads to total load of that node. Also available capacitor sizes are selected as Table 1.

Table 1. Available capacitor in KVAR

25	50	75	100	125	150	175
200	225	250	275	300	325	350

Figure 3 shows the tradeoff between total installed capacitors and voltage profile deviation. As seen in Figure 3, total installed capacitors increasing, lead to improvement of voltage profile deviation**.**

Figure 4 shows the tradeoff between total installed capacitors and voltage unbalancing index. As it is clear from Figure 4, in the point in which total installed capacitors equal to 1500 KVAR, the unbalancing of system is approximately minimal. As seen in Figure 4, increasing or decreasing of the capacitor installation can lead to increase of voltage unbalancing. Figure 5 shows the tradeoff between total installed capacitors and voltage *THD*. It is clear that decreasing of the total installed capacitors lesser than around 1500 KVAR can increase voltage *THD*, severely. Figure 6 shows the tradeoff between total installed capacitors and total active power loss. As seen in Figure 6, total installed capacitors increasing, lead to improvement of active power loss.

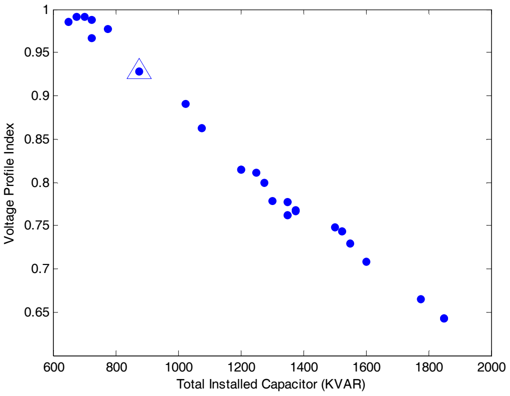

Figure 3. Tradeoff between total installed capacitors and voltage profile deviation

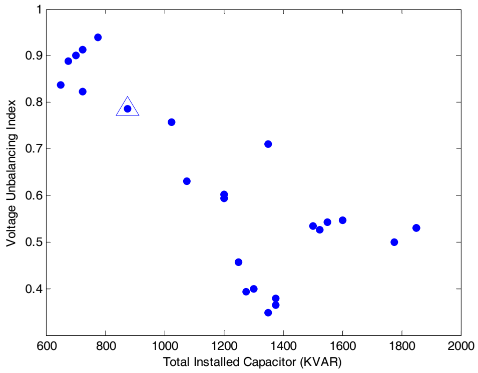

Figure 4. Tradeoff between total installed capacitors and voltage unbalancing index

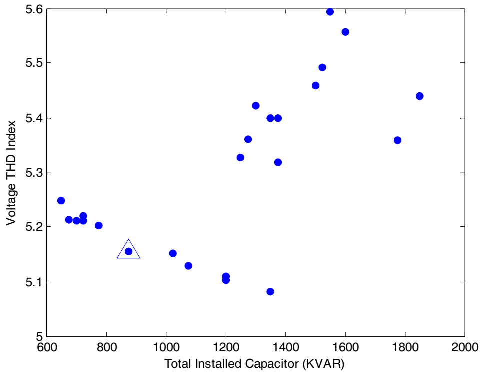

Figure 5. Trade off between total installed capacitors and *THD*

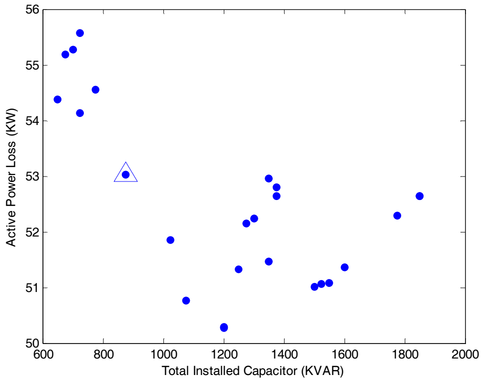

Figure 6. Trade off between total installed capacitors and total active power loss

According to Figures 3 to 6, limiting total installed capacitor to 75 percent of total reactive power demand of system i.e. 900 KVAR in which voltage profile index is equal to 0.9276, voltage unbalancing index is equal to 0.7851, voltage *THD* index is equal to 5.1556 and active power loss is equal to 53.032 KW, the algorithm proposes the locations and values of the capacitors as Table 2. This proposed solution is indicated with symbol Δ in Figures 3 to 6. Table 3 represents the defined indices before capacitor placement in test system and Table 4 represents the defined indices for test system after capacitor placement.

It can be seen from the Tables 3 and 4, the active power loss is decreased from 62.46 KW to 53.032 KW, the voltage profile index is decreased from 1.1737 to 0.9276, voltage unbalancing index is reached to 0.7851 from 0.8242 and voltage *THD* index is decreased to 5.1556 from 5.6729.

Voltage magnitude profile of all buses in three phases, before and after capacitor placement, is shown in Figure 7 and Figure 8 respectively. Also voltage *THD* of all nodes in three phases, after and before capacitor placement, is shown in Figures 9 and 10, respectively.

IX. CONCLUSIONS

This paper considered the capacitor placement problem using a multi objective genetic algorithm known as NSGA_II. The harmonic distorted nature of distribution system as well as system unbalancing was considered in solving this problem. The relationships between various components of objective function were obtained. This could be very effective to make the best decisions on trade-off between total capacitor installation, voltage profile improvement and system unbalancing improvement in the presence of non linear loads. Tradeoff curves could help the operator of system to choose the best solution with a proper compromise between various objectives. Considering the importance of different objectives, various solutions could be selected also, we selected a solution in a manner that all mentioned objectives were improved. Defined indices were compared to each other and the efficiency of proposed algorithm was shown.

Table 2. Proposed solutions to capacitor placement

Capacitor Location	Value of Capacitor (KVAR)		
Node	phase		
	a	b	c
2	75	75	50
13	-	-	25
14	-	-	25
15	0	0	-
16	25	-	-
17	-	-	0
18	-	150	0
19	-	25	-
20	-	25	-
21	-	-	25
22	25	0	50
23	25	-	-
24	-	-	25
25	-	75	-
26	-	-	0
27	0	-	-
28	-	-	0
29	-	-	0
30	-	25	-
31	50	-	-
32	25	-	-
33	-	-	50
34	-	-	0
35	0	25	-
36	0	-	-

Table 3. Defined indices before Capacitor placement

Index	Value
Active Power Loss	62.4659
Voltage Unbalancing Index	0.8242
Voltage Profile Index	1.1737
Voltage *THD* Index	5.6729

Table 4. Defined indices for test system after capacitor placement

Index	Value
Active Power Loss	53.032
Voltage Unbalancing Index	0.7851
Voltage Profile Index	0.9276
Voltage *THD* Index	5.1556

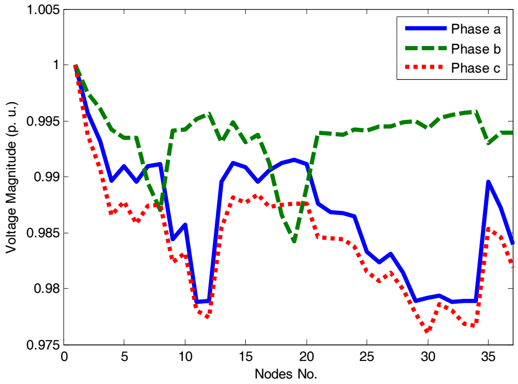

Figure 7. Voltage magnitude profile of test system in three phases before capacitor installation

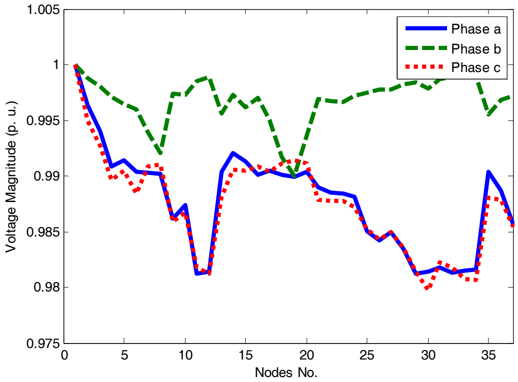

Figure 8. Voltage magnitude profile of all buses in three phases, after capacitor placement

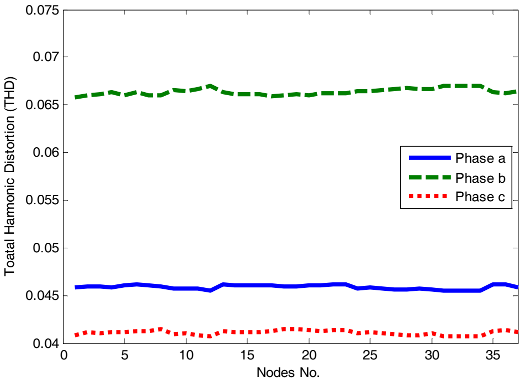

Figure 9. Voltage *THD* of test system in three phases before capacitor installation

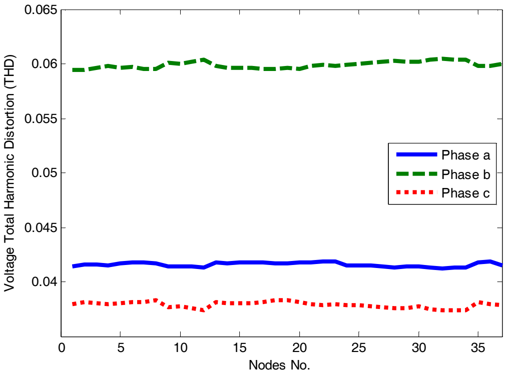

Figure 10. Voltage *THD* of all nodes in three phases, after capacitor placement

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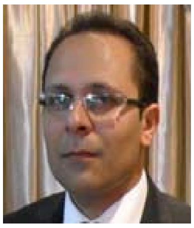

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