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Harmonic Analysis of Radial Distribution Systems Embedded Shunt Capacitors

Abdallah Elsherif,Tamer Fetouh and Hasan Shaaban
Department of Electrical Engineering, Faculty of Engineering, Menoufia University, Shebin El-Kom, Egypt
am.elsherif@sh-eng.menofia.edu.eg, tamer.attia@sh-eng.menofia.edu.eg, h.shaaban@sh-eng.menofia.edu.eg

***Abstract* -** Harmonic analysis is an important application for analysis and design of distribution systems. It is used to quantify the distortion in voltage and current waveforms at various buses for a distribution system. However such analysis has become more and more important since the presence of harmonic-producing equipment is increasing. As harmonics propagate through a system, they result in increased power losses and possible equipment loss-of-life. Further equipments might be damaged by overloads resulting from resonant amplifications. There are a large number of harmonic analysis methods that are in widespread use. The most popular of these are frequency scans, harmonic penetration and harmonic power flow. Current source (or current injection) methods are the most popular forms of such harmonic analyses. These methods make use of the admittance matrix inverse which computationally demand and may be a singular in some cases of radial distributors. Therefore, in this paper, a new fast harmonic load flow method is introduced. The introduced method is designed to save computational time required for the admittance matrix formation used in current injection methods. Also, the introduced method can overcome the singularity problems that appear in the conventional methods. Applying the introduced harmonic load flow method to harmonic polluted distribution systems embedded shunt capacitors which commonly used for losses minimization and voltage enhancement, it is found that the shunt capacitor can maximize or minimize system total harmonic distortion (THD) according to its size and connection point. Therefore, in this paper, a new proposed multi-objective particle swarm optimization "MOPSO" for optimal capacitors placement on harmonic polluted distribution systems has been introduced. The obtained results verify the effectiveness of the introduced MOPSO algorithm for voltage THD minimization, power losses minimization and voltage enhancement of radial distribution systems.

***Keywords* -** Total harmonic distortion, Power losses, Radial distribution systems, Particle swarm optimization, Harmonic load flow and Frequency scan.

I. INTRODUCTION

Harmonic analysis is an important application for distribution systems analysis and design. It is used to quantify the distortion in voltage and current waveforms, which are caused by nonlinear loads, electronically switched loads and converters etc., at various buses for a distribution system, and to determine whether dangerous resonant problem exists and how they might be mitigated. However such analysis has become more and more important since the presence of harmonic-producing equipment is increasing. As harmonics propagate through a system, they result in increased power losses and possible equipment loss-of-life. Further equipments might be damaged by overloads resulting from resonant amplifications [1]-[3].

Distortion in AC voltage and current waveforms can be studied by expressing the harmonic sources of the waveforms as a Fourier series with the fundamental frequency equal to the power frequency. Then, utilizing the harmonic analysis it can investigate the generation and propagation of these components throughout a given distribution systems. Research in this area has led to the availability of fairly general techniques and softwares for the formulations and solutions of harmonic propagation problem. The techniques vary in terms of data requirements, modeling complexity, problem formulation and solution algorithm. In [4]-[6] the frequency-domain was presented to calculate the frequency response of a system. In [7], it was presented a time-domain based transient-state analysis that utilize the EMPT program for harmonic analysis. However, one of the main disadvantages of the time-domain-based method is that the lack of the load flow constraints (such as, constant power specification at load buses) at the fundamental frequency. Recently, the idea of Wavelet Transform is integrated into the harmonic analysis [8], [9], for which system components and power devices need to be derived first and then the harmonic analysis is applied, and hence more computational time is needed.

The conventional harmonic load flow methods use load flow programs, and employing the frequency-based component model, for updating admittance matrix and then rerun the load flow program for each harmonic order. However, the decomposition of the admittance matrix is a time-consuming procedure and it makes the conventional methods difficult for real-time analysis. Furthermore, determination of the buses voltage values needs admittance matrix inverse computation, which in some cases of radial distribution systems is singular. In this paper, fast harmonic load flow method for radial distribution systems, which can overcome the singularity problems without excessive computation time need, is presented. Applying the introduced harmonic load flow method to harmonic polluted distribution systems embedded shunt capacitors which commonly used for losses minimization and voltage enhancement, it is found that the shunt capacitor can maximize or minimize system total harmonic distortion (THD) according to its size and connection point. Therefore, in this paper, a new proposed multi-objective particle swarm optimization "MOPSO" for optimal capacitor placement on harmonic polluted distribution systems, based on a modified Non-Dominated Sorting algorithm, has been introduced. The obtained results verify the effectiveness of the introduced MOPSO algorithm for voltage THD minimization, power losses minimization and voltage enhancement of radial distribution systems.

II. HARMONIC LOAD FLOW OF RADIAL DISTRIBUTION SYSTEMS

The Harmonic Load Flow (HLF) is one of the most important tools for distribution system analysis and design. It can be used to quantify the harmonic distortion in voltage and current waveforms at various buses for a given power system, and also to determine whether the dangerous resonant problems may exist and how they might be mitigated. Such analysis has become more important since the presence of harmonic-producing equipment is increasing. In this section a new introduced harmonic load flow technique for radial distribution systems is introduced. The introduced technique can overcome the difficulties faced by the conventional harmonic load flow methods, such as the needed computation time, the admittance matrix reformation for each considered harmonic order, and the admittance matrix singularity problem.

The introduced technique employs the equivalent current injection transformation and the BIBC and BCBV matrices, which can be constructed as mentioned in Ref. [10]. The computation steps of the introduced HLF technique can be summarized as follows.

1. Fundamental load flow

The fundamental load flow is carried out by the iterative solution of the following three equations, from which the buses voltage and load current can be obtained [10].

$$I_i^m = \left(\frac{P_i + jQ_i}{(V_i)^m}\right)^*$$
$$\left[\Delta V^{m+1}\right] = [BCBV][BIBC].\left[I^m\right]$$
$$\left[V^{m+1}\right] = \left[V_s^0\right] - \left[\Delta V^{m+1}\right] \qquad (1)$$

where P_i and Q_i are the specified active and reactive powers at the i^{th} bus, and V_i is the voltage at that bus.

2. Branches and harmonic sources injected currents relationship

In order to clear the branches and the harmonic sources currents relationship, let us consider the simple distribution system shown in Fig. 1, in which the harmonic injected currents are expressed as I2h, I4h, and I5h, while the distributor branch currents are expressed as Ib1h, Ib2h, ... and Ib6h. Firstly, the harmonic sources injected current, for each harmonic order, are calculated as a percentage of the obtained load fundamental current. Then the branch currents, for each harmonic order, can be obtained as,

$$\left[Ib^h\right]_{n\ell \times 1} = [BIBC]_{n\ell \times (nb-1)} . \left[I^h\right]_{(nb-1) \times 1} \qquad (2)$$

For the assumed simple distribution system shown in Fig. 1, the branches current can be simplified and obtained as follow,

$$\begin{bmatrix} Ib_1^h \\ Ib_2^h \\ Ib_3^h \\ Ib_4^h \\ Ib_5^h \\ Ib_6^h \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -I_2^h \\ -I_4^h \\ -I_5^h \end{bmatrix} \quad (3)$$

3. Distributor buses voltage computation

Referring to Fig. 1, the buses voltage for hth harmonic order can be computed as follow,

$$\left[V^h\right]=\left[V^h_{S/S}\right]-\left[BCBV^h\right].\left[Ib^h\right] \quad (4)$$

where $[V^h]$ is the vector of buses voltage except the substation, $V^h_{S/S}$ is the substation harmonic order voltage vector, and $BCBV^h$ is the Branch-Current to Bus-Voltage matrix and it is given for the considered system in the form,

$$\left[BCBV^h\right]=\begin{bmatrix} Z_{12}^h & 0 & 0 & 0 & 0 & 0 \\ Z_{12}^h & Z_{23}^h & 0 & 0 & 0 & 0 \\ Z_{12}^h & Z_{23}^h & Z_{34}^h & 0 & 0 & 0 \\ Z_{12}^h & 0 & 0 & Z_{25}^h & 0 & 0 \\ Z_{12}^h & 0 & 0 & Z_{25}^h & Z_{56}^h & 0 \\ Z_{12}^h & Z_{23}^h & 0 & 0 & 0 & Z_{37}^h \end{bmatrix} \quad (5)$$

It is to be noted that when a shunt capacitors are connected at a buses of a given distribution system to which a number of nonlinear loads are connected, it cannot determine the connected capacitor current for any considered harmonic order. This is because the harmonic voltage across its terminal is not known. Hence Eq. 2 cannot be applied to obtain the branches currents and the introduced harmonic load flow algorithm fails to be completed. However, using the repetitive load flow algorithm, the required capacitor harmonic current can be determined at each harmonic order but larger computation time values are needed. Assuming shunt capacitors to be connected to the distribution system then the distributor branches currents can be obtained from the general form,

$$\left[Ib^h\right]_{n\ell x1}=\left[DBIBC\right]_{n\ell \text{ x } 2(nb-1)}\cdot\left[Ihs^h\right]_{2(nb-1)x1} \quad (6)$$

where the DBIBC matrix is formed by placing two BIBC matrix side by side. Ihsh is the current vector of the harmonic source injected currents and shunt capacitors currents.

Considering capacitors connection at buses 3 and 6 of the simple assumed system as shown in Fig. 2, the branches currents are obtained in simplified form as follow,

$$\begin{bmatrix} Ib_1^h \\ Ib_2^h \\ Ib_3^h \\ Ib_4^h \\ Ib_5^h \\ Ib_6^h \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -Ih_2^h \\ -Ih_4^h \\ -Ih_5^h \\ +Is_3^h \\ +Is_6^h \end{bmatrix} \quad (7)$$

Applying Eq. (4), considering the substation harmonic voltage equals zero, the distributor buses voltage can be calculated from the equation,

$$\begin{bmatrix} V_2^h \\ V_3^h \\ V_4^h \\ V_5^h \\ V_6^h \\ V_7^h \end{bmatrix} = -\begin{bmatrix} (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h) \\ (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) \\ (Z_{12}^h) & (Z_{12}^h+Z_{23}^h+Z_{34}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) \\ (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h) \\ (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h+Z_{56}^h) \\ (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) \end{bmatrix} \begin{bmatrix} -Ih_2^h \\ -Ih_4^h \\ -Ih_5^h \\ +Is_3^h \\ +Is_6^h \end{bmatrix} \quad (8)$$

From Eq. (8), for the assumed distribution system, the voltage at the capacitor connected buses can be written as,

$$\begin{bmatrix} Vb_3^h \\ Vb_6^h \end{bmatrix} = -\begin{bmatrix} (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{23}^h) & (Z_{12}^h) \\ (Z_{12}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h) & (Z_{12}^h) & (Z_{12}^h+Z_{25}^h+Z_{56}^h) \end{bmatrix} \begin{bmatrix} -Ih_2^h \\ -Ih_4^h \\ -Ih_5^h \\ +Is_3^h \\ +Is_6^h \end{bmatrix} \quad (9)$$

Also, the voltage at the shunt capacitor can be given as a function of it impedance at h^{th} harmonic and the capacitor current as,

$$\begin{bmatrix} Vb_3^h \\ Vb_6^h \end{bmatrix} = \begin{bmatrix} ZC_3^h \text{ x } Is_3^h \\ ZC_6^h \text{ x } Is_6^h \end{bmatrix} \quad (10)$$

Substituting from Eq. (10) into Eq. (9),

$$\begin{bmatrix} ZC_3^h & 0 \\ 0 & ZC_6^h \end{bmatrix}\begin{bmatrix} Is_3^h \\ Is_6^h \end{bmatrix} = \begin{bmatrix} (Z_{12}^h) & \begin{pmatrix} Z_{12}^h \\ +Z_{23}^h \end{pmatrix} & (Z_{12}^h) \\ (Z_{12}^h) & (Z_{12}^h) & \begin{pmatrix} Z_{12}^h \\ +Z_{25}^h \end{pmatrix} \end{bmatrix}\begin{bmatrix} -Ih_2^h \\ -Ih_4^h \\ -Ih_5^h \end{bmatrix} + \begin{bmatrix} \begin{pmatrix} Z_{12}^h \\ +Z_{23}^h \end{pmatrix} & (Z_{12}^h) \\ (Z_{12}^h) & \begin{pmatrix} Z_{12}^h + Z_{25}^h \\ + Z_{56}^h \end{pmatrix} \end{bmatrix}\begin{bmatrix} +Is_3^h \\ +Is_6^h \end{bmatrix} \quad (11)$$

Solving Eq. (11), the shunt capacitor current can be obtained depending on the value of the known harmonic sources injected currents and given shunt capacitors and branches impedance. Note that Eqs. (8, 9 and 11) are written for the special case shown in Fig. 2.

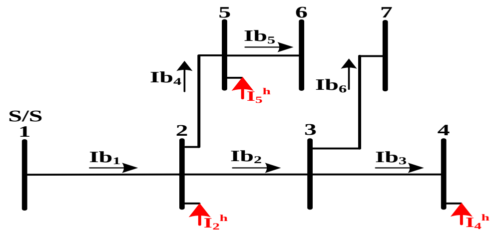

Fig. 1. Harmonic polluted simple distribution system

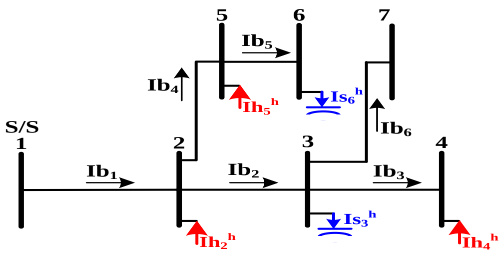

Fig. 2. Harmonic polluted distribution system with embedded shunt capacitors

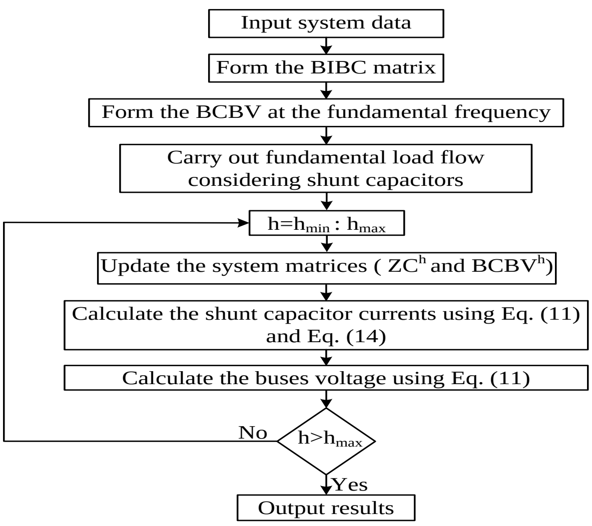

Fig. 3. Flowchart of harmonic load flow procedure

From the previous derivation, the harmonic load flow considering the connection of shunt capacitors can be obtained following the flowchart shown in Fig. 3,

A. Harmonic Load Flow Computation Results Considering the Shunt Capacitors Connection to the 11-Bus Test System

In this section the introduced harmonic load flow technique has been tested on the 11-bus test system, shown in Fig. 4, which introduced in Ref. [11]. Table 1 lists the 11-bus impedances of distribution feeders. The load demand at each bus has been recorded in Table-2.

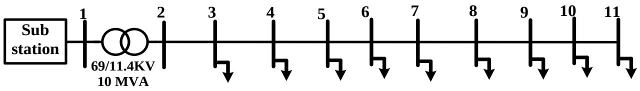

Fig. 4. Single line diagram of the 11-bus test system

Table 1. SYSTEM IMPEDANCE OF THE 11-BUS DISTRIBUTION FEEDERS

Bus		Impedance (p.u.)	
From	To	R	X
2	3	0.0932	0.2121
3	4	0.0106	0.1575
4	5	0.0643	0.4112
5	6	0.0523	0.4612
6	7	0.0531	0.2063
7	8	0.0845	0.4963
8	9	0.0554	0.3832
9	10	0.0491	0.4612
10	11	0.0554	0.4353

Table 2. LOADS DEMAND OF THE 11-BUS DISTRIBUTION SYSTEM

Bus	P (KW)	Q(Kvar)
2	0	0
3	427	140
4	684	224.8
5	534	400.5
6	534	544.8
7	1048	786
8	406	196.6
9	972	857.2
10	408	416.2
11	1487	921.6
Total	6610	5340

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Table 3. HARMONIC CURRENT GENERATED AT EACH BUS [11]

Harmonic order	Harmonic current (%)								
	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11
2	1.80	2.14	1.61	1.33	1.46	2.18	1.25	1.88	1.87
4	1.50	1.39	1.02	0.82	0.94	1.42	0.80	1.22	1.17
5	3.11	3.16	3.50	3.40	1.44	2.96	4.36	3.61	4.01
7	2.19	2.23	2.46	2.38	2.90	2.08	3.08	2.55	2.84
8	0.64	0.61	0.52	0.48	0.48	0.63	0.43	0.56	0.53
10	0.62	0.53	0.34	0.21	0.32	0.56	0.25	0.47	0.46
11	1.15	1.15	1.28	1.19	1.60	1.05	1.72	1.37	1.59
13	1.04	1.04	1.09	0.98	1.36	0.95	1.44	1.20	1.38
14	0.39	0.34	0.17	0.06	0.16	0.34	0.11	0.28	0.27
16	0.26	0.24	0.18	0.15	0.16	0.24	0.14	0.21	0.20
17	0.82	0.82	0.87	0.80	1.08	0.75	1.14	0.95	1.09
19	0.81	0.79	0.80	0.71	0.98	0.72	1.03	0.89	1.01
20	0.41	0.36	0.20	0.10	0.19	0.36	0.13	0.30	0.29
22	0.43	0.39	0.26	0.18	0.24	0.39	0.19	0.33	0.32
23	0.35	0.39	0.55	0.57	0.70	0.34	0.78	0.53	0.62
25	0.48	0.50	0.60	0.60	0.72	0.46	0.77	0.60	0.68

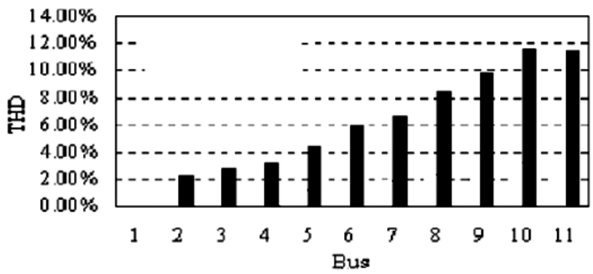

Fig. 5 Voltage THD of each bus of the 11-bus test system [11]

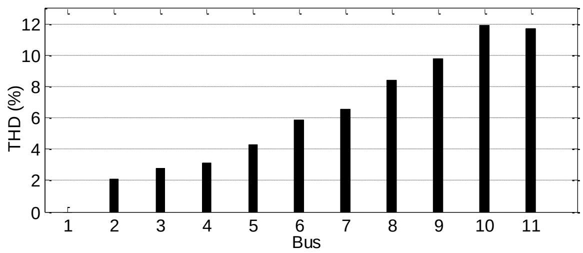

Fig. 6 Voltage THD of each bus of the 11-bus test system using the introduced method

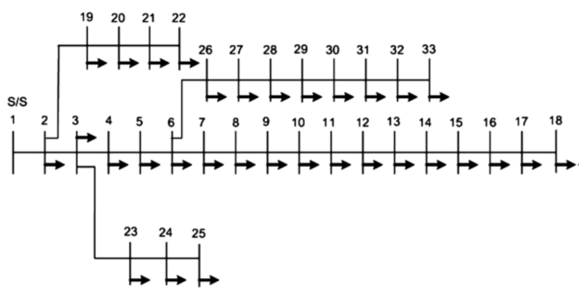

Fig. 7 Single line diagram of the 33-bus distribution test system

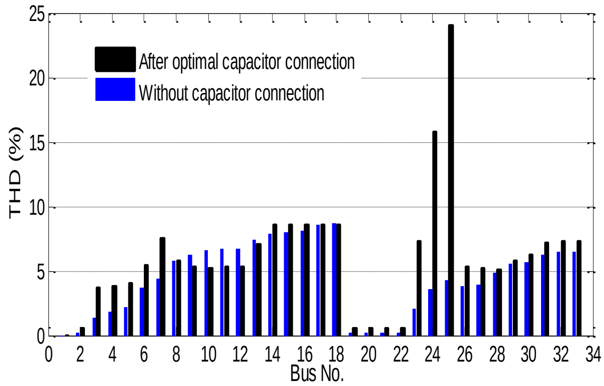

Fig. 8 Voltage THD of each bus of the 33-bus system with and without connection of optimal capacitors

The injected harmonic current values to the considered distribution system are given in Table III. Also, it is assumed that a capacitor banks with total capacity of 1500 kvar is connected to the distribution system at Bus 10 to provide the reactive power compensation for the feeder [11]. Fig. 5 shows the THD at each bus given in Ref. [11] while the THD value obtained from the introduced harmonic load flow method is given in Fig. 6. The obtained results verify the effectiveness of the introduced HLF method.

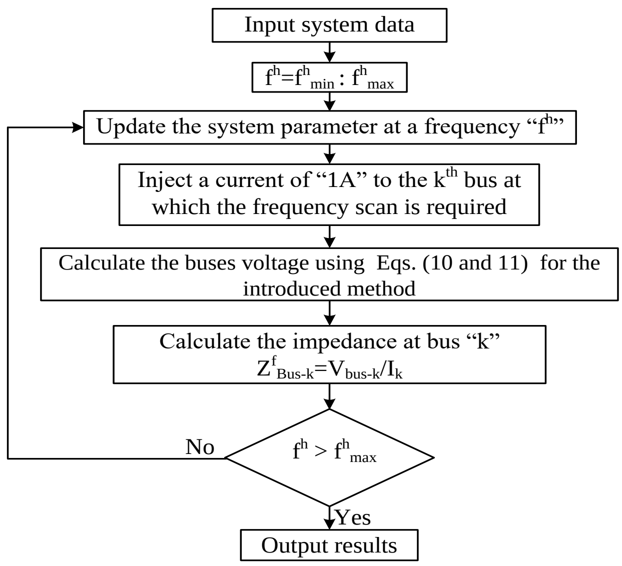

Fig. 9 Flowchart of the impedance scan algorithm

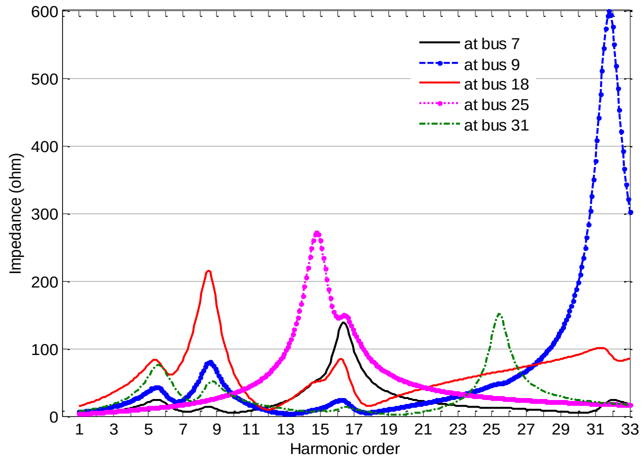

Fig. 10 Impedance scan at some buses of the 33-bus distribution system

B. Harmonic Load Flow Computation Results Considering the Shunt Capacitors Connection to the 33-Bus Test System

In this section, the harmonic load flow computations for the 33-bus distribution system, shown in Fig. 7 with the branches and loads data given in Ref. [12], are carried out considering the connection of shunt capacitors given in Ref [13]. The obtained capacitors sizes and connection point in Ref [13] represent the optimum values for loss minimization and voltage enhancement. Ref [13] obtains the optimal capacitors sizes at the fundamental frequency, not considering harmonic effect. The capacitors size are 600, 150, 300, 350, 600 and 450 Kvar and connected at buses 7, 9, 14, 25, 30 and 31, respectively. After carrying out the harmonic load flow computations considering the harmonic current injection of orders 5, 7, 11, 13, 15, 17, 23 and 25 with a ratio of 1/n from the fundamental load current value, where "n" is the harmonic order. The nonlinear loads are considered to be at buses 4, 8, 14, 18, 24, 29 and 32. Fig. 8 shows the computed THD at each bus with and without optimal capacitor connection, from which it is clear that the THD value at bus 25 after capacitor connection reaches a value about 25%, which unacceptable value according to [14]. The impedance scan at this bus, See Section III, shows that this bus is subjected to parallel resonance at the 13th harmonic order with the connection of previous optimal capacitors. Also, although, the connection of a capacitor at bus 9, the THD at buses 9, 10, 11 and 12 is less than that before optimal capacitor connection. Therefore, from the obtained results it can be said that the capacitor optimal size and location at fundamental frequency may lead to unacceptable THD at distribution system buses. On the other hand shunt capacitor connection to distribution systems can be used for THD minimization besides voltage enhancement and losses minimization if they properly sized and located.

III. FREQUENCY (IMPEDANCE) SCAN

A frequency or impedance scan refers to a plot showing the magnitude and phase angle of the driving point impedance (of the linear network) at an interested bus versus the frequency, and it can provide some useful, and sometimes qualitative, insight into the system performance under harmonic pollution. The term “scan” arises from the systematic variation of frequency from an initial value fmin to a final value fmax. The impedance scan computation steps can be summarized by the following flowchart shown in Fig. 9.

Now, considering the connection of the capacitors listed in Section II-B, and carrying out the impedance scan of the 33-bus system, the impedance scan at some buses are shown in Fig. 10, from which it is clear that bus 25 is subjected to parallel resonance at 15th harmonic order which prove the larger obtained THD value given in Fig. 8. Although a parallel resonance occurrence at bus 9 near 31th harmonic order, the THD at this bus with capacitor connection is smaller than its value without capacitor connection, see Fig. 8. The reason is the absence of injected harmonic current at this higher harmonic order. Also, although a parallel resonance occurrence at bus 18 as shown in Fig. 10, the THD at this bus, shown in Fig. 8 is the same for the cases with or without capacitor connection. The reason is the occurrences of parallel resonance at 9th harmonic order which not existing.

IV. CAPACITOR OPTIMAL PLACEMENT ON HARMONIC POLLUTED DISTRIBUTION SYSTEMS

It is found in Sections. II-B and III that considering only the fundamental frequency the optimal sizes and connection points for the connected capacitors with a given harmonic polluted distribution system may lead to an occurrence of a parallel resonance and larger THD values for the buses voltage. Therefore, in this section, it is introduced a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm for the optimal capacitor sizes and locations on a harmonic polluted distribution system. The buses voltage THD minimization, total power losses minimization and voltage enhancement are the considered objective functions. A modified Non-Dominated Sorting algorithm [15] has been used with PSO technique for achieving the optimum solution. The computation steps for the introduced MOPSO algorithm are given in the flowchart, shown in Fig. 11.

Applying the introduced MOPSO algorithm, the capacitor optimal placement on the 33-bus distribution system is carried out. Assuming that the loads connected to buses 5, 7, 8, 10, 11, 14, 15, 17, 24, 2, 27, 29, 30, 31 and 32 to be nonlinear loads, and each of them inject the harmonic orders 5, 7, 11, 13, 15, 17, 23 and 25 with the amplitude 1/n from the load fundamental current value, where "n" is the harmonic order. The assumed number of the connected capacitor, in this case, is five capacitors. The optimal capacitors sizes and connection point for the introduced MOPSO and individual objective functions are listed in Table 4. Fig. 12, and Fig. 13 show the buses voltage THD and the buses voltage values of the 33-bus system after optimal capacitor connection mentioned in Table 4.

Fig. 14 shows the impedance scan at bus 18 of the 33-bus distribution system with the connection of the obtained optimal capacitor given in Table IV. Case a, b, c and d, shown in Fig. 14, represent the frequency scan after the connection of the optimal capacitor obtained applying the MOPSO, f1 only, f2 only and f3 only, respectively.

Fig. 15 shows the convergence of the global best solution for the case of the multi-objective.

V. CONCLUSIONS

Harmonic analysis is an important application for distribution systems analysis and design. In this paper, a new fast harmonic load flow method has been introduced to overcome the shortage of the conventional HLF methods. The introduced method can overcome the singularity problems that appear in the conventional methods without excessive computational time required for the admittance matrix formation used in conventional harmonic load flow methods. The obtained results verify the effectiveness of the introduced HLF method.

Applying the introduced harmonic load flow method to harmonic polluted distribution systems embedded shunt capacitors which commonly used for losses minimization and voltage enhancement, it is found that the shunt capacitor can maximize or minimize buses voltage THD of distribution systems according to its size and connection point. Therefore, in this paper, a new proposed MOPSO algorithm for optimal capacitors placement on harmonic polluted distribution systems has been introduced based on a modified Non-Dominated Sorting algorithm. The obtained results verify the effectiveness of the introduced MOPSO algorithm for voltage THD minimization, power losses minimization and voltage enhancement of radial distribution systems.

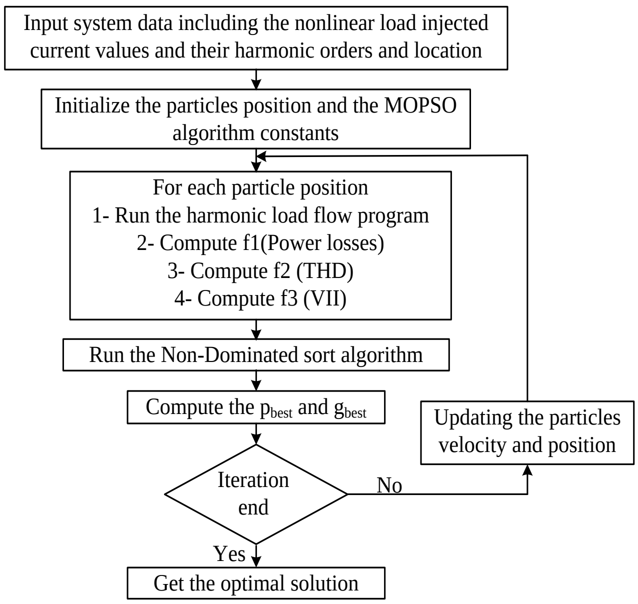

Fig. 11 Flowchart of the introduced multi-objective PSO algorithm

Table 4. Optimal capacitor placement on the 33-bus distribution system

Objective function	Optimal size and connection point						Losses (KW)
Multi-objective	Bus	16	14	32	33	33	200.74
	Size (Kvar)	582.8	510.4	513.4	648.4	665.7	
Ploss minimization only (f1)	Bus	7	17	29	30	3	185.86
	Size (Kvar)	624.2	348.1	356.2	220.1	680.8	
THD minimization only (f2)	Bus	18	31	9	14	20	228.45
	Size (Kvar)	540.3	635.0	470.2	566.6	363.9	
Voltage enhancement only (f3)	Bus	18	31	9	14	20	208.87
	Size (Kvar)	468.2	550.3	407.5	491.1	315.4	208.87
Without capacitors							**228.5**

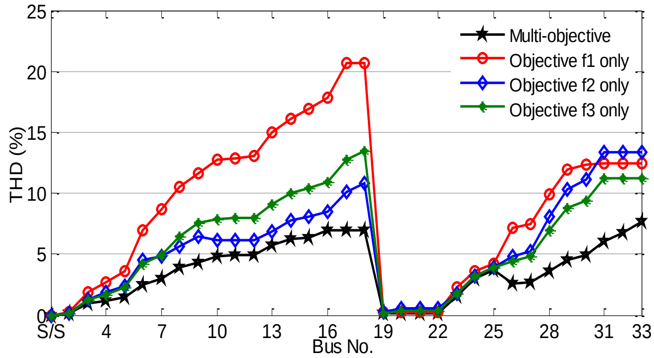

Fig. 12 Buses voltage THD of the 33-bus system

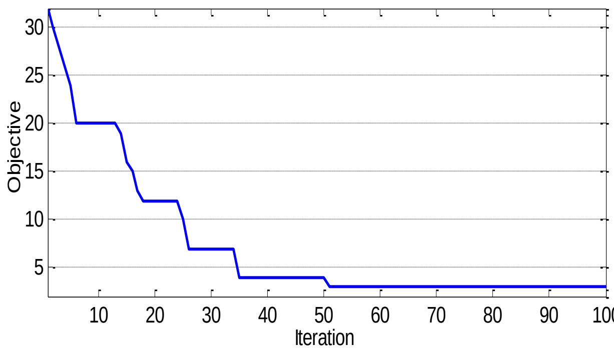

Fig. 15 Convergence of the objective function

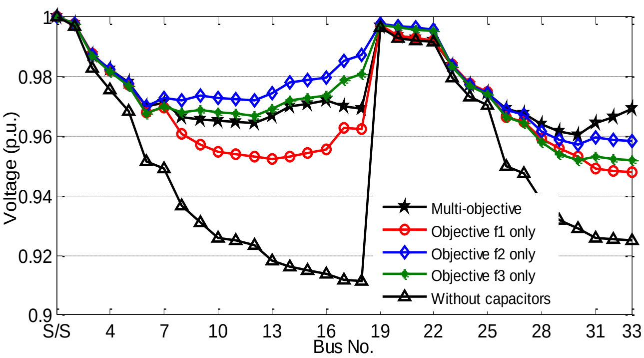

Fig. 13 Buses voltage of the 33-bus system

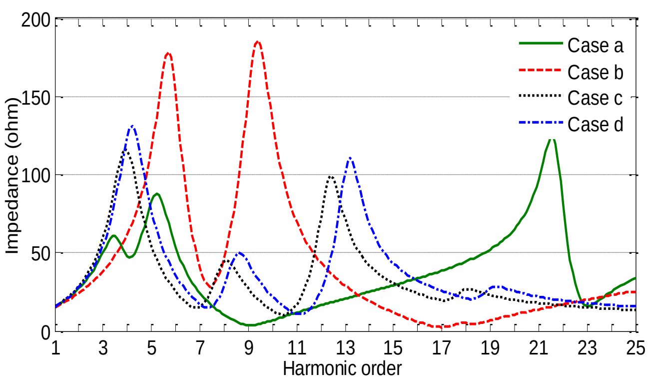

Fig. 14 Impedance scan at bus 18 of the 33-bus system

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