A Novel Algorithm for Optimal Harmonic Load Flow including Harmonic Compensation

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ABSTRACT

Load flow analysis is widely used for finding voltage at various parts of a large, interconnected power system. The exponential increase in the use of power electronic devices and the noticeable percentage of integration of renewable energy sources in modern power systems result in the occurrence of non-sinusoidal voltages at various parts of the power system. By reformation of the Newton-Raphson load flow method, a few harmonic load flow algorithms have been developed for modern transmission systems. However, for larger transmission systems, complexity and heavy computational burden are often encountered in the load flow solution process due to the increased size of the Jacobean matrix that further increases with multiple non-linear load buses and compensation requirements. This leads to convergence problems and increased execution time. In this paper, an optimal harmonic load flow algorithm is proposed, that employs a modified PSO technique to select control variables and the harmonic load flow method to find solutions for load flow analysis with a reduced size of the Jacobean matrix. The formulated method uses a simple technique to take into account nonlinear loads and results in faster convergence. The novelty of the algorithm is that an optimal load flow solution with the desired amount of reactive and harmonic compensation currents is obtained. The algorithm can help in getting load flow solutions in future power systems with distorted voltage and currents with compensation. The performance of the proposed algorithm is tested on a modified IEEE 30-bus system with multiple non-linear load buses and is validated with the Simulink model of the system.

Keywords-compensation; harmonic load flow; optimization; Particle Swarm Optimization (PSO); power system; transmission losses

I. INTRODUCTION

Load flow analysis plays an important role in power system operation, control, and planning. In modern power systems, the proliferation of power electronic-based nonlinear loads for industrial and commercial use results in the occurrence of non-sinusoidal bus voltages at various parts of the power system. As per [1], the Indian transmission system voltage and current were found to be rich in 5^{th} and 7^{th} harmonics due to large industrial loads such as rolling mills driven by variable speed drives and arc furnaces. Also, due to the integration of renewable energy sources in power grids [2], there is a noticeable decrease in voltage quality in modern transmission systems. The standard regulations and recommendations for harmonic studies [3] provide harmonic distortion limits for system voltage. As distributed generation and non-linear loads are increasing day by day, it is needed to find the desired reactive and harmonic compensation under non-sinusoidal voltage conditions while conducting load flow analysis in order to maintain stable operation in future transmission systems. Newton-Raphson Load Flow (NRLF) is widely used for power flow analysis under sinusoidal conditions of a power system. Under non-sinusoidal voltage conditions and in order to find harmonic load flow solution, authors in [4] have modified the conventional NRLF method with detail nonlinear load modeling and satisfactory results were obtained with reasonable accuracy. However, it is implemented for an 8-bus system. Different harmonic load flow methods have been developed in [5-7]. Most use nonlinear load modeling and gave satisfactory results. Authors in [5] used a unified Newton's approach to simplify the solution, while authors in [6] proposed a decoupled approach suitable for transmission systems. Recently, the harmonic monitoring method [7] has been developed using PMUs in the transmission system. By understanding the importance of the Optimal Power Flow (OPF) solution for economic and reliable operation under linear load conditions, traditionally, classical or deterministic optimization techniques have been used. Recently, comparatively easier to implement heuristic methods have been preferred to undertake global search [8-10].

The future transmission systems will be more and more at the risk of non-sinusoidal bus voltage conditions and under the adverse effects of harmonics. Under such conditions, with the optimal placement of capacitors and with strategic placement and sizing of passive or active filters for harmonic compensation using deterministic [11] and heuristic [12-14] optimization techniques, optimal load flow solutions can be obtained. However, in most of the reviewed studies, distribution systems have been considered for harmonic analysis and associated optimization using the decoupled harmonic load flow approach, as such systems are more sensitive to harmonic distortions. Looking at today's situation of modern transmission systems with noticeable percentage of harmonics, the utilities are redirecting their focus on transmission system harmonics and their mitigation. To the best of our knowledge, there is no sufficient solution available for harmonic load flow in transmission systems with compensation. In this paper, an optimal harmonic load flow algorithm is proposed for transmission systems with reduced size of Jacobean matrix which results in faster convergence. The desired amount of reactive and harmonic compensation is also addressed.

II. THE PROPOSED OPTIMAL HARMONIC LOAD FLOW ALGORITHM

A simple and efficient optimal harmonic load flow algorithm is developed by modifying the NRLF method and employing the PSO technique that helps in getting faster a global optimal solution under non-sinusoidal voltage condition.

Consider a n bus system with 1to m linear buses including the slack bus and $(m+1)$ to n nonlinear load buses out of which 2 to l buses as PV buses and $(l+1)$ to m buses as linear PQ buses, as shown in Figure 1. The specified variables and unknowns are given in Table I.

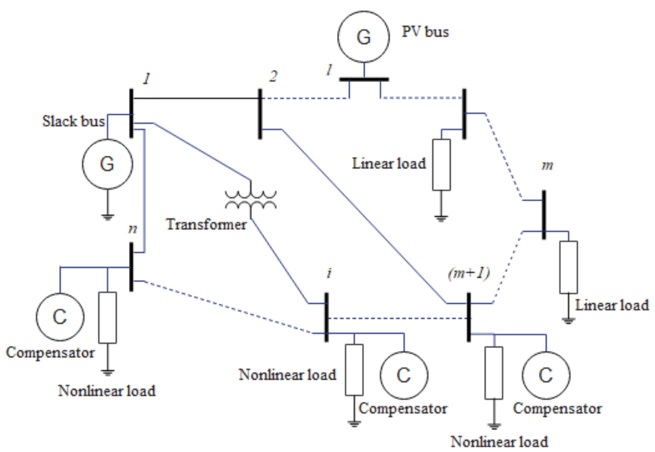

Fig. 1. Layout of a typical n-bus power system with compensators.

TABLE I. SPECIFIED AND UNKNOWN DATA OF VARIOUS BUSES

Bus No. (i)	Bus type	Specified variables	Unknown variables
1	Slack	$\lvert V_{1,1}\rvert, \delta_{1,1}$	$P_{1,1}, Q_{1,1}, \delta_{1,h}, \lvert V_{1,h}\rvert$
2 to l	PV	$P_{i,1}, \lvert V_{i,1}\rvert$	$\delta_{i,1}, Q_{i,1}, \delta_{i,h}, \lvert V_{i,h}\rvert$
$(l+1)$ to m	Linear PQ	$P_{i,1}, Q_{i,1}$	$\delta_{i,1}, \lvert V_{i,1}\rvert, \delta_{i,h}, \lvert V_{i,h}\rvert$
$(m+1)$ to n	Non-linear PQ	$P_{i,1}, S_{i,t}$	$Q_{i,1}, \delta_{i,1}, \lvert V_{i,1}\rvert, \delta_{i,h}, \lvert V_{i,h}\rvert$

In Table I, the first subscript of a variable represents the bus number and the second represents the order of harmonics. Under non-sinusoidal condition, the NRLF equation [15] can be modified as:

$$[\Delta\bar{M}_{(mod)}] = [\bar{J}_{(mod)}].[\Delta\bar{U}_{(mod)}] \quad (1)$$

where Δ represents change in the specified and calculated value of a parameter, while $[\Delta\bar{M}_{(mod)}]$ is the modified mismatch vector and $[\Delta\bar{U}_{(mod)}]$ is the modified correction vector. Equation (1) can be rewritten as:

$$\begin{bmatrix} \Delta\bar{W}_{i(mod)} \\ \Delta\bar{I}_{i,h} \end{bmatrix} = [\bar{J}_{mod}].\begin{bmatrix} \Delta\bar{\delta}_{i,1} \\ \Delta\lvert\bar{V}_{i,1}\rvert \\ \Delta\bar{\delta}_{i,h} \\ \Delta\lvert\bar{V}_{i,h}\rvert \end{bmatrix} \quad (2)$$

$[\Delta\bar{M}_{(mod)}]$ includes the power mismatch vector $[\Delta\bar{W}_{i(mod)}]$ and the harmonic current mismatch vector $[\Delta\bar{I}_{i,h}]$, which are explained below.

1)Power Mismatch Vector

$[\Delta\bar{W}_{i(mod)}]$ is given by:

$$[\Delta\bar{W}_{i(mod)}] = \begin{bmatrix} \Delta P_{2,1}, \dots, \Delta P_{m,1}, \Delta Q_{2,1}, \dots, \Delta Q_{m,1}, \\ \Delta P_{m+1,t}, \dots, \Delta P_{n,t}, \Delta Q_{m+1,t}, \dots, \Delta Q_{n,t} \end{bmatrix}^T \quad (3)$$

where subscript t represents the total power including fundamental and harmonic powers calculated at the i^{th} bus as:

$$P_{i,t} = \sum_{h=1}^{h_{max}}\left(\lvert V_{i,h}\rvert.\sum_{k=1}^{n}\lvert V_{k,h}\rvert.\lvert Y_{ik,h}\rvert.\cos\left(\theta_{ik,h} - \delta_{i,h} + \delta_{k,h}\right)\right) \quad (4)$$

$$Q_{i,t} = \sum_{h=1}^{h_{max}}\left(\lvert V_{i,h}\rvert.\sum_{k=1}^{n}\lvert V_{k,h}\rvert.\lvert Y_{ik,h}\rvert.\sin\left(\theta_{ik,h} - \delta_{i,h} + \delta_{k,h}\right)\right) \quad (5)$$

where $[Y_{ik,h}]$ is an element of bus admittance matrix $[Y_{bus,h}]$ at the h^{th} harmonic component with magnitude $\lvert Y_{ik,h}\rvert$ and phase angle $\theta_{ik,h}$. The size of $[\Delta\bar{W}_{i(mod)}]$ is $[2(n-1)]\,x\,1$. However, if we consider 2 to l buses as PV buses, the corresponding $\Delta\bar{Q}_{i,1} = 0$ reduces the size of the matrix.

2)Harmonic Current Mismatch Vector

$[\Delta\bar{I}_{i,h}]$ is formed for $i = 1$ to n and $h = 2$ to h_{max} given by:

$$[\Delta\bar{I}_{i,h}] = [\Delta I_{1,2}, \dots, \Delta I_{n,2}, \dots, \Delta I_{1,h_{max}}, \dots, \Delta I_{n,h_{max}}]^T \quad (6)$$

where $\Delta I_{i,h} = I_{i,h(spec)} - I_{i,h(cal)}$ while $spec$ and cal are representing the specified and calculated values of the parameters. $I_{i,h(spec)}$ at the i^{th} bus is obtained from the fundamental load current $I_{i,1(spec)}$ obtained using the specified powers as follows:

$$I_{i,1(spec)} = \left(\frac{P_{i,1(spec)}+jQ_{i,1(spec)}}{V_{i,1}}\right)^* \quad (7)$$

where $P_{i,1(spec)}$ and $Q_{i,1(spec)}$ are the specified fundamental active and reactive powers at nonlinear load buses. Equation (7) calculates $I_{i,1(spec)}$ for $i = (m+1)$ to n non-linear load buses. $Q_{i,1(spec)}$ is iteratively calculated using the $S_{i,t(spec)}$ equation that includes voltage and current distortion powers in addition to $P_{i,1(spec)}$ and $Q_{i,1(spec)}$:

$$S_{i,t}{}^2 = P_{i,t}{}^2 + Q_{i,t}{}^2 + D_{i,t}{}^2 \quad (8)$$

where $D_{i,t}{}^2 = (D_{Ii,t}{}^2 + D_{Vi,t}{}^2)$ with $D_{Ii,t}{}^2$ and $D_{Vi,t}{}^2$ are the squared values of total current and total voltage distortion powers respectively. The specified harmonic currents $I_{i,h(spec)}$ for $h = 2$ to h_{max} are obtained using a typical harmonic spectrum for non-linear load as follows [16]:

$$\left|I_{i,h(spec)}\right| = \left|I_{i,1(spec)}\right|.\alpha_h \quad (9)$$

$$\theta_{i,h(spec)} = \theta_{h-spectr} + h.\left(\theta_{i,1(spec)} - \theta_{1-spectr}\right) \quad (10)$$

where $\left|I_{i,1(spec)}\right|$ and $\theta_{i,1(spec)}$ are the magnitude and the phase angle for $I_{i,1(spec)}$, α_h is the ratio of the *h*-order harmonic component to the fundamental component of the current, and $\theta_{h-spectr}$ is the phase angle for the *h*-order harmonic component.

$I_{i,h(cal)}$ for $i = 1$ tp n to form the mismatch current vectors is obtained as:

$$I_{i,h(cal)} = \sum_{k=1}^{n}\left|Y_{ik,h}\right|.\left|V_{k,h}\right|.\left(\cos\left(\theta_{ik,h}+\delta_{k,h}\right) + jSin\left(\theta_{ik,h}+\delta_{k,h}\right)\right) \quad (11)$$

The elements of $\left[\Delta\bar{I}_{i,h}\right]$ are expressed in real and imaginary terms as:

$$\left[\Delta\bar{I}_{i,h}\right] = \left[\Delta\bar{I}_{ir,h}, \Delta\bar{I}_{ii,h}\right]^T \quad (12)$$

The harmonic current mismatch vector is updated with the desired harmonic compensation current, $\left[I_{i,h(comp)}\right]$ as:

$$\Delta I_{ri,h(mod)} = (I_{ri,h(spec)} - I_{ri,h(comp)}) - I_{ri,h(cal)} \quad (13)$$

$$\Delta I_{ii,h(mod)} = (I_{ii,h(spec)} - I_{ii,h(comp)}) - I_{ii,h(cal)} \quad (14)$$

where:

$$I_{ri,h(comp)} = I_{ri,h(cal)} \cdot a_{i,h} \quad (15)$$

$$I_{ii,h(comp)} = I_{ii,h(cal)} \cdot a_{i,h} \quad (16)$$

where $a_{i,h}$ is the fractional multiplier for the harmonic current to be compensated.

The desired reactive compensation current, $I_{ii,1(comp)}$ is obtained as:

$$I_{ii,1(comp)} = I_{ii,1} \cdot a_{i,1} \quad (17)$$

where $a_{i,1}$ is the fractional multiplier for the reactive current to be compensated.

$[\Delta\bar{U}_{(mod)}]$ includes fundamental voltage correction vectors, $\Delta\bar{\delta}_{i,1}$and $\Delta\left|\bar{V}_{i,1}\right|$ for $i = 2$ to n and harmonic voltage correction vectors, $\Delta\bar{\delta}_{i,h}$ and $\Delta\left|\bar{V}_{i,h}\right|$ for $i = 1$ to n as given below:

$$[\Delta\bar{U}_{(mod)}] = \begin{bmatrix}\Delta\delta_{2,1},\dots,\Delta\delta_{n,1},\Delta\left|V_{2,1}\right|,\dots,\Delta\left|V_{n,1}\right|,\Delta\delta_{1,h},\dots,\Delta\delta_{n,h}, \\ \Delta\left|V_{1,h}\right|,\dots,\Delta\left|V_{n,h}\right|\end{bmatrix}^T \quad (18)$$

Thus, the complete harmonic load flow equation with compensation can be written as:

$$\begin{bmatrix}\Delta\bar{W}_{i,1(mod)} \\ \Delta\bar{W}_{i,t} \\ \Delta\bar{I}_{ri,h(mod)} \\ \Delta\bar{I}_{ii,h(mod)}\end{bmatrix} = \begin{bmatrix}\bar{J}_{\bar{W}_{i,1},\bar{\delta}_{i,1}} & \bar{J}_{\bar{W}_{i,1},|\bar{V}_{i,1}|} & \bar{J}_{\bar{W}_{i,1},\bar{\delta}_{i,h}} & \bar{J}_{\bar{W}_{i,1},|\bar{V}_{i,h}|} \\ \bar{J}_{\bar{W}_{i,t},\bar{\delta}_{i,1}} & \bar{J}_{\bar{W}_{i,t},|\bar{V}_{i,1}|} & \bar{J}_{\bar{W}_{i,t},\bar{\delta}_{i,h}} & \bar{J}_{\bar{W}_{i,t},|\bar{V}_{i,h}|} \\ \bar{J}_{\bar{I}_{ri,h},\bar{\delta}_{i,1}} & \bar{J}_{\bar{I}_{ri,h},|\bar{V}_{i,1}|} & \bar{J}_{\bar{I}_{ri,h},\bar{\delta}_{i,h}} & \bar{J}_{\bar{I}_{ri,h},|\bar{V}_{i,h}|} \\ \bar{J}_{\bar{I}_{ii,h},\bar{\delta}_{i,1}} & \bar{J}_{\bar{I}_{ii,h},|\bar{V}_{i,1}|} & \bar{J}_{\bar{I}_{ii,h},\bar{\delta}_{i,h}} & \bar{J}_{\bar{I}_{ii,h},|\bar{V}_{i,h}|}\end{bmatrix} x \begin{bmatrix}\Delta\bar{\delta}_{i,1} \\ \Delta\left|\bar{V}_{i,1}\right| \\ \Delta\bar{\delta}_{i,h} \\ \Delta\left|\bar{V}_{i,h}\right|\end{bmatrix} \quad (19)$$

For *K* order of harmonics under consideration, the size of $[\Delta\bar{U}_{mod}]$ is $[2(n-1)+2Kn]x1$. However, for $i = 2$ to l as PV buses, $\Delta\left|V_{i,1}\right| = 0$. In the proposed method, due to the use of the harmonic current spectrum, the nonlinear load parameters are not required to be included in the unknown vectors, resulting in reduction in the size of $[\Delta\bar{U}_{mod}]$ by $2(n-m)$. Thus, the need of fundamental mismatch vector, $[\Delta\bar{I}_{i,1}]$ in $\left[\Delta\bar{M}_{(mod)}\right]$ has been eliminated and reduced by $2(n-m)$. This ultimately reduces the size of the modified Jacobean matrix $[\bar{J}_{(mod)}]$. $[\bar{J}_{(mod)}]$ is formed by sub-matrices represented with the notation as a partial derivative of the $\left[\Delta\bar{M}_{(mod)}\right]$ element given by the first subscript with respect to the $\left[\Delta\bar{U}_{(mod)}\right]$ element. The size of $[\bar{J}_{(mod)}]$ is $[2(n-1)+2Kn]\ x\ [2(n-1)+2Kn]$. However, for the system with $i = 2$ to l as *PV* buses, the size of $[\bar{J}_{(mod)}]$ is $[(2(n-1)-(l-1))+2Kn]\ x[(2(n-1)-(l-1))+2Kn]$. In the solution process, $I_{i,1(spec)}$ and $I_{i,h(spec)}$ are iteratively calculated using the updated bus voltages $V_{i,1}$, the specified powers $P_{i,1(spec)}$, and $Q_{i,1(spec)}$ until the convergence set by tolerance ϵ. This eliminates the decoupled effect to keep the solution accuracy unaffected.

In the proposed algorithm, the PSO technique is employed to find optimal harmonic load flow solution to achieve certain objectives keeping all inequalities within limits. Two types of inequalities, i.e. control variables and functional inequalities are considered. The optimization problem is formed as follows.

A. Selection of Control Variables and Formation of Penalty Function to Handle Functional Inequalities

The limits considered for inequalities are given in Table II. The control variables x_c are system parameters like generator voltage $V_{g,i}$, transformer tap ratio T_i, and current multipliers $a_{i,h}$ and $a_{i,1}$ for optimal compensation. The boundaries of the search space are set by control variable limits. In modified PSO, Michalewicz's non-uniform variable mutation operator, mp [17] is used to accelerate particles towards the global best solution by adding variability into the population in each iteration. Rather than generating particles with the random variables, a small differential variable dx is defined to generate new non-repeated particle positions in each iteration for enhanced search:

$$dx = mp.\left(x_{c(max)} - x_{c(min)}\right) \quad (20)$$

where $x_{c(max)}$ and $x_{c(min)}$ are the maximum and minimum limits of the control variables. All the selected control variables are applied to the system to get the optimal power flow solution.

The functional inequalities f_p considered are the generator reactive power Q_{gi}, the bus voltage magnitudes for PQ buses $|V_i|$, $\%V_{thdi}$, and the total MVA capacity of lines S_{tli} as mentioned in Table II that are handled by selecting optimum static penalty factor ρ_{f_p}. The corresponding penalty function, Ω_{f_p} for f_p inequality is defined for $i = 1$ to N_{f_p} parameters with maximum and minimum limits. The total penalty function, $\Omega_{f_{p(total)}}$ for N_p inequalities is:

$$\Omega_{f_{p(total)}} = \sum_{t=1}^{N_p} \Omega_{f_{pt}} \quad (21)$$

TABLE II. LIMITS FOR CONTROL VARIABLES AND FUNCTIONAL INEQUALITIES

System component / bus	Numbers	Inequality limits
Control variables x_c		
Generator bus	$i = 1$ to n_g	$\lvert V_g\rvert_{(min)} \le \lvert V_{gi}\rvert \le \lvert V_g\rvert_{(max)}$
Transformer	$i = 1$ to n_T	$T_{(min)} \le T_i \le T_{(max)}$
Compensator bus	$i = 1$ to n_{comp}	$a_{1(min)} \le a_{i,1} \le a_{1(max)}$ $a_{h(min)} \le a_{i,h} \le a_{h(max)}$
Functional inequalities f_{pi}		
Generator bus	$i = 1$ to n_g	$Q_{g(min)} \le Q_{gi} \le Q_{g(max)}$
PQ bus	$i = 1$ to n_{PQ}	$\lvert V\rvert_{(min)} \le \lvert V_i\rvert \le \lvert V\rvert_{(max)}$ $\%V_{thdi} \le \%V_{thd(max)}$
Transmission line	$i = 1$ to n_{tl}	$S_{tli} \le S_{tl(max)}$

n_g=no. of generators, n_T=no. of transformers, n_{comp}= no. of compensator buses, n_{PQ}= no. of *PQ* buses, n_{tl}=no. of transmission lines, All minimum and maximum limits are expressed with a subscript *min* and *max* respectively

B. Formation of the Objective Function

As active power loss P_{loss} is of great concern in modern deregulated transmission systems with huge power flows over a long distance, the main objective of the proposed algorithm is considered as the minimization of P_{loss} under non-sinusoidal voltage conditions.

$$F = P_{loss} = \sum_{h=1}^{h_{max}}\left(\sum_{i=1,i\neq k}^{n}\left(\sum_{k=1,k\neq i}^{n} P_{ik,h}\right)\right) \quad (22)$$

where $P_{ik,h}$ is the active harmonic power flow through transmission line between the i^{th} and the k^{th} bus.

The objective function is modified using the total penalty function, $\Omega_{f_{p(total)}}$ as:

$$F_t = F + \Omega_{f_{p(total)}} \quad (23)$$

This helps in getting a global solution to the power flow problem which makes the system parameters within the specified margin. The optimal harmonic power flow solution is obtained by selecting optimal control variables within the set PSO iterations $Iter_{max}$. The specialty of the algorithm is that voltage THD is allowed within the limit using harmonic compensation and voltage magnitude is controlled using fundamental reactive compensation with optimal multipliers for compensators. The flowchart for the optimal harmonic power flow is given in Figure2.

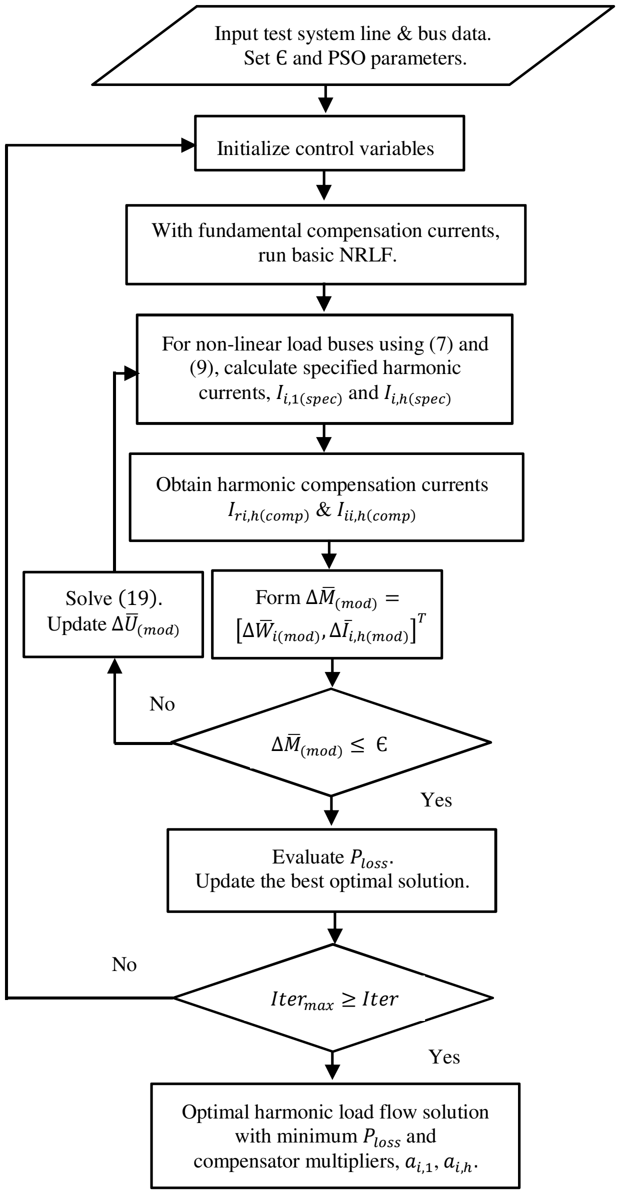

Fig. 2. Flowchart of the proposed optimal harmonic load flow algorithm.

III. SIMULATION RESULTS

A generalized program for the proposed optimization algorithm was developed in the MATLAB m-file platform. To verify the performance of the proposed harmonic optimization algorithm, the 30-bus IEEE system [18] is modified by connecting non-linear loads in a few buses. A 6-pulse rectifier is taken as the non-linear load connected at buses 7, 15, 21, and 30 with load demands and total apparent power demand $S_{i,t}$ that includes distortion powers in addition to active and reactive powers as shown in Table III. The load at these buses is assumed such to get distorted voltage at various buses.

TABLE III. NON-LINEAR LOAD BUS DATA FOR THE MODIFIED IEEE 30-BUS SYSTEM

Bus no.	P_d (MW)	Q_d (MVAr)	S_{total} (MVA)
7	22.8	0.9	25
15	15	2.5	17
21	22	0.2	24
30	10.6	1.9	12

The initial assumptions for the unknown variables are taken as $|V_{i,1}| = 1\text{p.u.}$, $|V_{i,h}| = 0.1$ p.u., $\delta_{i,1}$ and $\delta_{i,h} = 0$deg, and $Q_{i,1} = 0$p.u. for non-linear load bus and the harmonic load flow solution is obtained without optimal control. It is observed that the rms voltages $|V_i|$ and $\%V_{i,thd}$ are exceeding the limits specified by the statutory standards of 5% at some buses. It was also found that the total active power loss including harmonic loss P_{loss} is 6.83MW with fundamental active power loss, $P_{loss,1}$ = 6.76MW obtained from the power flows. The proposed optimization algorithm is implemented with the control variables and functional inequality limits shown in Table IV.

TABLE IV. CONTROL AND FUNCTIONAL INEQUALITY LIMITS

Control variable set limits [a]						
	T	$\lvert V_g \rvert$	a_5	a_7	a_1	
min. limit	0.95	0.95	0.5	0.5	0.8	
max. limit	1.05	1.1	1.0	1.0	1.0	
Functional variable set limits [b]						
	Q_{g1}	Q_{g2}	Q_{g5}	Q_{g8}	Q_{g11}	Q_{g13}	$\lvert V \rvert$
min. limit	-29.8	-24	-30	-26.5	-7.5	-7.8	0.95
max. limit	59.6	48	60	53	15	15.5	1.05

[a] $|V_g|$ limits are specified in p.u. while T and multipliers a_5, a_7 and a_1 are unitless. [b] All Q_g limits are specified in MVAr while those for $|V|$ are in p.u.

For rigid margins of functional inequalities like $|V|$ and voltage Total Harmonic Distortion (THD), the high value of static penalty factor of 200 is selected. For the soft margins of Q_g and S_{tl}, the comparatively smal static penalty factors of 5 and 10 are selected. The mutation ratios μ and the acceleration coefficients c_1 , c_2 are selected as 0.1, 2.05, and 2.05, respectively. The inertia coefficient ω used to control the convergence behavior of PSO is taken as 0.5 and set to gradually decrease using a damping factor of 0.7296 in each iteration. The population n_p and the maximum number of PSO iterations $Iter_{max}$ are set as 30 and 20. The optimal obtained values of the control variables are given in Table V. It is observed that the obtained optimal values of $a_{i,1}$ and $a_{i,5}$, $a_{i,7}$ are such that the required compensation will be provided depending on the fundamental reactive currents and the 5th and 7th harmonic components of the current, respectively, at that bus. PSO with careful selection of parameters and modified with mutation operator exhibits better convergence characteristics. The optimal obtained harmonic power flow solution is given in Table VI.

TABLE V. OPTIMAL CONTROL VARIABLES OBTAINED BY THE MODIFIED PSO

System control variables				
T_{6-9}	T_{6-10}	T_{4-12}	T_{27-28}	V_{g1}
1.0011	1.05	0.9916	0.9798	1.0615
V_{g2}	V_{g5}	V_{g8}	V_{g11}	V_{g13}
1.036	0.9904	1.0166	1.0384	1.0004
Compensator control variables				
$a_{3,1}$	$a_{10,1}$	$a_{24,1}$	$a_{7,1}$	$a_{7,5}$
0.942	0.846	0.8148	0.8151	1.0
$a_{7,7}$	$a_{15,1}$	$a_{15,5}$	$a_{15,7}$	$a_{21,1}$
0.7633	0.9774	0.6428	0.5413	0.9209
$a_{21,5}$	$a_{21,7}$	$a_{30,1}$	$a_{30,5}$	$a_{30,7}$
0.6030	0.8830	0.9343	0.5	0.784

It is observed from Table VI that all bus voltage magnitudes are within the limits of 0.95p.u. and 1.05p.u., showing effective reactive power compensation with optimal values of multipliers $a_{i,1}$ for the selected buses and system parameters. The voltage harmonic magnitudes at the buses are observed to be considerably reduced. As an effect, the values of $\%V_{thd}$ at all buses are reduced below 5%. This demonstrates the effectiveness of harmonic compensation with optimal values of multipliers $a_{i,5}$, $a_{i,7}$.

TABLE VI. OPTIMAL HARMONIC LOAD FLOW SOLUTION OBTAINED BY THE PROPOSED ALGORITHM

Bus i	$\lvert V_{i,1} \rvert$ (p.u.)	$\lvert V_{i,5} \rvert$ (p.u.)	$\lvert V_{i,7} \rvert$ (p.u.)	$\lvert V_i \rvert$ (p.u.)	$\%V_{i,thd}$
7	0.9999	0.0002	0.0015	0.9999	0.1550
10	0.9769	0.0009	0.0072	0.9769	0.7398
15	0.9692	0.0049	0.0109	0.9693	1.2375
21	0.9643	0.0071	0.0099	0.9644	1.2668
22	0.97	0.0025	0.0078	0.9700	0.8481
23	0.9638	0.0044	0.0093	0.9639	1.0665
24	0.96	0.0041	0.0088	0.9601	1.0082
25	0.9774	0.0049	0.0059	0.9774	0.7832
26	0.9599	0.0081	0.0038	0.9600	0.9286
27	0.9963	0.0003	0.0125	0.9964	1.2590
29	0.979	0.0067	0.0113	0.9791	1.3374
30	0.9695	0.0008	0.0445	0.9705	4.5859

To validate the above results obtained by the proposed optimization algorithm, a Simulink model was developed by the Simpower block set of MATLAB as shown in Figure 3. The complete system model consists of subsystems for group of buses, compensators, and nonlinear loads connected. The obtained results by the Simulink model and by the proposed algorithm are matching.

TABLE VII. RESULT COMPARISON BEFORE AND AFTER OPTIMIZATION

Parameter	Before compensation	After compensation
P_{loss}	6.83 MW	5.72 MW
$\%V_{thd}$	11.4935	4.5859
$\lvert V_{30} \rvert$	0.8783	0.9705

From Table VII, it is observed that P_{loss} is considerably reduced to 5.72MW from 6.83MW with 5th and 7th harmonic active power losses as 5.4037e^{-3}MW and 7.1817e^{-3}MW, respectively. The voltage magnitude at the highest affected bus 30 has been improved from 0.8783p.u. to 0.9705p.u.

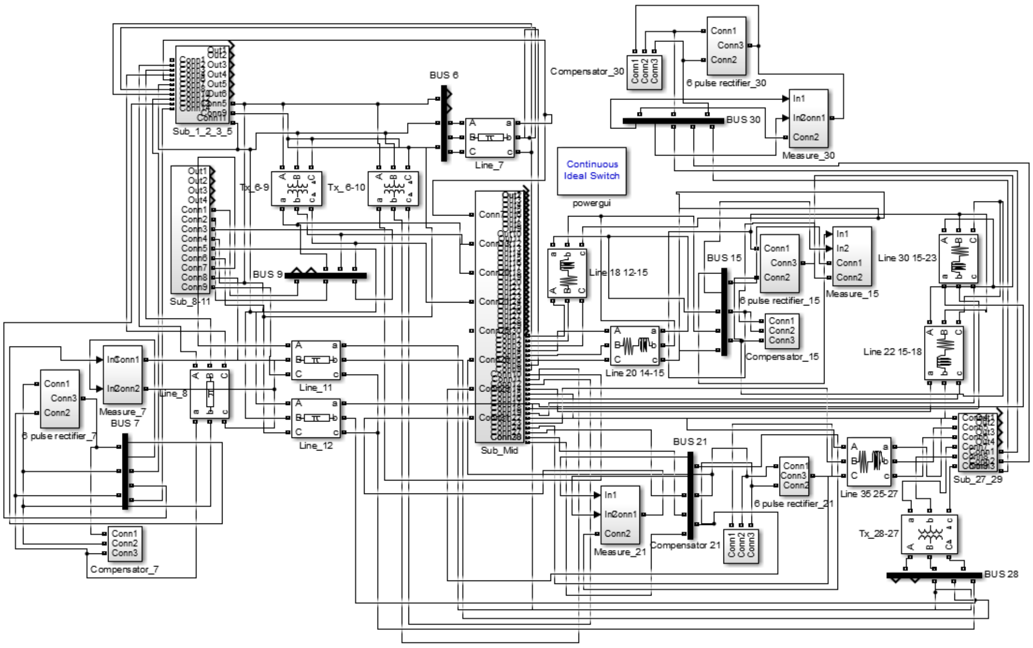

Fig. 3. Simulation model developed for IEEE 30 bus system with compensators.

IV. CONCLUSIONS

The increased use of power electronic-based devices in various applications along with the incorporation of renewable energy sources in modern power systems result in frequent occurrence of non-sinusoidal voltages at system buses. The proposed optimal harmonic load flow algorithm gives a global solution for the transmission systems under non-sinusoidal operation conditions with optimum amount of reactive and harmonic current compensation. The objective of the algorithm is to minimize the transmission losses while maintaining the fundamental voltage magnitude and $\%V_{thd}$ within limits, while the size of the Jacobean matrix is reduced, resulting in faster convergence. The specialty of the proposed method is that with the addition of a greater number of nonlinear loads, the size of the Jacobean matrix remains the same, being independent of the number of nonlinear loads. Another advantage of the algorithm is that the multipliers $a_{i,1}$, $a_{i,5}$, and $a_{i,7}$ in each bus are controlled for the desired current compensation. By optimally compensating reactive and distortion powers, the transmission power loss can be reduced to 5.72MW from 6.83MW.

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