Harmonic Power Flow Calculations for a Large Power System with Multiple Nonlinear Loads Using Decoupled Approach

A. Ulinuha, M.A.S. Masoum, *Senior Member, IEEE*, and S.M. Islam, *Senior Member, IEEE*

Abstract-- **Power flow calculation is normally carried out for fundamental frequency. Due to the extensive use of nonlinear loads, harmonic frequencies are present and need to be also considered. Unfortunately, unavoidable complexity and heavy computation burden are often encountered by involving nonlinear loads into the calculation. Multiple nonlinear loads typically employed in the real system will further weigh the computation down. This paper implements a decoupled approach to overcome the problem. The couplings between harmonics are rationally disregarded enabling separate calculations for every harmonic order. This will greatly reduce the complexity level and computation burden. However, the accuracy of this technique is somehow questioned due mainly to the neglected harmonic couplings. The accuracy of the implemented decoupled harmonic power flow (DHPF) algorithm is investigated by simulating the distorted IEEE 18-bus system and comparing the results with those generated by standard packages (e.g., HARMFLOW and ETAP). The implementation is then extended for the IEEE 123-bus system including multiple nonlinear loads.**

Index Terms— **Accuracy, decoupled, efficiency, harmonic power flow, multiple nonlinear loads**

I. INTRODUCTION

POWER flow calculation is backbone of power system analysis and design. It generates the results that are normally required for further calculation of analysis and design. The calculation is initially performed by formulating the network equation. Node-voltage method, which is the most suitable form for many power system analyses, is commonly used. Mathematically, power flow problem requires solution of simultaneous nonlinear equations and normally employs an iterative method, such as Gauss-Seidel and Newton-Raphson.

The aforementioned calculation is typically carried out by simply considering fundamental frequency. The extensive and ever increasing applications of nonlinear loads such as power electronic devices result in the existence of higher components other than that of fundamental frequency, called harmonics. The nonlinear voltage-current relationship of these devices results in harmonic currents that propagate through the system and produce potentially dangerous harmonic voltages. This phenomenon has become a major concern for power quality and therefore harmonics must be included in the calculations to predict their effects and to avoid possible severe damages. However, taking harmonics into account will lead the calculations to be very complicated.

Real power systems usually employ a number of nonlinear loads with different *v-i* characteristics. This results in multiple harmonic injection currents with different orders, magnitudes and phase angles. This will complicate the calculation even further.

Applications of decoupled approach for harmonic power flow calculation including multiple nonlinear loads are presented in this paper. The aim is to exhibit the inclusion of harmonics in power flow calculation with a reasonable computation burden. Due to the accuracy of decoupled harmonic power flow (DHPF) is somehow questioned, the accuracy of the algorithm is therefore verified by comparing its generated results with those generated by HARMFLOW [1] and ETAP [2]. The IEEE 18-bus distorted system [3] with one nonlinear load is simulated for comparison purposes. The application of the approach is then extended for IEEE 18-bus and IEEE 123-bus systems with multiple nonlinear loads. It is shown that the decoupled approach offers a compromise between result accuracy and computation complexity.

II. HARMONIC POWER FLOW

Harmonic power flow was initially introduced by Xia and Heydt [1] by involving nonlinear loads in power flow calculation. Conventionally, power flow is formulated on the basis that power sources are system generators and power "sinks" are the loads. Harmonic power flow, on the other hand, is more general in that loads may be the "source" of harmonic energy [4]. The ultimate source is system generators, but harmonic distortion that occurs at bus containing nonlinear load may be considered as a source of harmonic signal. For the system consisting of multiple nonlinear loads harmonic currents are therefore injected by a number of nonlinear loads. In addition to some results normally generated by power flow, harmonic power flow also generates other results that can be used to quantify voltage distortion and to determine whether dangerous resonant problem exists.

The nature of the harmonics (i.e., orders, magnitudes and phases) strongly depends on the nonlinear load involved.

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Therefore, nonlinear load modeling is essential part of harmonic power flow calculation. A particular nonlinear load needs to be specifically modeled. Therefore, a system including different types of nonlinear loads requires specific model for every nonlinear type.

Nonlinear loads can be modeled in time and/or frequency domain [5]. Time domain modeling is based on transient-state analysis while frequency domain modeling uses frequency-scan process to calculate the frequency response of a system. Time domain modeling requires detailed representation of the device that increases the problem complexity resulting in prohibitively long computation time. Therefore, frequency domain methods are commonly used for harmonic analysis to reduce the computation time. For nonlinear loads that can be presented as voltage-independent current sources, frequency domain model can be applied for harmonic power flow analysis [6].

Harmonic power flow calculations can generally be classified into coupled and decoupled methods. Coupled approach solves all harmonic orders simultaneously. This approach has good accuracy but leads to a greater computational cost as the problem becomes quite complicated. It also requires exact formulation of nonlinear loads that is sometimes practically unavailable resulting in limited applications [7]. On the other hand, decoupled approach assumes that the coupling between harmonic orders can be rationally disregarded and, as a result, the calculation can be separately carried out for every harmonic order. Therefore, this approach requires less computational charge. In addition, since nonlinear loads are modeled with harmonic current or voltage sources, it is very easy to include them in the calculations using measured non-sinusoidal current and/or voltage waveforms. For the system serving multiple nonlinear loads, the different type of nonlinear loads may be easily included in calculations by simultaneously considering harmonic currents injected by the nonlinear loads. Although the decoupled approach is not as accurate as the coupled technique, it offers a compromise between computational complexity and result accuracy.

A. *Decoupled Approach for Harmonic Power Flow*

At the fundamental frequency, system is modeled using the conventional approach where the admittance of line section between bus i and bus $i+1$ is expressed as follows.

$$y_{i,i+1} = \frac{1}{R_{i,i+1} + jX_{i,i+1}} \tag{1}$$

Where $R_{i,i+1}$ and $X_{i,i+1}$ are the respective resistance and inductance of line section between bus i and $i+1$. The magnitude and phase angle of bus voltage is then calculated using the following mismatch equations [8-10].

$$P_i - \sum_{j=i-1}^{i+1} \left|Y^1_{ji}\right|\left|V^1_j\right|\left|V^1_i\right|\cos(\delta^1_i - \delta^1_j - \theta^1_{ji}) = 0 \tag{2}$$

$$Q_i - \sum_{j=i-1}^{i+1} \left|Y^1_{ji}\right|\left|V^1_j\right|\left|V^1_i\right|\sin(\delta^1_i - \delta^1_j - \theta^1_{ji}) = 0 \tag{3}$$

Where

$$Y^1_{ji} = \left|Y^1_{ji}\right|\angle\theta^1_{ji} = \begin{cases} -y^1_{ji}, & \text{if } j \neq i \\ y^1_{i-1,i} + y^1_{i+1,i} + y^1_{ci}, & \text{if } j = i \end{cases} \tag{4}$$

V^1_i and y^1_{ci} are the respective fundamental voltage and admittance of shunt capacitor at bus i, while P_i and Q_i are the respective total (linear and nonlinear) active and reactive powers at bus i. Power loss in the line section between bus i and $i+1$ may be calculated by the following equation.

$$P^1_{loss(i,i+1)} = R_{i,i+1}\left(\left|V^1_{i,i+1} - V^1_i\right|\left|y^1_{i,i+1}\right|\right)^2 \tag{5}$$

At harmonic frequencies, power system is modeled as combination of passive elements and current sources [8]. The system can then be considered as a passive element with multiple harmonic injection currents. The generalized model is suggested for a linear load, which is composed by a resistance in parallel with an inductance to account for the respective active and reactive loads at fundamental frequency. Nonlinear loads, in general, are considered as ideal harmonic current sources that generate harmonic currents and inject them into the system [11]. The admittance-matrix-based harmonic power flow is the most widely used method as it is based on the frequency-scan process [12]. In this approach, admittance of system components will vary with the harmonic order. If skin effect is ignored at higher frequencies, the resulting h^{th} harmonic frequency load admittance, shunt capacitor admittance and feeder admittance are respectively given by the following equations [8-10, 13-16].

$$y^h_{li} = \frac{P_{li}}{\left|V^1_i\right|^2} - j\frac{Q_{li}}{h\left|V^1_i\right|^2} \tag{6}$$

$$y^h_{ci} = hy^1_{ci} \tag{7}$$

$$y^h_{i,i+1} = \frac{1}{R_{i,i+1} + jhX_{i,i+1}} \tag{8}$$

Where P_{li} and Q_{li} are the respective active and reactive linear loads at bus i. The nonlinear load is treated as harmonic current sources and the h^{th} harmonic current injected at bus i introduced by the nonlinear load with real power P_n and reactive power Q_n is derived as follows:

$$I^1_i = [(P_{ni} + jQ_{ni})/V^1_i]^* \tag{9}$$

$$I^h_i = C(h)I^1_i \tag{10}$$

Where I^1_i is the fundamental current and I^h_i is the h^{th} harmonic current determined by *C(h)*, which is the ratio of the h^{th} harmonic to the fundamental current. *C(h)* can be obtained by field test and Fourier analysis for all customers along the distribution feeder [8, 10, 16].

For decoupled harmonic power flow calculation, loop equations are written at each harmonic frequency of interest. Each loop is formed including the source nodes. After modifying admittance matrix and the associated harmonic currents, the harmonic load flow problem can then be calculated using the following equation [12, 15, 16].

$$Y^h V^h = I^h \tag{11}$$

At any bus i, the rms voltage is defined as:

$$|V_i| = \left(\sum_{h=1}^{H} \left|V_i^h\right|^2 \right)^{1/2} \tag{12}$$

Where H is the maximum harmonic orders considered. After solving load flow for different harmonic orders, the distortion of voltage indicated by total harmonic distortion at bus i (THD_{vi}) is expressed by the following equation.

$$THD_{vi}(\%) = \left[\frac{\left(\sum_{n \neq 1}^{H} \left|V_i^h\right|^2 \right)^{1/2}}{\left|V_i^1\right|} \right] \times 100\% \tag{13}$$

At the h^{th} harmonic frequency, real power loss in the line section between buses i and $i+1$ is expressed below [9, 10, 16].

$$P_{loss(i,i+1)}^h = R_{i,i+1}\left(\left|V_{i,i+1}^h - V_i^h\right| \left|y_{i,i+1}^h\right| \right)^2 \tag{14}$$

The total power loss including the loss at fundamental frequency is given by the following equation.

$$P_{loss}^h = \sum_{h=1}^{H} \left(\sum_{i=1}^{m} P_{loss(i,i+1)}^h \right) \tag{15}$$

Where m is number of bus. The computation procedure of the proposed approach is given by Fig. 1.

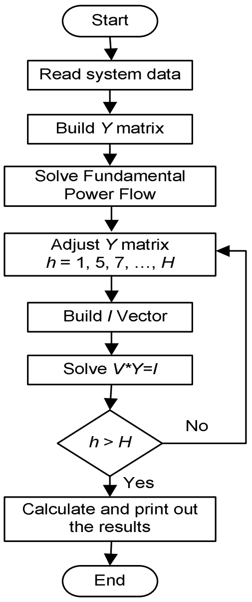

Fig. 1. Decoupled Harmonic Power Flow Calculation

III. RESULT AND DISCUSSION

A. Results

For verification purpose, the decoupled approach is initially implemented for the IEEE 18-bus distorted system [3] of Fig. 2 considering only one nonlinear load (six-pulse 1, 3 MW, 2.26 MVAR) installed at bus 5. The nonlinear is modeled as current sources with harmonic contents listed in Appendix. The generated results are then compared with those generated by standard packages (HARMFLOW [1] and ETAP [2]). The simulation is coded using MATLAB version 7.0.1 R14 and is run in a desktop PC with Pentium 4 Intel 3.0 GHz processor and 512 MB RAM.

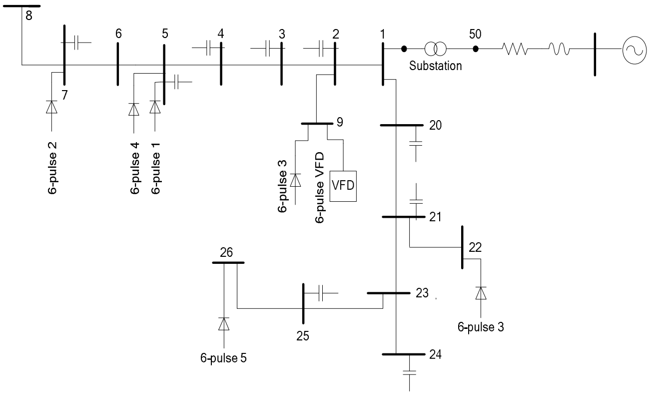

Fig. 2. The simulated IEEE 18-bus distorted distribution system [3]

The comparisons of the results generated by decoupled approach with those generated by the HARMFLOW and ETAP are separately performed due to the harmonic orders considered in HARMFLOW are different with those considered in ETAP. The comparisons with HARMFLOW are indicated in Fig. 3 (rms Voltage) and Fig. 4 (THD) while the comparisons with ETAP are shown in Fig. 5 (rms Voltage) and Fig. 6 (THD), respectively. As predicted, there are some slight differences at some buses due to the neglected harmonic couplings in DHPF. The comparisons are summarized in Table 1 demonstrating the fine accuracy of the implemented approach.

TABLE 1
AVERAGE DEVIATION OF THE RESULTS GENERATED BY DECOUPLED APPROACH AND HARMFLOW [1] AND ETAP [2]

Results	Average deviation (%) with	
	HARMFOW	ETAP
Vfund	0.005870	0.002134
Vrms	0.027797	0.026716
THDv	0.572418	0.499733

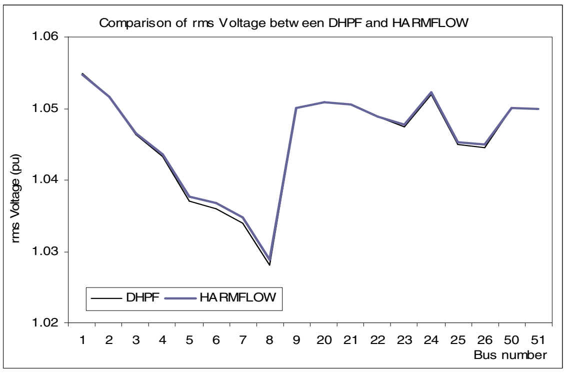

Fig. 3. rms Voltage comparison between DHPF and HARMFLOW

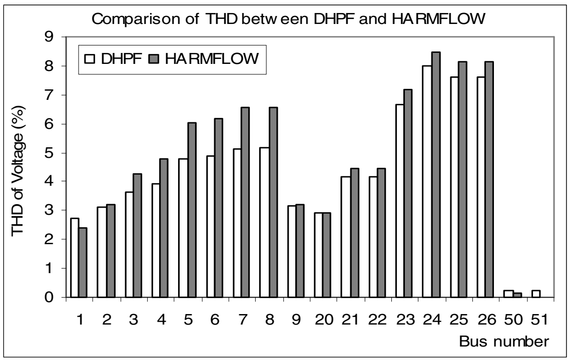

Fig. 4. THD comparison between DHPF and HARMFLOW

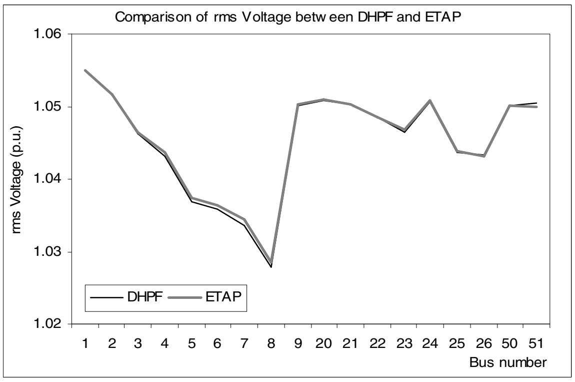

Fig. 5. rms Voltage comparison between DHPF and ETAP

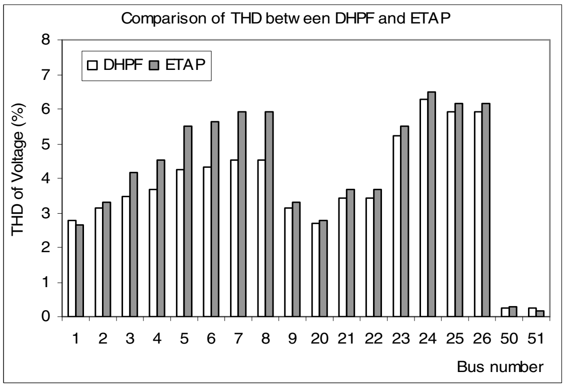

Fig. 6. THD comparison between DHPF and ETAP

The implementation of decoupled approach is extended for IEEE 18-bus system of Fig. 2 considering all installed nonlinear loads. The nonlinear loads are indicated in Table 2 and their harmonic contents are given in Appendix. Computationally, the voltage calculations at harmonic frequencies are carried out by initially forming vector of injection currents and finding the harmonic voltages by solving Eq. (11). The generated results including fundamental and rms voltages for the simulated system are given in Fig. 7 illustrating the increment of voltage caused by harmonic injection currents. The THD of voltage is shown in Fig. 8 showing the spreading of harmonic distortion among of buses due to the distributed nonlinear loads.

TABLE II

NONLINEAR LOADS USED IN IEEE 18-BUS SYSTEM

Nonlinear Load		Power	
Bus	Name	MW	MVAR
5	six-pulse 1	1.20	0.75
5	six-pulse 4	0.75	0.50
7	six-pulse 2	1.00	0.60
9	six-pulse VFD	1.50	0.75
9	Six-pulse 3	1.50	0.75
22	six-pulse 3	0.80	0.50
26	six-pulse 5	1.00	0.60

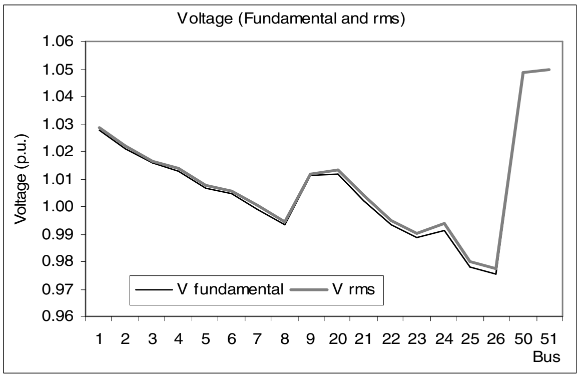

Fig. 7. rms Voltage of the distorted IEEE 18-bus system with multiple nonlinear loads generated by DHPF

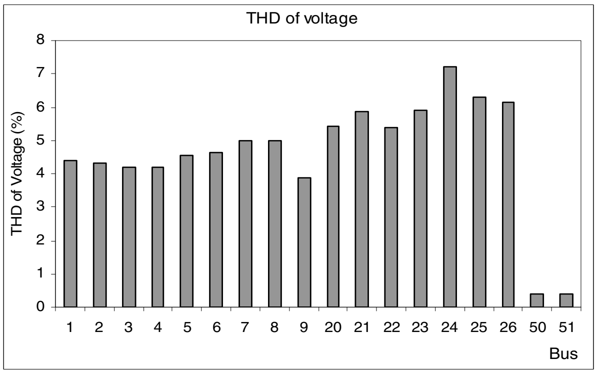

Fig. 8. THD of voltage of the distorted IEEE 18-bus system with multiple nonlinear loads generated by DHPF

To exhibit the ability of decoupled approach for handling large distorted system, the approach is now implemented for IEEE 123-bus distribution system [17]. The simulated system including 12 nonlinear loads is shown in Fig. 9. The installed nonlinear loads data are given in Table 3 and their harmonic contents are indicated in Appendix. The generated results including fundamental and rms voltages as well as THD of voltage are respectively shown in Fig. 10 and Fig. 11.

Successful application of DHPF for the IEEE 123-bus with multiple nonlinear loads confirms the ability of the approach simulating large distorted system without any convergence problem. The approach is also able accommodating multiple nonlinear loads necessary for practical calculation.

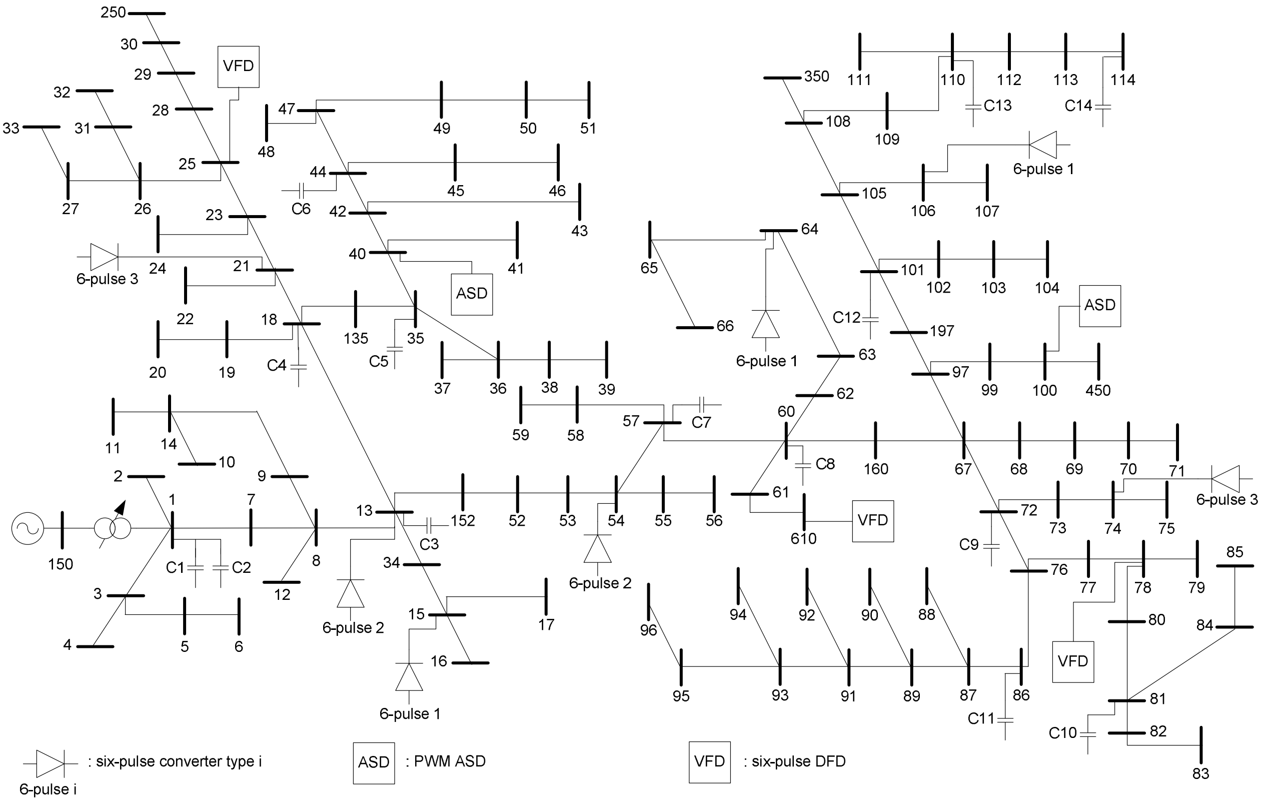

Fig. 9. The IEEE 123-bus distorted distribution system used for simulation

TABLE III
NONLINEAR LOADS USED IN IEEE 123-BUS SYSTEM

Nonlinear Load		Power	
Bus	Name	MW	MVAR
13	Six-pulse2	0.0247	0.0176
15	Six-pulse1	0.0315	0.0196
21	Six-pulse4	0.0383	0.0264
25	six-pulse VFD	0.0354	0.0179
40	PWM-ASD	0.0474	0.0293
54	Six-pulse2	0.0382	0.0151
64	Six-pulse1	0.0213	0.0093
74	Six-pulse4	0.0257	0.0172
78	six-pulse VFD	0.0384	0.0142
100	PWM-ASD	0.0247	0.0184
106	Six-pulse1	0.0192	0.0094
610	six-pulse VFD	0.0385	0.0195

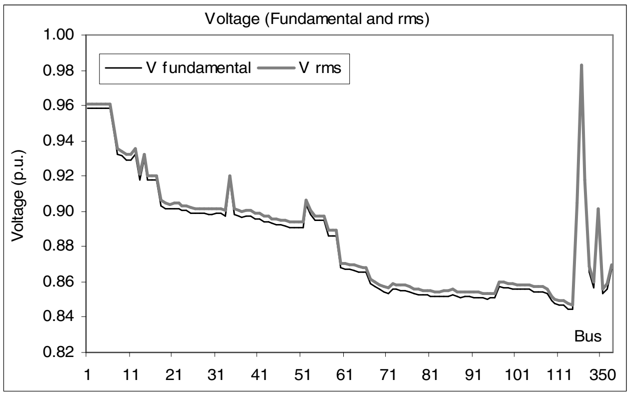

Fig. 10. rms Voltage of the distorted IEEE 123-bus system with multiple nonlinear loads generated by DHPF

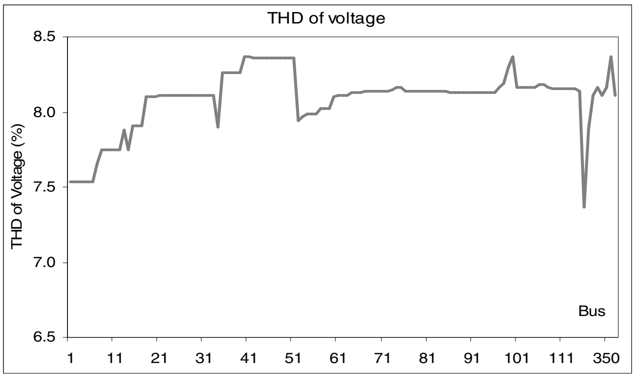

Fig. 11. THD of voltage of the distorted IEEE 123-bus system with multiple nonlinear loads generated by DHPF

B. Discussion

In decoupled approach, harmonic voltage calculations are separately performed for every harmonic order. This approach is therefore simple and can be used to simulate large systems without convergence difficulties. Most harmonic power flow algorithms are not capable for simulating large systems (e.g., with hundreds of buses). Representation of nonlinear load as current source leads to extensive applications as the approach accepts the nonlinear load data obtained from measurements. Coupled approaches require exact models of nonlinear loads that are not always available. Furthermore, DHPF has less computational burden resulting in less computation time. Furthermore, DHPF has less computational burden resulting in less computation time.

IV. CONCLUSION

Harmonic power flow calculations for distorted systems serving multiple nonlinear loads are carried out using decoupled approach. Main conclusions are:

- Decoupled approach offers compromise between results accuracy and calculations complexity.
- The approach is capable of simulating large system serving multiple nonlinear loads with different *v*-*i* characteristics.
- Modeling of nonlinear loads as current sources lead to extensive application as it accepts real measurement data.

V. APPENDIX

Harmonic contents of nonlinear loads used in this paper are given in Table A.1.

TABLE A.1
HARMONIC CONTENTS OF NONLINEAR LOADS USED IN THIS PAPER

order	Nonlinear Loads							
	Six-pulse1		Six-pulse2		Six-pulse3		Six-pulse 4	
	mag	deg	mag	deg	mag	deg	mag	deg
1	100	0	100	0	100	0	100	0
5	20	0	19.1	0	20	0	42	0
7	14.3	0	13.1	0	14.3	0	14.3	0
11	9.1	0	7.2	0	9.1	0	7.9	0
13	7.7	0	5.6	0	0	0	3.2	0
17	5.9	0	3.3	0	0	0	3.7	0
19	5.3	0	2.4	0	0	0	2.3	0
23	4.3	0	1.2	0	0	0	2.3	0
25	4	0	0.8	0	0	0	1.4	0
29	3.4	0	0.2	0	0	0	0	0
31	3.2	0	0.2	0	0	0	0	0
35	2.8	0	0.4	0	0	0	0	0
37	2.7	0	0.5	0	0	0	0	0
41	2.4	0	0.5	0	0	0	0	0
43	2.3	0	0.5	0	0	0	0	0
47	2.1	0	0.4	0	0	0	0	0
49	2	0	0.4	0	0	0	0	0

TABLE A.1 (CONTINUED)
HARMONIC CONTENTS OF NONLINEAR LOADS USED IN THIS PAPER

order	Nonlinear Loads					
	six-pulse 5		six-pulse VFD		PWM-ASD	
	mag	deg	mag	deg	mag	deg
1	100	0	100	0	100	0
5	28	0	23.52	111	82.8	-135
7	9	0	6.08	109	77.5	69
11	9	0	4.57	-158	46.3	-62
13	6	0	4.2	-178	41.2	139
17	5	0	1.8	-94	14.2	9
19	4	0	1.37	-92	9.7	-155
23	3	0	0.75	-70	1.5	-158
25	3	0	0.56	-70	2.5	98
29	0	0	0.49	-20	0	0
31	0	0	0.54	7	0	0

Note:
mag: Magnitude of harmonic currents with respect to its fundamental value (%)
deg: Angle of harmonic currents.

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