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Daftar Isi

APPLICATION OF DECOUPLE APPROACH FOR HARMONIC POWER FLOW CALCULATION

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ABSTRACT

Power flow calculation is backbone of power system analysis and design. This is normally carried out by simply considering fundamental frequency. Due to the extensive use of nonlinear loads that generate and inject harmonics into power system, harmonic frequencies are present and need to be also considered. Unfortunately, unavoidable complexity and heavy computation burden are often encountered by involving the nonlinear loads into the already complicated power flow calculation. This paper proposes a decouple approach to overcome the problem. This assumes that the couplings between harmonics can be rationally disregarded and as a result, the calculations can be separately performed for every harmonic order. This will greatly reduce the level of complexity and computation charge. To verify the accuracy of the proposed decoupled harmonic power flow (DHPF) algorithm, the simulation results are compared with those generated by standard packages (e.g., HARMFLOW and ETAP). The distorted IEEE 18-bus system is used for simulation purposes, while the nonlinear load involved in the system is modeled as harmonic current sources. The comparisons exhibit that the proposed approach offers the compromise between result accuracy and computation complexity.

Keywords: decouple, harmonic power flow, nonlinear load and power quality

INTRODUCTION

Power flow calculation is backbone of power system analysis and design. It generates the results that are normally required for further calculations of analysis and design. This 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. The calculation can be carried out by solving the following equation.

$$I_{bus} = Y_{bus} V_{bus} \tag{1}$$

Where I_{bus} and V_{bus} are vectors of bus injection current and bus voltage, respectively, while Y_{bus} is bus admittance matrix. 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 simple considering fundamental frequency. The extensive and ever increasing application of nonlinear loads such as power electronic devices result in 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 need to be included in the calculations to predict their effects and to avoid possible severe damages. However, taking harmonics into account will lead the calculations become very complicated.

This paper presents a decouple approach for harmonic power flow calculation. This is aimed to include harmonics with a reasonable computation cost. To show the accuracy of the implemented decoupled harmonic power flow (DHPF) algorithm, simulation results for the distorted IEEE 18-bus distribution system are compared with those generated by HARMFLOW and ETAP. It is shown that the decoupled approach offers the compromise between result accuracy and computation complexity.

HARMONIC POWER FLOW

Harmonic power flow was initially introduced by Xia and Heydt (Xia and Heydt, 1982) 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 loads. Harmonic power flow, on the other hand, is more general in that loads may be the "source" of harmonic energy (Semlyen and Shlash, 2000). The ultimate source is system generator system , but harmonic distortion that occurs at bus containing nonlinear load may be considered as a source of harmonic signal. In addition to some results normally generated by power flow, harmonic power flow also generates the other results that can be used to quantify voltage distortion and to determine whether dangerous resonant problem exists.

The nature of the harmonics (e.g., orders, magnitudes and phases) strongly depends on the nonlinear load involved. Therefore, nonlinear load modeling has become an essential part of harmonic power flow calculation. Nonlinear loads can be modeled in time and/or frequency domain (Moreno Lopez de Saa and Usaola Garcia, 2003). 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. Domain modeling requires time detailed representation of the device that increases the problem complexity result 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 (Hong, et al., 2000).

Harmonic power flow calculations can generally be classified into couple and decouple methods. Couple approach solves simultaneously the calculation for all of the harmonic orders. 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 (Williams, et al., 1993). On the other hand, decouple 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. Furthermore, since nonlinear loads are modeled with harmonic current or voltage sources, it is very easy to include them in the calculations using the measurement non-sinusoidal current and/or voltage waveforms.

Decouple Approach for Harmonic Power Flow

At the fundamental frequency, system is modeled where the admittance of line section between bus *i* and bus *i*+1 is expressed by the following equation.

$$y_{i,i+1} = \frac{1}{R_{i,i+1} + jX_{i,i+1}} \qquad (2)$$

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 (Baghzouz and S. Ertem, 1990; Chin, 1995; Y. Baghzouz, 1991).

$$P_i - \sum_{j=i-1}^{i+1} |Y_{ji}^1||V_j^1||V_i^1| \cos(\delta_i^1 - \delta_j^1 - \theta_{ji}^1) = 0 \qquad (3)$$

$$Q_i - \sum_{j=i-1}^{i+1} |Y_{ji}^1||V_j^1||V_i^1| \sin(\delta_i^1 - \delta_j^1 - \theta_{ji}^1) = 0 \qquad (4)$$

Where

$$Y_{ji}^1 = |Y_{ji}^1| \angle \theta_{ji}^1 = \begin{cases} -y_{ji}^1, & \text{if } j \neq i \\ y_{i-1,i}^1 + y_{i+1,i}^1 + y_{ci}^1, & \text{if } j = i \end{cases} \qquad (5)$$

V_i^1 and y_{ci}^1 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 power at bus *i*. The power loss in the line section between buses *i* and *i+1* may then be calculated by the following equation.

$$P_{loss(i,i+1)}^1 = R_{i,i+1}\left(|V_{i,i+1}^1 - V_i^1||y_{i,i+1}^1|\right)^2 \qquad (6)$$

At harmonic frequencies, power system is modeled as combination of passive elements and current source (Chin, 1995). 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 (Yu, et al., 2004). The admittance-matrix-based harmonic power flow is the widest used method as it is based on the frequency-scan process (Teng and Chang, 2003). In this approach, admittance of system components will vary with the harmonic order. If skin effect is ignored at higher frequencies, the resulting n^{th} harmonic frequency load admittance, shunt capacitor admittance and feeder admittance are respectively given by the following equations (Baghzouz and S. Ertem, 1990; Chin, 1995; Chung and Leung, 1999; Ghose and Goswami, 2003; Masoum, et al., 2004a; Masoum, et al., 2004b; Y. Baghzouz, 1991).

$$y_{li}^n = \frac{P_{li}}{|V_i^1|^2} - j\frac{Q_{li}}{n|V_i^1|^2} \qquad (7)$$

$$y_{ci}^n = n y_{ci}^n \qquad (8)$$

$$y_{i,i+1}^n = \frac{1}{R_{i,i+1} + jnX_{i,i+1}} \qquad (9)$$

Where P_{li} and Q_{li} are the respective active and reactive linear loads at bus *i*. The n^{th} harmonic current injected at bus *i* introduced by the nonlinear load is derived as follows:

$$I_i^1 = [(P_{ni} + jQ_{ni}) / V_i^1]^* \qquad (10)$$

$$I_i^n = C(n) I_i^1 \qquad (11)$$

Where I_i^1 is the fundamental current and I_i^n is the n^{th} harmonic current determined by *C(n)*, which is the ratio of the n^{th} harmonic to the fundamental current. *C(n)* can be obtained by field test and Fourier analysis for all customers along the distribution feeder (Chin, 1995; Chung and Leung, 1999; Y. Baghzouz, 1991).

For decouple 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 current, the harmonic load flow problem can then be calculated by the following equation (Chung and Leung, 1999; Ghose and Goswami, 2003; Teng and Chang, 2003).

$$\mathbf{Y}^n \boldsymbol{V}^n = \boldsymbol{I}^n \qquad (12)$$

At any bus *i*, the rms voltage is defined by:

$$|V_i| = \left(\sum_{n=1}^{N} |V_i^n|^2 \right)^{1/2} \qquad (13)$$

Where *N* is the maximum harmonic order considered. The total harmonic distortion at bus *i* (THD$_{vi}$) is expressed by the following equation.

$$THD_{vi}(\%) = \left[\frac{\left(\sum_{n \neq 1}^{N} |V_i^n|^2 \right)^{1/2}}{|V_i^1|} \right] \times 100\% \qquad (14)$$

At the n^{th} harmonic frequency, real power loss in the line section between bus *i* and *i*+1 is expressed below (Baghzouz and S. Ertem, 1990; Chung and Leung, 1999; Y. Baghzouz, 1991).

$$P^n_{loss(i,i+1)} = R_{i,i+1} \left(|V^n_{i,i+1} - V^n_i| \, |y^n_{i,i+1}| \right)^2 \qquad (15)$$

The total power loss of the system for all harmonics is therefore given by the following equation.

$$P^n_{loss} = \sum_{n=1}^{N} \left(\sum_{i=0}^{m-1} P^n_{loss(i,i+1)} \right) \qquad (16)$$

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

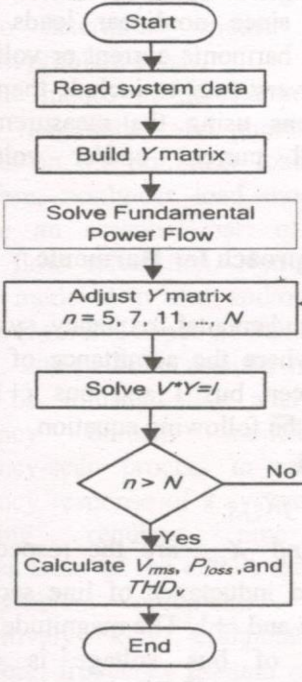

Figure 1. Decouple Harmonic Power Flow Calculation

RESULT AND DISCUSSION

The IEEE 18-bus distorted distribution system (Grady, et al., 1992) as shown in Figure 2 is simulated using the proposed decoupled harmonic power flow (DHPF). This system includes a 3 MW 6-pulse converter as nonlinear load, which is modeled as current sources. The non-sinusoidal current waveform injected by this nonlinear load is shown in Figure 3 and its harmonic contents are presented in the Appendix. The proposed approach 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.

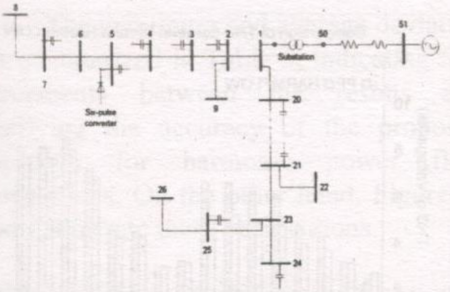

Figure 2. The simulated IEEE 18-bus distorted distribution system

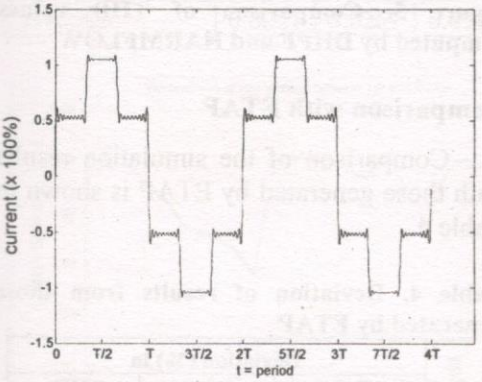

Figure 3. The non-sinusoidal current waveform of nonlinear load used in this paper

The generated results of the proposed DHPF including fundamental voltage (V_{fund}), rms voltage (Vrms), and THD of voltage (THDv) are shown in Table 1. For verification of accuracy, these results are compared with those generated by standard software packages (HARMFLOW and ETAP). The main reason of the comparison is to demonstrate its accuracy.

Table 1. Simulation results of the Harmonic Power Flow

Bus	Vfund (p.u.)	Vrms (p.u.)	THDv (%)
1	1.0545	1.0550	2.79
2	1.0511	1.0516	3.13
3	1.0456	1.0462	3.49
4	1.0425	1.0432	3.67
5	1.0359	1.0368	4.23
6	1.0348	1.0358	4.31
7	1.0326	1.0336	4.52
8	1.0268	1.0278	4.52
9	1.0496	1.0501	3.13
20	1.0505	1.0508	2.69
21	1.0496	1.0502	3.44
22	1.0479	1.0485	3.44
23	1.0451	1.0465	5.22
24	1.0485	1.0506	6.30
25	1.0419	1.0437	5.93
26	1.0415	1.0433	5.93
50	1.0501	1.0501	0.26
51	1.0500	1.0504	0.26

Comparison with HARMFLOW

The deviations of results generated by the proposed DHPF from those generated by HARMFLOW are indicated in Table 2. The maximum and average deviation is also provided in Table 3. In addition, figures 4 and 5 respectively illustrate the deviation of Vrms and THDv. Tables 2-3 and Figures 4-5 indicate that, in general, the results generated by the proposed approach are fairly close to the results generated by HARMFLOW. As expected, there are some slight differences at some buses due to the neglected harmonic coupling by the proposed DHPF. As the THD values are calculated in percentages of the fundamental voltage, their deviations values are relatively large.

Table 2. Deviation of results from those generated by HARMFLOW

Bus	Deviation (%) of		
	V_{fund}	V_{rms}	THDv
1	0.0000	0.0095	0.33308
2	0.0095	0.0000	0.05890
3	0.0096	0.0191	0.60019
4	0.0096	0.0288	0.83510
5	0.0097	0.0675	1.28137
6	0.0097	0.0676	1.31939
7	0.0097	0.0774	1.41657
8	0.0097	0.0778	1.42473
9	0.0000	0.0000	0.05879
20	0.0095	0.0000	0.00808
21	0.0095	0.0095	0.28274
22	0.0000	0.0095	0.28347
23	0.0000	0.0286	0.49441
24	0.0000	0.0380	0.49794
25	0.0096	0.0287	0.51851
26	0.0096	0.0383	0.51908
50	0.0000	0.0000	0.12646
51	0.0000	0.0000	0.24472

Table 3. The Maximum and Average Deviations of Table 2

Deviation (%)	V_{fund}	V_{rms}	THDv
Maximun	0.0097	0.0778	1.42473
Average	0.0059	0.0278	0.57242

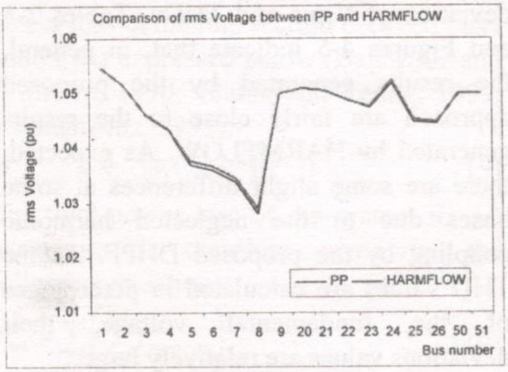

Figure 4. Comparison of Vrms values computed by DHPF and HARMFLOW

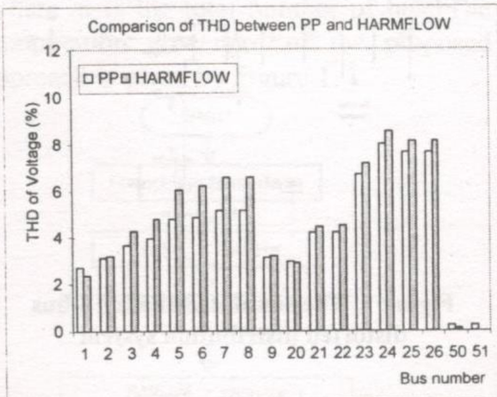

Figure 5. Comparison of THD values computed by DHPF and HARMFLOW

Comparison with ETAP

Comparison of the simulation results with those generated by ETAP is shown in Table 4.

Table 4. Deviation of results from those generated by ETAP

Bus	Deviation (%) in		
	Vfund	Vrms	THDv
1	0.0000	0.0095	0.12390
2	0.0000	0.0095	0.18930
3	0.0000	0.0287	0.66160
4	0.0000	0.0383	0.87260
5	0.0000	0.0579	1.30290
6	0.0000	0.0579	1.32050
7	0.0000	0.0774	1.37540
8	0.0000	0.0681	1.37600
9	0.0000	0.0095	0.18930
20	0.0000	0.0095	0.09630
21	0.0000	0.0095	0.24390
22	0.0000	0.0095	0.24350
23	0.0000	0.0191	0.26580
24	0.0000	0.0095	0.18060
25	0.0000	0.0096	0.21690
26	0.0384	0.0192	0.21670
50	0.0000	0.0000	0.04480
51	0.0000	0.0381	0.07520

The maximum and average deviation are summarized in Table 5, indicating fine agreements between the results and justifying the accuracy of the proposed approach for harmonic power flow calculations. On the other hand, Figures 6 and 7 illustrate these verifications.

Table 5. The Maximum and Average Deviations of Table 4

Deviation (%)	Vfund	Vrms	THDv
Maximum	0.0384	0.0774	1.3760
Average	0.0021	0.0267	0.4997

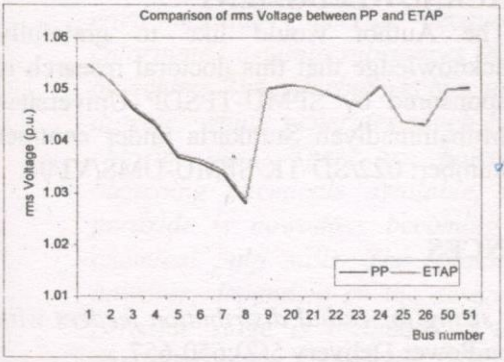

Figure 6. Comparison of Vrms values computed by DHPF and ETAP

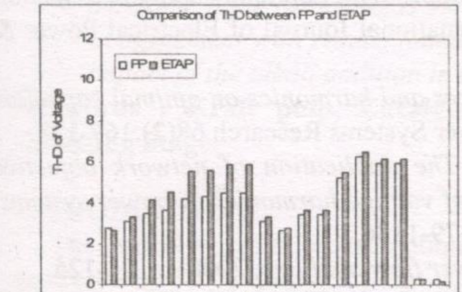

Figure 7. Comparison of THD values computed by DHPF and ETAP

The abovementioned comparisons confirm that the results generated by the decouple approach is fairly accurate. The proposed DHPF has also been employed to simulate an IEEE 9-bus distorted distribution system (Y. Baghzouz, 1991; Yu, et al., 2004) and fairly accurate results were generated.

Efficiency of the proposed DHPF

In the proposed DHPF algorithm, calculations are separately performed for every harmonic order. Therefore, this approach is very simple compared with the couple harmonic power flow algorithm and can be used to simulate large distorted distribution systems without any convergence difficulties. The algorithm was also used to simulate a 300-bus distorted system. Most harmonic power flow algorithms are not capable of simulating large systems (e.g., with hundreds of bus). DHPF is therefore suitable for simulating large distorted distribution systems

The nonlinear load modeling is another advantage of the proposed approach. This approach simply estimates nonlinear loads as harmonic current sources that can be obtained easily from measurements. In contrast, the couple approach requires exact models for nonlinear loads that are not usually available.

Computation time is another aspect that needs to be considered. DHPF has less computation burden and therefore requires less computation time compared with that required by couple harmoncic power flow.

CONCLUSION

The application of decouple approach for harmonic power flow is presented. Comparisons of the generated results with those calculated by standard software packages are presented and discussed. Main conclusions are:

1. The formulation and nonlinear load modeling of the decouple approach leads the calculation to be simple.
2. From the comparisons, the decouple approach offers a compromise between the result accuracy and calculation complexity.
3. The decouple approach can be extensively applied due to its simple nonlinear load modeling and is more practical as it can handle large systems.

Appendix: Harmonic Model of 6-pulse Converter

Nonlinear loads are modeled as decoupled harmonic current sources. Table A gives the current magnitudes (as percentages of the fundamental current) used to model 6-pulse converter loads. Harmonic phase angles are assumed to be zero.

Table A. Magnitude (%) of harmonic currents for 6-pulse converter

Order	Mag.	Order	Mag.	Order	Mag.
1	100	19	5.3	37	2.7
5	20	23	4.3	41	2.4
7	14.3	25	4	43	2.3
11	9.1	29	3.4	47	2.1
13	7.7	31	3.2	49	2
17	5.9	35	2.8		

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REFERENCES

Baghzouz Y, S. Ertem. 1990. *Shunt capacitor sizing for radial distribution feeders with distorted substation voltage*. IEEE Trans. on Power Delivery 5(2):650-657.

Chin H-C. 1995. *Optimal shunt capacitor allocation by fuzzy dynamic programming. Electric Power Systems Research* 35(2):133-139.

Chung TS, Leung HC. 1999. *A genetic algorithm approach in optimal capacitor selection with harmonic distortion considerations*. International Journal of Electrical Power & Energy Systems 21(8):561-569.

Ghose T, Goswami SK. 2003. *Effects of unbalances and harmonics on optimal capacitor placement in distribution system*. Electric Power Systems Research 68(2):167-173.

Grady WM, Samotyj MJ, Noyola AH. 1992. *The application of network objective functions for actively minimizing the impact of voltage harmonics in power systems*. IEEE Transactions on Power Delivery 7(3):1379-1386.

Hong Y-Y, Lin J-S, Liu C-H. *Fuzzy harmonic power flow analyses*; 2000. p 121-125.

Masoum MAS, Jafarian A, Ladjevardi M, Fuchs EF, Grady WM. 2004a. *Fuzzy approach for optimal placement and sizing of capacitor banks in the presence of harmonics*. IEEE Transactions on Power Delivery 19(2):822 - 829.

Masoum MAS, Ladjevardi M, Jafarian A, Fuchs EF. 2004b. *Optimal Placement, Replacement and Sizing of Capacitor Banks in Distorted Distribution Networks by Genetic Algorithms*. IEEE Transactions on Power Delivery 19(4):1794-1801.