Analysis of the unbalanced harmonic propagation in a three-phase power system using a parallel program

S Yunus¹, U G S Dinata², R Nazir², Aulia¹

¹Electrical Engineering Department, Universitas Andalas, Pauh, Padang, 25163, Indonesia
²Mechanical Engineering Department, Universitas Andalas, Pauh, Padang, 25163, Indonesia

E-mail: syukriyunus@eng.unand.ac.id

Abstract. Operation of non-linear in an unbalance condition can cause harmonic problems in the power system. There are two parts in the use of computing time in harmonic load flow, the first in the construction of harmonic admittance matrix and the second is the iteration scheme for solving systems of linear equations. The solution technique of the harmonic admittance was developed as a parallel application, and a direct algorithm to calculate the admittance matrix elements. The three-phase power flow program is divided into three independent subproblems, namely: positive, negative, and zero sequence network. Positive sequence network had been solved by using the Newton Raphson method without modifying their formulation. Negative and zero sequence networks had been solved using nodal voltage equation. All three sequence networks have been modeled by three independent circuits and solved simultaneously using multi-core processors in parallel programming. The results showed that the parallel three-phase load flow speed is higher than the sequential.

1. Introduction

The purpose of the harmonic study is to measure the distortion in voltage and current. The study of harmonics can also determine the presence of hazardous resonance conditions and checking for compliance with harmonic limits. Harmonic study needs may be indicated by excessive waveforms at various points in the power system. The results are useful for evaluating the improvement distortion measured on existing systems or with the installation of equipment producing harmonics [1].

Analysis of harmonic caused by non-linear equipment is increasing with the growing electronic equipment and computers that used for controlling and monitoring the electricity [2]. These instrumentations contribute the harmonics and spread in the greater part of the buses distribution system. This nonlinear device is a producer of harmonic waves will cause propagation of voltage and the current waveform. The harmonic that passes through the system will lead to the addition of losses in the distribution system even damaged the equipment due to the overload generated [3] and shorten the equipment live in its services.

The procedure for analyzing the harmonic problems can be classified into two methods: the method and time domain frequency domain. Therefore, an interest in the study of harmonic power flow has grown which was originally developed by network analysis which is stable in conditions that expects a
balanced three-phase voltage at the load terminals to be symmetrical. However, harmonic analysis requires more tools to obtain accurate and sensitive harmonic impact on the power system. A three-phase power flow program related to the unbalanced power system is a solution to this problem, on its ability to consider the asymmetry that is usually ignored by conventional procedures load balanced harmonious flow [4]. Penetration harmonic is the earliest and most simple method that assumes no influence between the networks voltage and non-linear devices. Then this method iteratively modified before penetration harmonics influence on the behavior of non-linear devices can be considered.

2. Methodology

Power flow calculation method based on a symmetrical three-phase component has been developed for the completion of taleral multiphase using the virtual node approach and virtual lines. Therefore, the method based on symmetrical components selected in this study[7][8].

2.1 Decoupled model sequence asymmetrical lines

Series resistance and inductance of the three Phase transmission path between nodes are lumped in the middle. Shunt capacitance of the transmission line is divided into two parts and equalized in the node connected to the line terminal. Series line and shunt impedance matrix entry given the right by:

$$Z_{abc}^{ij} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix} \quad Y_{abc}^{ij} = \begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix}$$

Channel series impedance and shunt impedance matrix of the three-phase line is given by (1) converted in the form of their partners in order components. The resulting series impedance and shunt impedance matrix in order component is given by:

$$Z_{012}^{ij} = \begin{bmatrix} z_{00} & z_{01} & z_{02} \\ z_{10} & z_{11} & z_{12} \\ z_{20} & z_{21} & z_{22} \end{bmatrix} \quad Y_{012}^{ij} = \begin{bmatrix} y_{00} & y_{01} & y_{02} \\ y_{10} & y_{11} & y_{12} \\ y_{20} & y_{21} & y_{22} \end{bmatrix}$$

If a three-phase line is fully transposed, then its impedance and admittance matrices in equation (1) will be symmetrical. Its sequence components will be diagonal matrices. However, if the three-phase line is untransposed, the phase components admittance matrices in (1) will be full and symmetrical but not phase-wise balanced, i.e., therefore, the sequence admittance matrix will be full and unsymmetrical.
The sequence coupled line model can be decomposed into three independent sequence circuit\cite{5}\cite{8}. This can be achieved by replacing the coupling, i.e., the elements of the off-diagonal in (2), by an equivalent current compensation as follows:

$$\Delta I^s = \frac{1}{V^s} (V^s_i - V^s_f) + \frac{1}{V^s} (V^s_f - V^s_i) + y^s \Delta V^s_i + y^s \Delta V^s_f$$

(3)

On figure.1 shows the decomposed line model in sequence components. The coupling among the sequence networks is included by the current compensation calculated using (3). The basis of Newton Raphson's method of solving the power flow is the Taylor series for a function with two more variables. The Newton Raphson method solves the power flow problem by using a set of nonlinear equations to calculate the magnitude of the voltage, as follows:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V^f \end{bmatrix}$$

(4)

Jacobian matrix elements are calculated using the magnitude of the voltage and the phase angle of the initially estimated voltage. Using the direct inverse method, the linear equations can be solved to obtain the values of the magnitude of the voltage and the phase angle of the newly estimated voltage on each bus (except the slack bus), as follows:

$$\begin{bmatrix} \Delta \theta \\ \Delta V^f \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

(5)

2.2. Parallel Process

Parallel processing architecture can be used as multiple internal processors (PC based parallel system) or multiple interconnected computers (multiple computers) environment. Traditionally, programming calculations carried out sequentially (serial computation), execution on one computer occurs in a Central Processing Unit (CPU). By using a multi-core system is upgrading the computer to process a job can be enhanced by the CPU make a parallel in carrying out a simultaneous work with another job. An interface to parallelize application programs in work on more than one CPU that meets a standard for shared memory parallel high programming level is to use OpenMP. OpenMP provides a facility where a simple and flexible interface to parallelize memory in C ++ language program. To use the C ++ OpenMP to parallelize the process so that the memory can be implemented, it begins with the command:

```
#pragma omp
```

This command is followed by a special keyword that identifies the user with one or more of the provisions. This provision will define the action or further control in the implementation of the parallel program. Before a job completed using OpenMP, the first advance is expressed with a statement:
(Void) omp_set_num_threads (NP);

To parallelize a job on the CPU must also be some attention, whether the work is repetitive work (loop) or an independent job, if the job is a recurring job, then use the prefix:

#pragma omp for

Meanwhile, if a job is a job that independent is expressed with a statement:

#pragma omp section

To set up access shared data on a multi-sequence used OpenMP synchronization program, where there is a barrier (barrier) which is one point in the implementation of the program in which a sequence of program wait for one sequence to another. On the OpenMP provide this facility with writing:

#pragma omp barrier

The speedup produced by parallel programming algorithm for parallel multi-core architecture of sequence decoupled three-phase power flow can be calculated using equation (6):

\[
\text{Speedup} = \frac{ET (\text{+sequence}+\text{serial execution}+\text{overhead})}{ET (\text{+,-,0 sequence}+\text{serial execution})}
\]  

Where ET is the execution time, +, - , 0 sequence for the positive, negative and zero sequence is the execution time for each sequence. Overhead is the time spent in the management of parallel computing, including thread creation and scheduling, communication, and synchronization. In the multi-core parallel processing, the overhead is very small compared to some of the interconnected computer parallel system. The amount of speedup performance by using multi-core processors is highly dependent on parallel algorithms and implementation. In particular, the speedup may be limited by the small part of the program code that can be parallelized to run on multiple cores simultaneously. Amdahl's law describes this effect. The maximum speedup will be achieved when all parts of the program code can be in the parallelism near the number of cores. Many typical applications, however, are not aware of such a large speedup.

2.3 Load and Capacitor Bank

Burdens can be a spot burden or expense that are distributed along the channel. They can be connected as a delta or star and can be modeled as constant power (PQ), constant current (I), or a constant impedance (Z) or a combination of these types of expense is modeled by current injection on phase components. Then, the injection of current in phase coordinates converted to partner in order components. Distributed load are modeled using concentrated load models. This model divides the load distributed between channel specific end-use ratio η. This ratio is calculated based on the amount of voltage on the line terminal node. It is possible to consider the ratio η becomes 0, 5. In this paper, the η ratio is calculated per iteration during the power-flow solution. Application of sequence components effectively reduces the magnitude of the problem of three-phase power-flow. Also, the order of rotting tissue, positive sequence, negative sequence, and zero sequences can also be solved by using parallel processing. Power flow sequence is utilizing a balanced formulation of the established three-phase power-flow method for solving positive sequence network. Decomposition is based on symmetrical components allow integration of power study many systems such as balanced and unbalanced three-phase electric current and-error calculations in a single tool. Three phase power flow
program based on symmetrical components developed in the independent [5] consists of three sub-problems associated with the network of positive, negative, and zero-sequence as in figure 2.

The solution of both the negative- and zero-sequence networks can be expressed by ordinary nodal voltage equations as follows, using matrix notation:

\[ V_2 = I_2 \times \text{specified} \]  
\[ V_0 = I_0 \times \text{specified} \]  

After solving the sequence networks, phase voltage for the base can be calculated. The process is repeated until the convergence criterion reached. In the program phase voltages mismatch, positive sequence voltage mismatch and the positive sequence power mismatch can be used as convergence criterion.

The total current harmonic changes can be obtained by the following equation:

\[ I_{\text{har}} = \sqrt{I_{\text{fund}}^2 + I_{\text{har}}^2} \]  
\[ I_{\text{total}} = \frac{I_{\text{fund}}}{100} \]  

The total of rms current:

\[ I_{\text{rms}} = \sqrt{I_{\text{fund}}^2 + I_{\text{har}}^2} \]  

or

\[ I_{\text{rms}} = \frac{I_{\text{fund}}}{\sqrt{1 + I_{\text{har}}^2}} \]  

The fundamental current (in fundamental frequency)

\[ I_{\text{fund}} = \frac{I_{\text{rms}}}{\sqrt{1 - I_{\text{har}}^2}} \]  

Total change in fundamental current

\[ I_{\text{fund}(\text{fund})} = \frac{(I_{\text{rms}})^2}{I_{\text{fund}}} - 1 \]  

Total demand Distortion (TDD) =

\[ I_{\text{fund}} = \frac{\sqrt{\sum I_i^2}}{I_{\text{fund}}} = I_{\text{TDD}} = \frac{\sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots \cdot I_n^2}}{I_{\text{fund}}} \]
3. Methodology

The purpose of this study is more concerned about the development of solution-harmonic electric current. The results presented here will discuss the issue of reuse (reuse). Also, a numerical example of the completion of the 45-bus system is not balanced [12] is given when the nonlinear device is on the network.

3.1. Benchmark of Reuse (Reuse)

The result presented here will discuss the issue of reuse (reuse). Also, a numerical example of the completion of the 45 –bus system is not balanced [12] is given when the nonlinear device is on the network. The size of the class and the re-use of components are summarized in Table 1.

| Reuse                      | Composition | Inheritance | Scratch | % Reuse     |
|----------------------------|-------------|-------------|---------|-------------|
| Power system Model (classes) | 2           | 6           | -       | Composition 25% |
|                           |             |             |         | Inherited 75%  |
| Solution Algorithm (component) | 4           | -           | 1       | Composition 80% |
|                           |             |             |         | Inherited 20%  |

First, the model of the electrical system that represents the actual device from the power grid, there are 6 classes which are a derivative form of basic power system libraries where there are two classes reused by composition. In connection with the solution algorithm, there are four components are reused. They are two components to the flow of power is not balanced, one component of the admittance matrix, and a linear component to the settlement. In addition to high reusability, components must be reused without knowing the algorithms that are packed in it.

Harmonic power flow analysis using the CBD application has been tested by using 45 buses, to obtain or calculate the harmonic voltage deviation on all buses are as follows:

Case 1: Harmonic voltage for connection of wind power.
Case 2: Harmonic voltage due to unbalanced load demand.

In the first case, there is a wind power which is connected to the 45-bus test systems where Converters Six Pulse no.ID connected on the bus: 32, 41 and 45 on the 45 bus, with 50% of a total bus connected to the load, the result there are irregularities pointed it towards total harmonic voltage at all buses in the system.
If only one device is connected to a system of nonlinear 45 bus test system, harmonic distortion is low. This is because when more non-linear devices connected to the bus network, harmonic voltage deviation will increase at all buses in the network. This is because the total or the amount of harmonic current injected into the network have increased and thus will increase the harmonic voltage deviation in the bus network. Voltage THD (%) for the 32 - bus system when Pulse Stories are connected on the bus no.ID 32, 41 and 45 with 50 % of the total load (balanced).

In the second case, the voltage harmonics due to the demand load is not balanced, nonlinear devices connected to the bus are asked loads adapted to increase 20 % for phase A, an increase of 10 % for phase B and a decrease of 5 % for phase C. For example, demand loading on the bus with the ID number 41 for the 45 - bus test system tailored to the individual will increase 20 % for phase A, an increase of 10 % for phase B and a decrease of 5 % for phase C. Adjustment of demand loading is done so that the harmonic voltage deviation in the bus network as the demand is not balanced in the loading obtained and examined. In the parallel program can be compared between the computation times for parallel and serial execution of three-phase load flow is shown in Table 1 for all cases.

| Case       | Serial Algorithm (s) | Parallel Algorithm (s) | Speedup |
|------------|----------------------|------------------------|---------|
| Interconnection 45 Node | 2.3875               | 1.7750                 | 1.35    |

The speedup produced by parallel programming algorithm for parallel multi-core architecture of sequence decoupled three-phase power flow as shown in Table 2, and 3 can be calculated using equation (9). Where the execution time using single-core processor equal to three-time 3TS+TPY+ k.(TPN+TS). However, the execution time using multi-core processors equal to 3TS+TPYmax+ k.(TPNmax+TS). The TPYmax and TPNmax refer to maximum TPY and TPN task execution time.

4. Conclusions
This study has presented the development of object components for the three-phase power flow analysis of unbalanced harmonic Algorithms used harmonic penetration and nodal voltage method for harmonics has been developed as a component object. Harmonic analysis is required as an extension of the basic libraries for the wind power. Components of the nodal voltage method have been integrating the components of three-phase power flow into the existing new component-based applications. The solution time of the proposed algorithm for this case is faster than compare backward/forward methods. The result showed that parallel three-phase load flow produced execution speedup and proved the ability to handle large-scale problems.

Acknowledgments
The authors thank Engineering Faculty of Andalas, that support this research. Authors also thank PLN company that provide us the data of the grid in the region of West Sumatera. Many thanks to PLN company that has supported the provision of information about the data grid in the region of West Sumatra.

References
[1] F Safargholi, B Vahidi and J Moghani 2015 Improved algorithm for harmonic load flow solution in radial distribution networks *Dielec. And Elec. Ins., IEEE Transactions* 97-103
[2] Bollen M H J and Hassan F 2011 Integration of distributed generation in the power system (Hoboken, Wiley-IEEE Press)
[3] Fox B, Flynn D, Bryans L et al. 2007 Wind power integration: connection and system operational aspects *Ins. Eng. Technol.*
[4] Chang C Y and Teng J H 2002 Three-Phase harmonic load flow method, Industrial Technology, 2000 *IEEE ICIT ’02. 2002 IEEE Int. Conf.* 2 839 – 44
[5] M Abdel-Akher, K M Nor and A H Abdul-Rashid 2005 Improved three-phase power-flow methods using sequence components *IEEE Trans. on power sys.* 20 3 1389-97

[6] Herraiz S, Sainz L and Clua J Review of harmonic load flow formulations *Pow. Del., IEEE Trans.* 18 3 1070-87

[7] K L Lo and C Zhang 1993 Decomposed three-phase power flow solution using the sequence component frame *Proc. IEE, Gen., Trans., and Dist.* 140 3 pp 181-8

[8] Zhang X P, Chu W J and Chen H 1996 Decoupled asymmetrical three-phase load flow study by parallel processing *IEE Proc. Generation, Transmission and Distribution* 143

[9] J H Teng 2003 A direct approach for distribution system load flow solutions *IEEE Trans. on Pow. Sys.* 18 3 882-7

[10] C S Cheng and D Shirmohammadi 1995 A three-phase power flow method for real-time distribution system analysis *IEEE Trans. on Pow. Sys.* 10 671–9

[11] X P Zhang 1996 Fast three-phase load flow methods *IEEE Trans. on Pow. Sys.* 11 3 1547-53

[12] M Abdel-Akher, K M Nor and A H Abdul Rashid 2007 Revised sequence component power system models for unbalanced power system studies *Proc. of 3rd IASTED Asia Conf. on Pow. And Ener. Sys.*

[13] R H Kitchin 1981 Converter harmonics in power system using state-variable analysis *IEE Proc. Part C* 128 4 567-72

[14] Xu W, Marti J R and Dommel H W 1991 A multiphase harmonic load flow solution technique *Ieee Trans. On Pow. Sys.* 6 1 174 – 82