PARALLEL UNBALANCED THREE-PHASE POWER FLOW ANALYSIS INCLUDING DISTRIBUTED GENERATION MODELS

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SYAFII

A thesis submitted in fulfilment of the
requirements for the award of the degree of
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To my beloved mother, Hj. Safiah Hasan, my wife Wati, S.Pd and my childrens

Farah, Muthia, Fatimah,Umar, Nauroh dan Naila

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ABSTRACT

Recently, the usage of smart grid has increased and there is a need for more efficient and comprehensive distribution system analysis tools to make proper operation and control system decisions. These requirements have given a motivation for researchers to apply innovative technologies in power system computation and modelling. This thesis presents a parallel unbalanced power flow algorithm including Distributed Generation (DG) models. DG models that have been considered are cogeneration, Photovoltaic (PV), and Wind Turbine Generator (WTG). The Radial Distribution Analysis Package (RDAP) program is used to validate the algorithm, and the performance for large-scale system is further examinedby comparing with OpenDSS software. One of the test system is a combination of a mesh network and radial feeder system that has many typical characteristics of unbalanced active systems. IEEE 8500node test system is used to test the performance of the algorithm for large unbalanced multi-phase distribution system problem. The variation of wind speed for WTG, solar radiation, and temperature for PV have been simulated. Simulation results show that the proposed DG model can be used to analyse DG impacts in unbalanced meshed and radial distribution system. The results show that the computation time of the proposed algorithm is faster than forward/backward sweep and hybrid methods. The computation time result for the 8500 test case less than 1 second showed that the proposed program is applicable to handle large-scale problems. The parallel implementation of the proposed algorithm for the combination system has improved the speedup to 2.33 times faster over the forward/backward method and have produced a computational speedup in all other cases.

ABSTRAK

Pada masa ini, penggunaan grid pintar telah meningkat dan memerlukan alat analisis sistem pengagihan yang lebih cekap dan menyeluruh bagi membuat keputusan operasi dan kawalan sistem yang sepatutnya. Keperluan ini telah memberi motivasi kepada para penyelidik untuk mengaplikasikan teknologi inovatif dalam pengiraan dan pemodelan pengkomputeran sistem kuasa. Tesis ini memperkenalkan algoritma ketidakseimbangan pengaliran kuasa selari termasuk model penjanaan agihan (DG). Model DG yang diambil kira adalah penjanaan bersama, fotovoltan (PV) dan penjana turbin angin (WTG). Program analisis pengagihan jejari (RDAP) digunakan bagi mengesahkan algoritma, dan untuk prestasi sistem berukuran besar, ianya diuji lebih lanjut dengan menggunakan perisian OpenDSS. Salah satu sistem ujian adalah gabungan rangkaian jaringan dan sistem pengagih jejari yang mempunyai banyak ciri-ciri tipikal sistem aktif yang tidak seimbang. Sistem ujian IEEE 8500 nod digunakan untuk menguji prestasi algoritma bagi masalah berbilang fasa tidak seimbang yang berukuran besar. Perubahan kelajuan angin untuk WTG, radiasi solar dan suhu untuk PV telah disimulasikan. Keputusan simulasi menunjukkan bahawa model DG yang dicadangkan boleh digunakan untuk menganalisis kesan DG dalam sistem jaringan yang tidak seimbang dan juga pengagihan jejari. Keputusan menunjukkan bahawa algoritma yang dicadangkan adalah lebih pantas daripada kaedah ke hadapan/ke belakang dan kaedah hibrid. Keputusan masa pengiraan untuk kes ujian 8500 kurang daripada 1 saat menunjukkan bahawa program yang dicadangkan boleh digunakan untuk menangani masalah berskala besar. Pelaksanaan selari bagi algoritma yang telah dicadangkan untuk sistem gabungan telah meningkatkan kecepatan 2.33 kali lebih laju berbanding kaedah ke hadapan/ke belakang dan boleh mempercepatkan pengiraan komputer bagi semua kes yang lain.

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0, 1, 2	-	Suffix or prefix for sequence components
a, b, c ,n	-	Suffix or prefix for phase components
j,k,l	-	Suffix of busbar indices
I, V, φ	-	Current, voltage, phase angle
P, Q, S	-	Active-, reactive-, and apparent-power
I_a, I_b	-	Secondary line current of CT Transformer
I_{pv}	-	Current generated by the incident light
I_0	-	Reverse saturation of the diode
Voc	-	Open-circuit voltage
I_{sc}	-	Short circuit current
a	-	Diode ideality constant
r	-	iteration number
q	-	The electron charge (1.60217646 x 10^{19} C)
k	-	Boltzmann constant (1.3806503 x 10^{-23} J/K)
T	-	Temperature of the PV module
N_s	-	Number of cells connected in series
G	-	Irradiation
STC	-	Standard test condition.
K_V, K_I	-	Voltage and Current coefficient
Δ_t	-	Difference between actual and standard temperatures
CT	-	Centre-tapped
C_p	-	Power coefficient of the rotor
R	-	The total machine winding resistance
X	-	The total machine winding leakage reactance.
$X_{c,}$	-	Capacitive reactance of capacitor bank
X_m	-	Magnetizing reactance of Induction generator

s	-	slip
Y	-	Admittance matrix
H, N, J, L	-	Sub-matrices of Newton Raphson Jacobian matrix
α , β	-	primary and secondary side off-nominal turns ratio
A	-	Phase to Symmetrical component transform matrix
Z^{abc}	-	The impedance matrix for phase a, b and c
TS	-	Time serialtask
TPY	-	Time parallel construct admittance
TPN	-	Time parallel network solver
max	-	Maximum
ADS	-	Active distribution system
DG	-	Distributed generation
WTG	-	Wind turbine generator
PV	-	Photovoltaic
FF	-	Fill factor
SVCM	-	Static voltage characteristic model
OOP	-	Object-oriented programming
CBD	-	Component based development
NEMA	-	National Electrical Manufacturers Association
VUF	-	Voltage Unbalanced Factor
FACTS	-	Flexible ac transmission system
VSC	-	Voltage source converter
FC	-	Fuel cell
PC	-	Personal computer
RDAP	-	Radial distribution analysis package
MPPT	-	Maximum power point tracking
TPC	-	Taiwan Power Company

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CHAPTER 1

INTRODUCTION

1.1. Background

Power-flow analysis is the heart of most system planning activities and design for future expansion as well as in determining the best operation of existing power systems. Power flow analysis has begun to be explored since the introduction of digital computers. Most challenges in power flow algorithms have been met successfully. However, as power system engineering and computation technology develop, new issues cropped up that need new approach and direction. Therefore, algorithm and technological applications need to be enhanced and there will always be new developments and new areas for researchers to explore.

In the coming years there will be greater growth in distributed generation (DG) and what has been described as smart grid. A DG is an electric power source connected to utility networks at the distribution level typically ranging from 10 kW up to tens of MW capacity. The integration of DG in the distribution networks can provide a variety of benefits, including improved reliability and reduced transmission and distribution losses [1].

The increasingly significant number of installation of many DGs has changed distribution systems from a passive system to an active network [2], known as an active distribution system (ADS). Some of the DGs, such as photovoltaic modules, are single phase components, which increase the unbalance in the ADS. Distribution networks may have many multi-phase line sections with balanced and unbalanced load connected in star or delta. Therefore, the unbalanced power flow is required when solving active distribution networks, including DG models.

The conventional power-flow analysis methods, that are widely used for large power transmission systems are based on the system positive-sequence representation. These methods do not take into account the following ADS characteristics:

1. The presence of single-phase laterals, single and two-phase loads, centre-tapped transformer loads and unbalanced three-phase loads [3], [4].

2. The presence of non-dispatchable DG units such as wind and photovoltaic units [5], [6].

3. Many photovoltaic modules are connected as a single phase component [7], which increases the unbalanced conditions in the ADS.

4. The large-scale problem associated to meshed and radial transmission and distribution system analysis.

In order to analyse unbalanced systems, a full three-phase network representation needs to be employed. The unbalanced power flow solution has been used for general network topologies with DG units based on forward/backward method [8-9] and sequence component method [10]. The program in [10] has been developed in MATLAB environment and tested using two study systems, i.e. small and medium size ADS. However, the models and programming techniques can be enhanced in order to improve the robustness, accuracy and speedup the analysis for large-scale problem. In this research, the basic sequence-decoupled power-flow method [11] is extended to solve large-scale unbalanced active distribution network problem.

The three-phase power flow based on the symmetrical components has some advantages such as fast execution time and low memory requirements. The forward/backward method [8] cannot deal with a highly meshed system such as the

IEEE 118 and 300 buses test systems. On the other hand, the hybrid method [10-11] which solves the three-phase system using symmetrical component and forward-backward sweep approach in handling laterals will lose its computational advantage when dealing with large number of multi-laterals system such as in the IEEE 8500 distribution feeder test system [4]. The weakness of the power-flow methods in [10-11] can be overcome by using dummy lines and dummy nodes approach in [12]. Based on this method, unbalanced three-phase power flow will be solved faster than the previous methods.

The fossil fuels such as coal, oil and natural gas are non-renewable, limited in supply and one day will be depleted. The price of this energy increase year by year related to its decreasing availability. With the increase in the price of traditional petrochemical fuels for generating energy, the employment of renewable resource generation as alternative energy becomes more practical, feasible and realizable. Therefore, distributed generation (DG) using renewable-energy sources will increase in the coming years.

Distributed generation using renewable-energy sources, such as wind, solar photovoltaic and hydro power has received considerable attention in recent research interest. Wind turbine generation (WTG) and photovoltaic (PV) are the world's fastest growing electricity generation technology. Global wind power capacity reached 94,100 megawatts by the end of 2007 [13]. Grid-connected photovoltaic generation has been increasing by an average of more than 20 percent each year since 2002 [14]. At the end of 2009, the cumulative global PV installations exceeded 21,000 MW [15].

The specific DG technologies have different electrical characteristics, which affect in the power system analysis. The electric power supply by photovoltaic is dependent on sunlight radiation and ambient temperature. Meanwhile, the active power generated by wind turbine generation depends on wind speed. Therefore, weather related DG units have to be modelled in order to get an accurate analysis result. The weather related DG will be modelled more comprehensively than that has been considered earlier [10]. By using the proposed model and algorithm the impacts of DG can be analyzed accurately and optimum technical design can be determined.

Power flow analysis involves computer hardware and software. Over the last few decades, computing technology continues to advance rapidly. The performance of microprocessors improved at the rate of 52% per year from 1986 to 2002 [16]. Today, its performance is improved by the addition of processors in the same machine. The so called multi-core systems are now quite common. Multi-processor machines are now becoming a standard while the speed of single processor has almost stabilized or is increasing slowly compared to its development in the past. Therefore, in the present trend of computing technology, performance improvements can now be increasingly achieved with the ability to run a program on multiple processors in parallel. In other words, the multi-core approach improves performance only when software can perform multiple activities in the same period of time.

The applications have to go parallel to profit from this development. Unfortunately, it is still very challenging to write algorithms that really take advantage of multiple processors. Most applications presently use a single core processor. They see no speed improvements when run on a multi-core machine, since it is executed serially which, in fact, means that it is really running as if it is in a single core machine mode. Therefore, the algorithm needs to be changed in order to take advantage of new developments in computing technology.

In this research, the sequence full decoupled three-phase power flow was used. The existence of two-phase and single-phase line segments which is difficult to be modelled in sequence components [10-11] can be solved by using the dummy lines and dummy node approach in [12]. The method will convert the two-phase and single-phase line segments into virtual three-phase lines and hence eliminate the need to use forward/backward method to handle multi-phase laterals. Based on this method, the structure will be fully decomposed, which makes it amenable to be implemented in parallel computing.

Previous implementations of parallel processing in power flow calculation were done using interconnected processors [17] and personal computer (PC) cluster connected via Ethernet communication link [18]. These parallel systems are costly and the computation time also depends on speed of communication media used among processors. The high cost of the hardware has made the advantages of faster parallel solution not worthwhile and practical. Another alternative to reduce cost and communication time is by using multi-core processors in single computer known as PC based parallel system. In the very near future all new computers will be parallel computers. This also means that the hardware cost is the same, whether a standard basic PC is used as a serial processing system or a parallel processing system.

The multi-core processor speedup performance is dependent on the algorithms and software. The problem should be decomposed into tasks in parallel programming algorithm. These tasks can be worked on independently of the others and run under the multiple processors system. The problem that cannot be decomposed into independent tasks will use a parallel loop. Both parallel techniques are used in the algorithm development to speedup the three-phase flow calculation. This new computation technology can solve power system computation efficiently.

The object components based programming that combines object oriented programming and component based development have been used in this research. By using object components, updating or adding new algorithm can be done to any specific component without affecting or escalating the modification to other components inside the software [19]. The DG models have been developed using the state-of-the art of object component based approach, so the models can be integrated with existing object component software previously developed in [11].

The new development in distribution system analysis tools needs to test the robustness of their algorithm using IEEE 8500-node test feeder provided by IEEE PES distribution system analysis subcommittee [4]. The characteristics of the test system have included almost all practical distribution system features, including CT transformer load. The developer has to deal with this load model and support large-scale mesh and radial system [20].

1.2. Thesis Objective, Scope and Contribution

1.2.1. Thesis Objectives

The main focus of this research is to develop a parallel three-phase power flow algorithm, including DG models for large-scale balanced/unbalanced mesh and radial system. The followings are the specific objectives of the research:

1) To develop an efficient sequence full decoupled three-phase power flow algorithm and apply parallel processing.

2) To model the distributed generations based on object component. The models will be developed including co-generation, wind turbine and photovoltaic in steady state analysis.

3) To solve unbalanced active distribution system with mesh network and radial feeders and analyse the impact of DGs.

1.2.2. Scope of Work

In order to achieve the above mentioned objectives, the followings are the scopes that governed the research activities:

1) The DGs to be developed are cogeneration, wind turbine and photovoltaic generation based on steady state models.

2) The parallel technique to be used is multi-core processors in single computer as known as PC based parallel system. The application was developed using visual C++ programming under Visual Studio 2008 with OpenMP and Intel

C++ Compiler to support parallel processing.

3) The proposed method was validated with radial distribution analysis package (RDAP) program and the performance for large-scale system was further examined by comparison with EPRI OpenDSS software.

4) The technical impacts analyzed include voltage violation, network losses and power flow via simulation studies.

1.2.3. Thesis Contributions

This research will contribute in developing efficient parallel three-phase power flow algorithm for large active distribution system.

The main contributions of this thesis are listed as follows:

1) Novel parallel algorithm for sequence decoupled three-phase power flow analysis (Multi-core PC based parallel programming).

2) Development of DG models as new class library including cogeneration, wind turbine and photovoltaic as weather related DG models and CT transformer load model.

3) Applicable for large-scale power system network with faster computation.

1.3. Thesis Outline

This thesis is organised into seven chapters. The contents are outlined as follows:

Chapter 2 of this thesis presents the previous work by researchers on three-phase power flow development, especially on the algorithm of the solution, application of parallel computing, distributed generation modelling, and DG impact analysis. The important findings from past works were used as guidelines in this research.

Chapter 3 discusses the methodology used to extend the power system model with the presence of a variety of DG models. The DG models that have been developed include cogeneration, three-phase and single phase PV and synchronous/asynchronous generation based WTG. These models made the algorithm capable in solving ADS networks. In addition, the impacts of DGs penetration on system performance are also discussed in this chapter.

Chapter 4 discusses the methodology used in this study to develop the parallel algorithm for unbalanced three-phase power flow. The multi-core and multithread parallel programming were utilized in the algorithm development.

Chapter 5 discusses the application on the large-scale mesh and radial unbalanced active distribution system. The test systems development using the data available in public domain is presented in this chapter. The test systems are the combination of a mesh network and radial feeder that have many typical characteristics of unbalanced active systems. Another test system is the IEEE 8500-node test feeder, which is used to test the performance of the algorithm for large unbalanced multi-phase distribution system problem. The CT transformers load was solved using voltage drop analysis in the three-phase interactive scheme.

Chapter 6 presents comprehensive results for the parallel unbalanced three-phase power-flow analysis including distributed generation models.

Finally, chapter 7 concludes the overall study and provides recommendation for future works related to parallel three-phase power flow algorithm and DG models presented in this thesis.

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