DEVELOPMENT OF DYNAMIC EQUIVALENTS FOR INTERCONNECTED POWER SYSTEMS USING IDENTIFICATION APPROACHES

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Special dedication to my beloved mum and dad, brothers and sisters and all my friends who have always been there, for their love, supports and confidence in me.

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ABSTRACT

This research presents new methods to develop power system dynamic equivalent for real time digital type power system simulator. Digital type power system simulators such as Power System Computer Aided Design/Electromagnetic Transient for Direct Current (PSCAD/EMTDC) plays an important role in cases where real time dynamic studies are required. In dynamic studies of large power system, it is vital to model the external system by their dynamic equivalents in order to retain the dynamic characteristics of the original power system as well as to reduce the problem to a solvable size. The power system structures will include studied system (internal system) and dynamic equivalents system (external system). Two methods have been proposed to identify the dynamic equivalents, i.e. using the parametric and non-parametric identification methods. Parametric identification method is based on the line flow function of the original system. The active power (*P*) is utilised to estimate the dynamic parameters of the equivalent generators such as inertia constant (*H*), damping factor (*D*) and the transient reactance ($x_d^{'}$), etc. In the non-parametric identification method, Artificial Neural Networks (*ANNs*) is employed to solve the hard task of constructing the dynamic equivalents. Both approaches are optimised by Levenberg-Marquardt (*LM*) and Particle Swarm Optimisation (*PSO*) algorithms, respectively. The performances of the dynamic equivalents resulting from the proposed methods are compared to its original networks. The analysis and discussions on both optimisations algorithms are also presented. The proposed methods have been verified through simple test systems and realistic TNB network model. Simulations have been performed using the in-house Matlab-based Power System Dynamic Equivalents Toolbox (PSDYNET) which contains power flow analysis, time domain simulation, and identification based dynamic equivalents program.

ABSTRAK

Penyelidikan ini mempersembahkan kaedah baru di dalam pembangunan sistem kuasa setara dinamik untuk simulator digital sistem kuasa masa sebenar. Simulator digital sistem kuasa seperti *Power System Computer Aided Design/ Electromagnetic Transient for Direct Current* (PSCAD/EMTDC) memainkan peranan penting di dalam kes-kes yang memerlukan kajian dinamik masa sebenar. Di dalam kajian dinamik sistem kuasa yang besar, adalah penting untuk memodelkan sistem luaran dengan sistem setara dinamik bagi mengekalkan ciri-ciri dinamik sistem kuasa asal dan mengurangkan masalah kepada saiz yang boleh diselesaikan. Struktur sistem kuasa akan merangkumi sistem kajian (sistem dalaman) dan sistem setara dinamik (sistem luaran). Dua kaedah telah dicadangkan untuk mengenalpasti sistem setara dinamik, iaitu melalui kaedah berparameter dan kaedah tak berparameter. Kaedah pengenalpastian berparameter berasaskan fungsi aliran talian sistem asal. Kuasa aktif (*P*) digunakan untuk menganggarkan parameter dinamik penjana setara seperti pemalar inersia (*H*), faktor redaman (*D*), regangan fana (x_d') dan sebagainya. Di dalam kaedah pengenalpastian tak berparameter, Jaringan Saraf Buatan (*ANNs*) digunakan untuk menyelesaikan tugasan sukar di dalam pembinaan sistem setara dinamik. Kedua-dua kaedah telah dioptimumkan masing-masing dengan algoritma Levenberg-Marquardt (*LM*) dan algoritma Particle Swarm Optimization (*PSO*). Prestasi sistem setara dinamik hasil daripada kaedah yang dicadangkan telah dibandingkan dengan jaringan asal. Analisis dan perbincangan ke atas kedua-dua algoritma optimum juga dipersembahkan. Kaedah yang dicadangkan telah ditentusahkan melalui sistem pengujian ringkas dan model jaringan TNB yang realistik. Simulasi telah dilaksana dengan menggunakan *Power System Dynamic Equivalents Toolbox* (*PSDYNET*) yang dibina sendiri berasaskan *Matlab* dan ia mengandungi perisian analisis aliran kuasa, simulasi domain masa dan sistem setara dinamik berasaskan pengenalpastian.

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LIST OF SYMBOLS AND ACRONYMS

A	-	Eigenvalues' diagonal matrix of the state matrix
ANN	-	Artificial neural network
c_1	-	Constant weighting factor related to pbest
c_2	-	Constant weighting factor related to gbest
D	-	Damping coefficient
$E_q^{'}$	-	q-axis transient electro-motive forces
$E_d^{'}$	-	d-axis transient electro-motive forces
E_{fd}	-	Excitation voltage
EGAT	-	Electricity Generating Authority of Thailand
FACTs	-	Flexible AC Transmission Systems
FDPF	-	Fast Decoupled Power Flow
gbest	-	Global best
GSMD	-	Grid System Division Management
GUI	-	Graphical user interfaces
H	-	Inertia constant
HVDC	-	High Voltage Direct Current
HVAC	-	High Voltage Alternating Current
I_d	-	d-axis armature currents
I_q	-	q-axis armature currents
$\underline{I}_G$	-	Complex vector of currents in subsystem
J	-	Jacobian matrix
K_A	-	Voltage regulator gain
K_E	-	Exciter constant

K_F	-	Stabiliser gain
LM	-	Levenberg-Marquardt algorithm
M	-	Inertia coefficient
P	-	Active power
pbest	-	Personal best
P_m	-	Mechanical input power, MW
PSS	-	Power System Stabiliser
PSCAD/ EMTDC	-	Power System Computer Aided Design/ Electromagnetic Transient for Direct Current
PSDYNET	-	Power System Dynamic Equivalents Toolbox
PSO	-	Particle Swarm Optimisation algorithm
PSS™NETOMAC	-	Power System Simulator Network Torsion Machine Control
p.u.	-	Per unit system
Q	-	Reactive power
rand()	-	Random number between 0 and 1
R_S	-	Stator resistance
S_E	-	Exciter saturation function value
SESCO	-	Sarawak Electricity Supply Corporation
SVC	-	Static VAR compensator
s_i^k	-	Position of particle *i* at iteration *k*
s_i^{k+1}	-	Position of particle *i* at iteration *k+1*
T_A, T_B, T_C	-	Voltage regulator time constants
$T_{do}^{'}$	-	d-axis open-circuit time constant
$T_{qo}^{'}$	-	q-axis open-circuit time constant
$T_{\max}$ and $T_{\min}$	-	Maximum and minimum turbine outputs, p.u.
TNB	-	Tenaga Nasional Berhad
TNBR	-	TNB Research Sdn. Bhd.
T_R	-	Input filter time constant
T_S	-	Governor time constant, sec.
V_T	-	Terminal voltage

v_i^k	-	Velocity of particle *i* at iteration *k*
v_i^{k+1}	-	Velocity of particle *i* at iteration *k+1*
V_{err}	-	Terminal voltage error signal
$\underline{V}_G$	-	Complex vector of generator voltages in subsystem
V_{SI}	-	Power system stabiliser input signal
X	-	State vectors of subsystem
X_d	-	d-axis synchronous reactance
$X_d^{'}$	-	d-axis transient reactance
$X_d^{''}$	-	d- axis subtransient reactance
X_q	-	q-axis synchronous reactance
$X_q^{'}$	-	q-axis transient reactance
$X_q^{''}$	-	q- axis subtransient reactance
Y	-	Network admittance matrix
z	-	Modal components' vector of the state variables
δ	-	Power angle position, degree
Δ	-	Deviation
ΔI_f	-	Injected current deviation vectors at the interconnection buses
ΔV_f	-	Voltage deviation vectors at the interconnection buses
ε	-	Tolerance
γ	-	Inverter side extinction angle, degree
ψ	-	Armature flux linkages
$\hat{\gamma}$	-	Demapping component
ω	-	Machine angular speed, rad/s
θ	-	Rotor angle, degree or terminal bus angle, degree
$\hat{\varphi}$	-	Mapping component

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CHAPTER 1

INTRODUCTION

1.1 Dynamic Equivalents of Power Systems

A dynamic equivalent is a simplified dynamic model of power systems that, in a given time perspective and for certain types of faults etc., reproduces the dynamic characteristics of the complete model with adequate accuracy [1]. Dynamic equivalents play an important role in modern power system dynamic studies as it may involves bulky of generating units and their associated control elements. The power system size is increasing due to the load growth from time to time. The works in system planning studies as well as in the technical analysis studies become more complex and require expensive cost in term of computation memory and speed. The power system dynamic study is one of the more complicated analysis that requiring solutions of hundred of differential equations [2]. In practice, it is imperative to segregate the huge power system into a study system and the rest as external system. If the external system can be replaced dynamically by one or more suitable equivalents, a remarkable amount of computational efforts can be saved.

As a consequence of recent significant developments in computer technologies, digital type power system simulation programs such as Power System Computer Aided Design/ Electromagnetic Transient for Direct Current (PSCAD/ EMTDC) and Power System Simulator Network Torsion Machine Control (PSS™NETOMAC) are well established as reliable and cost effective tools for the study of power system [3]. Unfortunately, detailed representation of large power systems network is restricted in such digital simulation programs. The factor that are taken into consideration during dynamic simulation include time consuming in initial modelling preparatory works and the CPU simulation run time of the computer [4]. More often, little can be gained by having the whole detailed 3-phase AC system modelled in the transient simulation program as the similar results can be obtained if carefully designed of dynamic equivalent circuits is used. An accurate modelling of dynamic equivalents at the interconnection points is an important prerequisite for meaningful investigative studies, analysis and design of power systems involving power electronic applications such as HVDC (High Voltage Direct Current) transmission, Static VAR Compensators and FACTs (Flexible AC Transmission Systems) [5].

Efforts to find appropriate power system dynamic equivalents have been reported since more than 4 decades ago [6]. In the common practice, the external system is normally replaced by one or more coherent groups of synchronous machines. Several methods of implementing reduced-order power system such as modal analysis, coherency identification techniques, modal-coherency technique, and identification based methods can be found in the literature review section that follows.

Dynamic equivalents of non-coherent groups are usually more difficult to determine. The system external to the study system may be represented by an equivalent synchronous machine with unknown parameters. Non-parametric identification and parameters estimation techniques have been employed in this research in order to determine the unknown parameters for dynamic equivalents [7]. The objective is to estimate a set of unknown parameters belonging to a model that is assumed to represent the external system, based on the measurements of some important signals.

1.2 Problem Statement

The analysis of electromechanical transient or dynamic analysis during fault conditions can be solved only under condition that results are obtained from [1]:

(i) measurements,

(ii) calculations made in complex system without any simplification with detailed representation of each element of system,

(iii) calculations made in equivalent network.

First condition is mostly not possible for realisation because of technical, economical and security reasons. The second condition is also mostly not possible, because of acquiring the data of each element of large power system. Third condition is possible after verifications of results received in equivalent network with the help of comparison with measured or calculated results in primary (not reduced) system.

The introducing of dynamic equivalents for large power system principally involves the reduction of numbers of differential equations to be solved while preserving the most important dynamic characteristics of the external system. This problem can be presented as follows. Consider a large power system and define a particular area of interest within the system (study system), to be retained in full detailed. Then obtain a model reduction of the system external to the area of interest (external system) with the following characteristics:

(i) the external system will be replaced by equivalent generator model at each frontier bus linked with the study system such that the external network equations are greatly reduced.

(ii) models for equivalent generators and the control devices are suitable for use by any standard transient stability computer program.

(iii) the indispensable dynamic behaviours of the reduced order system resemble that of the full system.

Consider a power system having dynamic devices such as generators and their control devices, motors, and network control devices such as static VAR compensators. Equations expressing the dynamics of each device can be written as follows [8, 9]:

$$\frac{dx_d}{dt} = f_d(x_d, V_d) \tag{1.1}$$

$$I_d = g_d(x_d, V_d) \tag{1.2}$$

where x_d is the vector of state variables for each device, I_d are the real and imaginary part of the current injection from the device into the network, and V_d are the real and imaginary components of the bus voltage. In this approach, the effect of each dynamic device is reflected as boundary conditions providing additional relationships between voltage and current at the nodes where they are connected. Hence, the algebraic equation (1.2) can be integrated into the network equation [8]:

$$\bar{I} = Y_N \bar{V} \tag{1.3}$$

to give the overall system equations, expressed in terms of set of first-order differential equations:

$$\frac{dx}{dt} = f(x, V) \tag{1.4}$$

and a set of algebraic equations resulting from the combination of equations (1.2) and (1.3) can be rewritten as follows:

$$I(x, V) = Y_N V \tag{1.5}$$

with a set of known initial conditions (x_0, V_0), where $x \in R^n$ is the state vector of the system, V is the bus voltage vector, and $I(x, V)$ is the vector of current injections.

A reduced-order model of the original full model as presented in equations (1.4) and (1.5) could be described by:

$$\frac{dx_r}{dt} = f_r(x_r, V_r) \tag{1.6}$$

$$I_r(x_r, V_r) = Y_{Nr} V_r \tag{1.7}$$

where $x_r \in R^{nr}$ is the state vector of the reduced system with $n_r < n$, V_r and I_r are the vector of bus voltages and the current injections of the reduced system, respectively. Notice that the equations expressing the reduced model, equations (1.6) and (1.7), are of the same form as the equations expressing the full model, equations (1.4) and (1.5). The only differences are the number of state variables and the dimension of the nonlinear functions and matrices.

The reduced-order model has a smaller number of equations to be solved than the full model mainly due to the fact that fewer dynamic devices are included in the equivalent external system. Consequently, the equivalent reduced model has less state variables and differential equations than the full model. The complexity of obtaining a reduced-order model for a power system can be mainly attributed to [9]:

(i) the highly nonlinear characteristics of the power system models,

(ii) the diversity in models for exciters, turbine-governors, and other dynamic devices,

(iii) the equations describe the equivalent reduced model (equations (1.6) and (1.7)) are in the same form as that for the full model (refer to equations (1.4) and (1.5)),

(iv) the need for constructing reduced models suitable for transient stability analysis with different types of disturbances,

(v) the fact that the error produced in the approximation is a nonlinear combination of errors produced in the reduction procedure, and

(vi) the effort and experience required to effectively balance the classical dilemma in model order reduction: accuracy vs. model order.

1.3 Research Motivation

The electric power system analysis has always been characterised to be a hard duty to face due to all the issues that they represent, bearing in mind the complex topics that they signify. This challenging task has been confronted by different ways and by many researchers worldwide. There are too many notable, successful and important results achieved in this area but, in spite of everything there continue a vast quantity of problems that are hardly difficult to solve employing recent advances in numerical analysis and decision support systems. Commonly, these troubles are summarised in the following manner [10]:

(i) inappropriate model of the real world.

(ii) complexity and size of the problems which prohibit computation time.

(iii) solution methods employed by the human are not capable of being expressed in an algorithm or mathematical form. They usually involve many rules of thumb.

(iv) the operator decisions are based on unclear linguistics descriptions.

(v) analysis of security related with voltage or angle is based on human experience judgment.

Owing to all the preceding drawbacks and the great computational innovations that have been evolved for the human well-being, important mechanisms to develop modern techniques to solve these kinds of problems have come up. Thus, for the past few decades, researchers have done numerous efforts to develop new approaches in power system dynamic equivalents which are mainly based on coherency approaches, modal analysis, combined coherency-modal approaches, and identification technique in order to improve on speed, accuracy, efficiency, and ability to handle stressed or ill-conditioned of the larger power systems.

In this research, the efficiency and feasibility of the identification techniques to estimate the dynamic parameters of external system is proposed to obtain dynamic equivalents. Due to the great potential applications in power systems planning and operation, dynamic equivalents have attracted much research attention worldwide over the last 4 decades. The motivation to develop accurate, low-order dynamic equivalent models has been aimed at reducing the very considerable computing times associated with large-scale transient stability studies in multi-machine power systems.

Although several methods have been published to advance this research issue but problems remain, particularly in the areas of flexibility and robustness. In other words, they have limitations such as the machine model order, many of them do not include static excitation system, power system stabilisers (PSS) or merely the tested system do not include flexible alternate current transmission systems (FACTS) devices [11]. Nowadays almost the whole electric grids around the world comprise with one of these devices, so then, they take a very important role to bear in mind. Above and beyond these restrictions, all these works have been solved by classical techniques.

Thus, these are the main motivations to construct dynamic equivalents that overtake the limitations that others can not do. Moreover, with the advent of market forces in the electricity supply industry, and the ensuing confidential status given to all utility data, network information exchange between neighbouring utilities may be in the form of reduced equivalent circuits. Hence, it becomes essential to develop a new generation of power system dynamic equivalents that are robust and have self-learning capabilities. This research is in relation to propose an alternative method in excess of the current methods for constructing power system dynamic equivalents which will accurately retain the dominant dynamics for digital simulation purposes. In additional, it is desirable that the resulting reduced system would be suitable for use with standard power system analysis computer programs.

The computational burden of determining the study system behaviour, as it is affected by the external system, will then be reduced with tolerable error. Another important reason of constructing the dynamic equivalents is that they provide additional insights to a power system. It is anticipated that significant benefits from this work for its employment in the utility industry in the areas of planning, operation, and control.

1.4 Research Objectives

From the previous discussions, it can be seen that there is a need to develop a simpler yet self-learning capability approach to construct the power system dynamic equivalents for external system. Therefore, the objectives of this thesis consist of the following aspects:

(i) to propose a new alternative approach of power system dynamic equivalents, namely identification based techniques.

(ii) to propose an effective optimisation algorithms in the identification based techniques.

(iii) to develop the dynamic equivalents program into MATLAB® based Graphic User Interface (GUI) Toolbox.

(iv) to apply the new alternative approach of dynamic equivalents into real power system network for dynamic analysis purposes.

1.5 Research Contributions

Part of the work presented in this thesis has already been published [12-16]. The main contributions are listed as follows:

(i) the development of new methods to solve one of the most difficult problems that encompasses power systems as dynamic equivalents is proposed. Not much research has been done by other researchers using the identification technique in power system dynamic equivalents. Thus, new approaches for constructing the power system dynamic equivalents which is based on the parametric and non-parametric identification methods are proposed in this research.

(ii) the proposed methods are then further investigated to solve optimisation problem by employing two different optimisation algorithms; Levenberg-Marquardt algorithm and Particle Swarm Optimisation algorithm. The problem is based on preserving closely those modes highly related with the dynamic of the study subsystem.

(iii) a user-friendly analysis tool of constructing the power system dynamic equivalents, namely, Power System Dynamic Equivalents Toolbox (PSDYNET) in MATLAB® environment had been developed. This toolbox mainly consists of three power system analysis routines, power flow analysis, transient analysis, and dynamic equivalents identification program.

(iv) Malaysian power system network and its neighbouring power network have been analysed in this thesis and consequently, a more accurate dynamic studies have been granted.

1.6 Organisation of the Thesis

The remainder of this thesis is divided into six chapters as follows:

Chapter 2 reviews some previous relevant work and introduces the background of this research. Brief classification of power system dynamic equivalents is specified. The concept of a new algorithm in power system dynamic equivalents is also presented in this chapter.

Chapter 3 describe the standard equations for power system dynamic simulation. The dynamic models of power system are derived mathematically in this chapter followed by the discussion on the concepts used in studying the reduction procedures.

Chapter 4 describes the software tools which have been developed for the simulations and the construction of the power system dynamic equivalents is reported in this thesis. The developed software is a suite of general routines for static and dynamic power system analysis in MATLAB® environment.

Chapter 5 proposes two identification approaches, namely parametric identification technique and non-parametric identification technique. Besides, two optimisation algorithms which are specifically involved in this research, namely, Levenberg-Marquardt (LM) and Particle Swarm Optimisation (PSO) algorithms are also been highlighted.

Chapter 6 gives the validation results of the proposed new method as well as its optimisation algorithms in the real power networks are reported in this chapter.

Chapter 7 concludes the three major findings in this thesis and gives the recommendations on the future developments of power system dynamic equivalents.