UNIVERSITI PUTRA MALAYSIA

RECURRENT NEURAL NETWORK APPROACH FOR STABILITY ANALYSIS AND SPECIAL PROTECTION SCHEME OF POWER SYSTEMS WITH DISTRIBUTED GENERATION

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By

VEERASAMY VEERAPANDIYAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

June 2021

DEDICATION

This thesis is gratefully dedicated to my beloved parents for their love, patience and understanding and my beloved brother and sisters.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Ir. Noor Izzri bin Abdul Wahab, PhD
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Power system stability and protection is important due to the complexity of power system, uncertainties in load, generation and integration of large number of renewable energy sources that forces the system to operate close to its stability limits. Voltage stability analysis (VSA) is a part of static stability analysis which involves performing power flow analysis (PFA). The Newton Raphson (NR) based PFA technique is conventionally used for VSA which requires formation and inversion of Jacobian matrix that increases the computational burden and requires large memory. Hence, a Jacobian less power flow technique using Recurrent Hopfield Neural Network (HNN) has been proposed for on-line contingency ranking (CR) and VSA. Furthermore, the potential of proposed Recurrent HNN is used for analyzing the frequeny stability of the power system by employing advanced controllers in automatic load frequency control (ALFC) application. The conventional design of gain parameters of proportional-integral-derivative (PID) controller has poor performance in case of large disturbanaces due to its static gain. By using the proposed Recurrent HNN method of tuning the PID controller, the gain values become self-adaptive to handle the system uncertainties and restore to steady state quickly. Moreover, to enhance the reliability and stability of the power system in case of large disturbances (like severe fault or contingencies) that leads to cascading failures or blackouts, a special protection scheme to detect the high impedance fault (HIF) has been proposed using Recurrent Long short term memory (LSTM) network as the conventional protection scheme fails to detect the HIF that occurs in the power network. The results obtained from the developed PFA technique reveal that the convergence time is improved by 32 % to 76 % than conventional approaches. In case of ALFC, the proposed h-HNN based PID controller is studied in single- and multi-loop (cascade) for multi-area power system. The results obtained prove that the proposed design of h-HNN based controller outperforms by 13.22 % to 98.55 %, 12 % to 99 %, and 18 % to 22 % in terms of steady state performance indices, transient performance indices, and control effort, respectively than other tuning methods. In terms of detection of HIF, the proposed Recurrent LSTM network method is validated in IEEE 13-bus power network integrated with solar photovoltaic system.

The results obtained reveal that the proposed LSTM network gives the maximum classification accuracy of 91.21 % with a success rate of 92.42 % in identifying the HIF compared to other intelligence classifiers.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENDEKATAN RANGKAIAN NEURAL BERULANG UNTUK ANALISIS KESTABILAN DAN SKIM PERLINDUNGAN KHAS SISTEM KUASA DENGAN PENJANAAN TERAGIH

Oleh

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Kestabilan dan perlindungan sistem kuasa penting kerana peningkatan kerumitan sistem kuasa, ketidakpastian beban, penjanaan dan integrasi sebilangan besar sumber tenaga boleh diperbaharui yang memaksa sistem beroperasi hampir dengan had kestabilannya. Analisis kestabilan voltan (VSA) adalah sebahagian daripada analisis kestabilan statik yang melibatkan analisis aliran kuasa (PFA). Teknik PFA berdasarkan Newton Raphson (NR) digunakan secara konvensional untuk VSA yang melibatkan pembentukan dan penyongsangan matriks Jacobian yang meningkatkan beban komputasi dan memerlukan memori yang besar. Oleh itu, teknik aliran kuasa baru tanpa Jacobian menggunakan Rangkaian Neural Hopfield (HNN) Berulang telah diusulkan untuk menentukan tahap luar jangka secara dalam talian (CR) dan VSA. Selanjutnya, potensi cadangan HNN berulang digunakan untuk menganalisis analisis kestabilan frekuensi sistem kuasa dengan menggunakan kawalan maju dalam apilkasi Kawalan Frekuensi Beban Automatik (ALFC). Reka bentuk konvensional gandaan untuk parameter pengawal terbitan-kamiran-berkadar (PID) mempunyai prestasi yang buruk sekiranya terdapat kerosakan besar oleh kerana gandaannya statik. Dengan menggunakan pengawal HNN Berulang yang dicadangkan dengan pengawal PID yang diselaras, nilai gandaan menjadi sesuai-diri untuk menangani ketidaktentuan sistem dan mengembalikan sistem ke keadaan stabil dengan cepat. Lebih-lebih lagi, untuk meningkatkan kebolehpercayaan dan kestabilan sistem kuasa sekiranya berlaku gangguan besar (seperti kerosakan teruk) yang menyebabkan kegagalan atau pemadaman, satuskim perlindungan khas untuk mengesan kesalahan impedans tinggi (HIF) telah dicadangkan menggunakan Rangkaian Memori Jangka Pendek (LSTM) Berulang bersama dengan teknik pemprosesan isyarat transformasi gelombang diskri tdalam penyelidikan ini. Oleh itu, hasil yang diperoleh menunjukkan bahawa teknik HNN mengungguli 32% hingga 76% dari segi masa penumpuan daripada pendekatan aliran kuasa yang lain. Dalam kes ALFC, pengawal PID berasaskan h-HNN yang dicadangkan dipelajari dalam tunggal- and pelbagai-gelung (lata) untuk sistem kuasa yang mempunyai berbilang kawasan. Hasil yang diperoleh membuktikan bahawa cadangan rekabentuk pengawal berasaskan h-HNN mengungguli 13.22% hingga

98.55%, 12% hingga 99%, dan 18% hingga 22% dari segi indeks prestasi keadaan tetap, indeks prestasi sementara, dan usaha pengawalan, masing-masing daripada teknik penalaan yang lain. Dari segi pengesanan HIF, kaedah rangkaian LSTM Berulang yang dicadangkan dan disahkan dalam rangkaian kuasa 13-bus IEEE yang disepadukan dengan sistem fotovoltaik solar (PV). Hasil yang diperoleh menunjukkan bahawa rangkaian LSTM yang dicadangkan memberikan ketepatan klasifikasi maksimum 91.21% dengan kadar kejayaan 92.42 % dalam mengenalpasti HIF berbanding pengklasifikasi kecerdasan lain.

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AC	Alternating Current
ACE	Area Control Error
AE	Aqua Electrolyzer
AGC	Automatic Generation Control
AI	Artificial Intelligence
AIEE-ASME	American Institute of Electrical Engineers-American Society of Mechanical Engineers
ALFC	Automatic Load Frequency Control
ALO	Ant Lion Optimization
ANFIS	Adaptive Neuro Fuzzy Inference System
ANN	Artificial Neural Network
BESS	Battery Energy Storage System
BNN	Bayesian Neural Network
CA	Classification Accuracy
CB	Circuit Breaker
CC	Cascade Control
CCS	Cascade Control Scheme
CE	Control Effort
CHNN	Continuous Hopfield Neural Network
Ch-NN	Chebyshev Neural Network
CLTF	Closed Loop Transfer Function
CNN	Convolutional Neural Network
CR	Contingency Ranking
CS	Capacitor Switching
CSI	Composite Severity Index
CWT	Continuous Wavelet Transform

DAE	Dynamic Algebraic Equation
Db	Daubechies
DC	Direct Current
DEG	Diesel Energy Generator
DFT	Discrete Fourier Transform
DG	Distributed Generation
DT	Decision Tree
DWT	Discrete Wavelet Transform
ELM	Extreme Learning Machine
ESS	Energy Storage System
EV	Electric Vehicle
Ev	Energy value
FACTS	Flexible Alternating Current Transmission System
FC	Fuel Cell
FD	Fast Decoupled
FFT	Fast Fourier Transform
FIS	Fuzzy Inference System
FLS	Fuzzy Logic System
FPA	Flower Pollination Algorithm
FT	Fourier Transform
FVSI	Fast Voltage Stability Index
GA	Genetic Algorithm
GDB	Governor Dead Band
GHNN	Generalized Hopfield Neural Network
GRC	Generator Rate Constraints
GS	Gauss-Seidal
GSA	Gravitational Search Algorithm

GWO	Grey Wolf Optimization
HDE-PS	Hybrid Differential Evolution-Pattern Search
h-HNN	Heuristic based Hopfield Neural Network
HIF	High Impedance Fault
HNN	Hopfield Neural Network
HPS	Hybrid Power System
I	Integral
IAE	Integral Absolute Error
ICs	Intelligent Classifiers
IGWO	Improved Grey Wolf Optimization
IoT	Internet of Things
IPD	Integral minus Proportional Derivative
ISE	Integral Square Error
ITAE	Integral Time Absolute Error
ITSE	Integral Time Square Error
JDT	J48 based decision tree
KCL	Kirchoff's Current Law
KF	Kalman Filter
KNN	K-Nearest Neighbors
KS	Kappa Statistics
LCPI	Line Collapse Proximity Index
LFC	Load Frequency Control
LG	Line to Ground Fault
LIBSVM	Library Support Vector Machine
LL	Double Line Fault
LLG	Double Line to Ground Fault
LLLG	Three Phase Fault

L_{mn}	Line Stability Index
LQP	Line Stability Factor
LRGDN	Low-Resistance Grounded Distribution Network
LSTM	Long Short Term Memory
MAE	Mean Absolute Error
MF	Membership Function
MG	Microgrid
MHNN	Modified Hopfield Neural Network
MLP	Multi Layer Perceptron
MODWPT	Maximum Overlap Discrete Wavelet Packet Transform
MRA	Multi Resolution Analysis
MV	Medium Voltage
NB	Naïve Bayes
NLS-CLM	Non-monotone line search with corrected Levenberg–Marquardt
NLSI	Novel Line Stability Index
NN	Neural Network
NR	Newton Raphson
NRJM	Newton Raphson-Jacobian Marquardt
NVSI	New Voltage Stability Index
PD	Proportional Derivative
PEV	Plug-in Electric Vehicle
PF	Power Flow
PFA	Power Flow Analysis
PFEs	Power Flow Equations
PI	Proportional Integral
PID	Proportional Integral Derivative
PInd	Performance Index

PI-PD	Proportional Integral-Proportional Derivative
PIs	Performance Indices
PMU	Phasor Measurement Unit
|P-O|	Magnitude of Peak Overshoots/Undershoots
PSO	Particle Swarm Optimization
PSO-GSA	Particle Swarm Optimization-Gravitational Search Algorithm
PTSI	Power Transfer Stability Index
PVDG	Photovoltaic Distributed Generation
PWM	Pulse Width Modulation
RBF	Radial Basis Function
RC	Resistor- Capacitor
RE	Renewable Energy
RES	Renewable Energy Sources
RFB	Redox Flow Battery
RK4	4^{th} order Runge Kutta
RMSE	Root Mean Square Error
RNN	Recurrent Neural Network
SD	Standard Deviation
SDA	Standard Deviation of phase A
SDB	Standard Deviation of phase B
SDC	Standard Deviation of phase C
SE	Steady state Error
SI	Stability Index
SLP	Step Load Perturbation
SMC	Sliding Mode Control
SOC	State of Charge
SPS	Special Protection Scheme

SPT	Signal Processing Technique
SPV	Solar Photovoltaic
ST	Settling Time
STC	Standard Test Conditions
STFT	Short-Time Fourier Transform
STPG	Solar Thermal Power Generation
SVM	Support Vector Machine
THD	Total Harmonic Distortion
TLBO	Teaching Learning Based Optimization
UPFC	Unified Power Flow Controller
VCPI	Voltage Collapse Proximity Index
VCPI_1	Voltage Collapse Proximity Index
VQI_{line}	Voltage reactive power Index
VS	Voltage Stability
VSA	Voltage Stability Analysis
VSI	Voltage Stability Indices
VSI_1	Voltage Stability Index
VSI_2	Voltage Stability Indicator
VSLI	Voltage Stability Load Index
VSMI	Voltage Stability Margin Index
VSM_s	Voltage Stability Margin
WECS	Wind Energy Conversion System
WT	Wavelet Transform
WTG	Wind Turbine Generator
Z-N	Ziegler and Nichols

CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, the liberation of electricity market, increasing in size and complexity of power system network, use of new technologies and control, emerging new Renewable Energy Sources (RES) to meet the growing need for electrical energy causes the power system to operate in a highly stressed condition close to its stability limits (Bevarani, 2009). When such power system (PS) is perturbed, it will lead the system to collapse or black out. The occurrences of many well-known blackouts experienced in Western United States in 1996, North America and Canada in 2003, (Andersson et al., 2005), Europe in 2006, Greek island of Kefalonia in 2006, India and Vietnam in 2013, Bangladesh in 2014, Ukraine in 2015, and several other blackouts demonstrates the weakness of the grid (Wu et al., 2017, Haes Alhelou et al., 2019). These blackouts or cascading failures happen due to many reasons such as transmission line tripping, line over loading, failure of protection and control, voltage and frequency collapse, cyber-attack and so on (Kamali et al., 2017, Veloza et al., 2016). The occurrence of blackouts worldwide has illustrated the importance of power system stability assessments and control for secure and reliable operation of power system with effective protection schemes (Hare et al., 2016).

Power system stability is defined as the ability of power system, for a given initial operating condition, to regain a state of equilibrium after being subjected to disturbances. This is further categorized into rotor angle stability, voltage stability and frequency stability (Kundur, 2007). This thesis focuses on voltage and frequency stability analysis, in addition with effective special protection scheme for reliable operation of system. By definition, voltage stability is the ability of power system to maintain the voltage of each bus or node within the acceptable range subjected to uncertain disturbances from an assumed initial equilibrium point (Kundur, 2007). The voltage stability assessment of power system is done in static mode i.e. via load flow or power flow studies (Modarresi et al., 2016).

On the other hand, a severe stress on power system results in imbalance between the load and generation causing frequency instability. The frequency stability assessment of power system is done in dynamic mode, in which the generators' inertia constants and other system parameters are considered. Generally, this type of phenomenon must be assessed in relation with frequency control issue of power system (Bevarani, 2009). A permanent off-nominal frequency deviation may affect the power system operation, security, reliability, efficiency of the system and tripping of protection devices. The large frequency deviation (off-nominal operation) can be restored to normal steady-state frequency according to available generating power reserve using Automatic Generation Control (AGC) or Automatic Load Frequency Control (ALFC) (Bevarani, 2009, Elgerd, 1982, Bevrani, 2017). Thus, ALFC is one of the significant control problems in PS design and operations which need to be investigated.

Furthermore, to enhance the stability and reliability of power system an effective tool of special protection scheme (SPS) is employed to maintain the satisfactory operation of power system. In general, SPS are those designed to detect one or more predetermined system conditions which causing unusual stress on the network, and for that preplanned remedial actions are necessary (Anderson et al., 1996). Apart from detecting normal faults, i.e. conventional symmetrical and unsymmetrical faults, there is also growing concern on SPS to also detect the High Impedance Fault (HIF) happening in power system. HIF is defined as a distribution primary fault with current amplitude too low that cannot be detected or cleared by the traditional overcurrent protection (Aucoin, 1985a). Generally, these fault current amplitude ranges from 0 to 75 A which is extremely low, whereas the magnitude of conventional fault current is sufficiently high that can be detected by the conventional overcurrent protection (Ghaderi et al., 2017). Hence in this thesis, the SPS is designed to detect the HIF in the power system. The HIF usually caused by contact of bare-energized conductor with a surface that contribute high impedance such as tree limb, wet and dry sand, wet and dry asphalt and so on (Mishra et al., 2019a). Therefore, the SPS need to be considered and explored further to enhance the system stability and reliability.

1.2 Problem Statement

The reliability of power system in today's modern society is a crucial problem due to the presence of large uncertainties in grid operations. A stable and reliable electric system requires control of various power system phenomena. Figure 1.1 illustrates the time frames of power system phenomena and the studies involved to analyze the operation of power system which occurs from milliseconds to hours. Among the various studies, this thesis addresses the stability analysis and fault study of power system. The critical problems involved in analyzing the voltage stability, frequency stability and protection of power system are discussed in the upcoming section of the thesis.

In general, the techniques employed to assess the voltage stability analysis (VSA) includes static and dynamic analysis (Huang et al., 2020, Doroudi et al., 2017). The static stability analysis comprises of continuous power flow (PF) methods, sensitivity analysis, and singular value decompositions (Adewuyi et al., 2019, Aghdam et al., 2020, Montoya et al., 2019). On the other hand, the dynamic stability analysis includes small-signal analysis, singularity point, time-domain analysis, and Lyapunov-based energy function approaches (Overbye et al., 1991). Dynamic analysis techniques require a precise modeling of the system that coordinates the control and protection of the power system. However, these techniques require numerous highly configured computer systems and lengthy computational time to analyze single sequences of the events (Devaraj et al., 2011). Hence, static analyses that approximate the dynamic modeling have been widely adopted for stability studies that necessitate the solution of power flow analysis (PFA). The solution of power flow equations (PFEs) are obtained using conventional numerical approaches like Newton Raphson (NR), Gauss-Seidal (GS), Fast decoupled and other forms of modified NR technique to assess the VSA of the system. But, these numerical

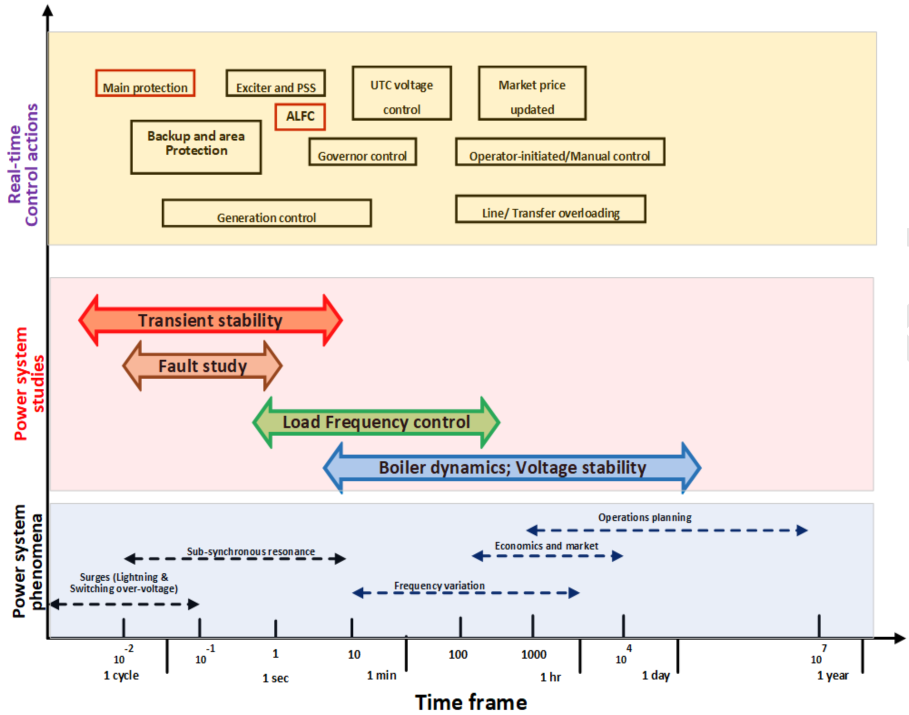

Figure 1.1 : Power system time frame, control action and studies

approaches are not suitable for on-line application owing to the large computational time and requirement of high speed computers. To cater this problem, a rule based Fuzzy load flow approach was used for evaluation of contingency ranking (CR) and stability indices (Kanimozhi et al., 2015). However, this method requires an expert to tune the membership function for deducing the bus parameters. On the flipside, the multi-layered feed-forward network based PFA technique fails to respond for system with dynamics and uncertainties. The complexity of artificial neural network (ANN) increases as the size of power system increases which in turn raises the computational burden of the network due to longer time required for training (Wen et al., 2009). Subsequently, the frequency control is a part of frequency stability analysis which is assessed using time-domain simulation of power system model. Depending on the frequency deviation range, various frequency control loop may be adopted for maintaining the system stability. In case of small disturbances, the primary control loop of generator will regulate the frequency deviations. If the frequency deviation increases substantially due to islanding of network or other disturbances, the secondary control of Load Frequency Control (LFC) is responsible to restore the system frequency (Bevarani, 2009). Thus, maintaining the frequency and real power exchange with neighbouring areas is done by choosing appropriate controller for ALFC operation. In general, the integral (I), proportional-integral (PI), and proportional-integral-derivative (PID) controller have been widely used for ALFC of real-time power system (Sahu et al., 2016, Saha et al., 2017). However, tuning the gain parameters of these controllers was conventionally done using Ziegler and Nichols (Z-N), Cohen –Coon’s Astrom, Hagglund and other traditional methods. In this case, the gain parameters of controller are well designed for a given operating conditions and become ineffective for wider operating range of real power system (Ziegler et al., 1942, Das et al., 2014). To overcome this, the gain values of controller applied for ALFC of interconnected system are optimized using computational intelligence (CI) techniques (Arya, 2019). However, the CI technique doesn't provide robust operation of system with uncertainties as the gain values of the controller are static. Therefore, the proper type and design of controller parameters influences the performance and stability of any system which need to be explored further.

Apart from developing the techniques for voltage and frequency stability study, the stability of the system is further enhanced by employing the SPS. The SPS is used to detect the HIF involves a two-stage process: feature extraction and classifier construction (Xiao et al., 2019a). The feature extraction was done using various signal processing techniques (SPTs) such as Fast Fourier Transform (FFT), Short-Time Fourier Transform (STFT), and Wavelet Transform (WT) in order to obtain the information of particular type of disturbances that occur in power system (Mishra et al., 2019a). The FFT possesses the problem of spectral leakage and loss of time information on analyzing the signal for feature extraction. The STFT was widely used for fault analysis, however it is unsuitable because of its fixed window length for analyzing the non-stationary transient signals that comprises both time and frequency component (Huo et al., 2017). On the other hand, the continuous wavelet transform (CWT) is an alternative approach to overcome the problem of resolution as in STFT. But, this method also has low redundancy during reconstruction of signal (James et al., 2017). The extracted features using the aforementioned SPTs are used to train and test the various intelligent classifiers of support vector machine (SVM), Artificial Neural Network (ANN), adaptive neuro fuzzy interference system (ANFIS), and fuzzy logic system to detect the occurrence of HIF. However, these techniques are unable to handle large set of data as it increases the computational cost (Qu et al., 2020, Zhang et al., 2020). An efficient intelligent classifier need to be designed for improving the SPS to detect the HIF in power system.

All these aforementioned problems of power system stability and protection can be solved by appropriate selection of intelligence techniques. Among the various AI techniques, the recurrent neural network (RNN) is a feedback network with content associative memory and gradient type network (Wen et al., 2009). It can converge for any initial conditions, also the network doesn't require training and the output is obtained by deriving the weight function of the network explicitly from the energy function or Lyapunov function to be minimized (Mishra et al., 2006). Hopfield network is a special kind of RNN which can solve any linear or non-linear optimization functions, but suffers from the limitation of local minima and there is no systematic design for Hopfield model. Also, the conventional model is sensitive to various setting parameters of momentum, bias and slope which affect the convergence stability (Takahashi, 1997, Duong et al., 2019, Dieu et al., 2013). Hence, an appropriate designing of Hopfield model or modification of conventional model with other optimization approaches of gradient descent or evolutionary algorithms may helps to reach the global minima of the RNN based Hopfield model that need to be explored further.

The above problem statements can be summarized as follows:

1. An appropriate intelligence method using the concept of RNN for solving power system problems in real-time need to be developed to overcome the drawbacks of conventional RNN of reaching local minima.

2. The need to develop a fast and robust power flow technique for solving the non-linear transcendental PFEs to perform online VSA of power systems.

3. Certain problems are faced by conventional tuning of PID controller for ALFC operation, it is necessary to develop a new method for design of gain parameters of PID controller with self-adaptiveness to handle the system uncertainties.

4. An efficient SPS need to be developed to detect the occurrence of HIF in the system with solar photovoltaic distributed generation and to protect the system from blackouts or voltage collapse.

1.3 Objectives

The main focus of this research is to develop a method using Recurrent Neural Network (RNN) that can provide superior properties than other traditional artificial intelligence (AI) methods for various power system applications of power flow study, ALFC, and detection of HIF. In order to achieve this, three specific objectives of the study are:

1. To propose and develop a Jacobian-less power flow technique using a RNN based approach and the method is validated by employing contingency ranking and voltage stability analysis.

2. To design a proportional-integral-derivative (PID) controller using a hypothesis of RNN and PSO-GSA technique for ALFC of power system to maintain the frequency stability of the system by regulating the area control error.

3. To propose a new technique for identification of HIF in a solar photovoltaic integrated distributed power network using RNN-based classifier by discriminating them from other abnormal events.

1.4 Scope of the study

The scope and limitation of this research work are as follows:

1. The scope of the research is limited to proposing an effective intelligence technique in solving power system problems of power flow study, designing the gain parameters of PID controller for ALFC, and developing a classifier to identify the HIF.

2. Particularly, the developed power flow technique in MATLAB software is tested on various standard IEEE bus systems of 14-bus, 30-bus, 57-bus and 118-bus, as well as 1354-bus test system. Furthemore, the method is applied for voltage stability analysis and contingency ranking (CR) of power system. To study this, the scope of this research includes proposing a new index for contingency ranking to identify the critical lines for evaluating the system stability. The CR and VSA are carried out on IEEE 14-bus system. Notably, this research includes the following stability indices namely Voltage Stability Load Index, Line Stability Index, Fast Voltage Stability Index, and Line Stability Factor due to its simplicity.

3. The proposed design of controller for ALFC model is tested on two- and three-area system with integration of RES, energy storage devices and Electric Vehicle (EV). The investigation is limited to design of single-loop and multi-loop (cascade) PID controller for ALFC application. However, the ALFC under deregulated environment were not studied in this thesis. Furthermore, to validate the proposed design of controller a comprehensive analysis is made on steady state and transient performance indices, and control effort of the controller.

4. Moreover, to deal with detection of HIF using the proffered recurrent classifier, the scope of the research includes discrete wavelet transform based signal processing technique in pre-processing stage. Also, the study is limited to detection of HIF on Spanish distribution network, and IEEE 13-bus network with integration of solar photovoltaic (PV) distributed generation.

1.5 Thesis outline

This thesis is organized into 9 chapters according to alternative thesis format of Universiti Putra Malaysia (UPM) based on the publications, in which each chapter (4-9) comprises of introduction, methodology, results and discussion, and conclusions. Brief explanation of each chapter has been discussed in the following section.

Chapter 1 presents overview of the thesis by describing the summary of the background and its problem statements. Furthermore, the research objectives and its scope of works are presented followed by the organization of the thesis. After that, Chapter 2 provides the detailed and comprehensive literature review of recurrent neural network, power flow analysis (PFA), application of PFA for contingency ranking and voltage stability analysis, automatic load frequency control, and high impedance fault detection scheme in power system.

Next, Chapter 3 portrays the detail explanation on materials and methodology of solving PFEs using RNN, method for CR and VSA. Moreover, presents the design of self-adaptive PID controller in single- and multi-loop for ALFC application and describes the recurrent Long Short Term Memory (LSTM) classifier with Discrete Wavelet Transform (DWT) technique for detection and discrimination of HIF. In

Chapter 4, the first objective supported by the first research article entitled "A novel RK4-Hopfield Neural Network for Power Flow Analysis of power system" is presented. This research work is focused on solving the PFEs of power system using 4^{th} order Runge Kutta (RK4)-based Hopfield Neural Network (HNN) called Modified HNN. This method reduces the computational burden, infeasibility and complexity of reaching the solution compared to the conventional HNN.

Subsequently, Chapter 5 deals with first objective supported by the second research article entitled "Recurrent network based Power Flow solution for voltage stability assessment and improvement with distributed energy sources". In this study, the solution of PFEs is obtained by updating the dynamics of HNN using heuristic PSO-GSA. Further, this technique is used for CR and VSA of power system by evaluating the voltage stability indices (VSI). Thereafter, Chapter 6 describes the second objective subsidized by the third research article entitled "A Hankel Matrix Based Reduced Order Model for Stability Analysis of Hybrid Power System Using PSO-GSA Optimized Cascade PI-PD Controller for Automatic Load Frequency Control". This research investigates the effect of cascade control (CC) scheme for ALFC application of hybrid power system. A Hankel method of model order reduction was proposed to study the frequency stability of CC scheme.

After that, Chapter 7 portrays the fourth research article of second objective entitled "Design of Single- and Multi-loop Self-Adaptive PID Controller using Heuristic based Recurrent Neural Network for ALFC of Hybrid Power System". In this research work, the PID controller is designed using HNN concept and then, the initial value of controller gain parameters are obtained using PSO-GSA technique. This study analyses the effect of single and cascade control for ALFC application.

In Chapter 8, the third objective supported by the sixth research article entitled "LSTM based Recurrent Neural Network classifier for High Impedance Fault detection in Solar PV integrated Power System" is presented. This study presents the detection of HIF in IEEE 13-bus distribution power system with presence of solar PV based distributed generation. The results obtained are compared with other well-known classifiers. Lastly, Chapter 9 summarizes the conclusions from individual research articles, overall conclusions and recommendations for future work. The contributions of the thesis are also presented in this chapter.

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The student Veerapandiyan Veerasamy was born on 13th January 1992 in Tamilnadu, India. His educational journey started at Fatima Matriculation Higher Secondary School, Virudhachalam, Cuddalore, where he completed his high school education in 2007. Later, he continued his higher secondary education at Tagore Matriculation Higher Secondary School, Salem and completed his school education in 2009. He has completed his Bachelor's degree in Electrical and Electronics Engineering with Distinction from Anna University in 2013. He secured Anna University 18th Rank and Department 3rd Rank in Panimalar Engineering College affiliated to Anna University, Chennai with Gold Medal. Then, he finished his Master's degree in Power Systems Engineering with Distinction from Government College of Technology affiliated to Anna University, Chennai in 2015. Thereafter, he started his teaching career as an Assistant Professor at Rajalakshmi Engineering College, India (Jun 2015- Jun 2018). During his tenure at Rajalakshmi Engineering College, he received Faculty Publication awards in 2018, and under his guidance the UG students received Grants of Rs. 10,000 from Tamilnadu Government under the Scheme of Tamilnadu State Council for science and technology in 2018, also received Best Project awards in 2017 and 2018. In 2018, he started his PhD study in the field of Electrical Power Engineering at Faculty of Engineering, University Putra Malaysia. His main research areas include application of Recurrent Neural Networks to power system, Computational Intelligence techniques, High Impedance Fault detection, Power Flow and Optimal Power Flow, Advanced Signal Processing Techniques, and Robust controllers.

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