AN INTEGRATED UNDER FREQUENCY LOAD SHEDDING PROTECTION BASED ON HYBRID INTELLIGENT SYSTEM

OMID SHARIATI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Electrical Engineering)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

FEBRUARY 2015

To My Dear Father and Kind Mather,
To Hesam, Hanna, Ali
and
To the Hidden Kindness

ACKNOWLEDGEMENT

First and foremost, praises and thanks to God the Merciful and Compassionate to whom I owe my very existence. Without His blessings of wisdom and perseverance, none of this would have been possible.

I would like to express heartfelt gratitude to my supervisors **Professor Dr. Ir. Abdullah Asuhaimi Mohd Zin** for his constant support during my study at UTM. He inspired me greatly to work in this project. I also wish to appreciate **Assoc. Professor Dr Azhar Khairuddin** and **Assoc. Professor Dr. Mohammad Reza Aghamohammadi.** Their willingness to motivate me contributed tremendously to our project. I have learned a lot from them and I am fortunate to have them as my mentors and supervisors.

Besides, I would like to thank the authority of Universiti Teknologi Malaysia (UTM) for providing me with a good environment and facilities which I need during the process. I also offer my enduring gratitude to Islamic Azad University (IAU)-Birjand Branch and Iran Dynamic Research Centre (IDRC) for their kind support scientific and financially.

ABSTRACT

Recent blackouts, which are associated with severe technical and economic damages, show that current protection systems are not reliable enough when power system is in an emergency condition. This research attempts to address the issue by introducing a novel, integrated and optimized frequency modelling approach and Under Frequency Load Shedding (UFLS) protection for electric power systems. This system is capable to consider various aspects of the problem simultaneously in modern power systems. Furthermore, it takes advantage of a new multi-objective decision making approach considering all required criteria and risk indicators based on the related standards of power system operation. In this approach, a new frequency response modelling system, named Extended System Frequency Response (ESFR) model and new aggregated load modelling system are proposed. This approach does not only consider all factors which contribute to frequency performance of power system simultaneously, but also is capable to consider advanced components of electric power systems. This modelling system is designed in consistent with the new generation of advanced power system simulators. In the next step, Genetic Algorithm (GA) as an Artificial Intelligent (AI) method is used for designing an optimal and integrated UFLS system. The technical implementation of this step leads to the creation of a new methodology for coupling two software or simulators together. This approach is applied to create a junction between the advanced power system simulator and the GA provider. This method does not only decrease the simulation time dramatically, but also makes the remote communications possible between two or more software. Finally, an AI system, namely Artificial Neural Network (ANN), is used in a hybrid structure to execute the GA UFLS system design as an online Wide Area Protection (WAP) system. The results of the first step show the high capability of the proposed frequency response modelling system. The new approach of under frequency protection system design shows clear advantages over the conventional methods. Finally, the performance of ANN is promising as a new generation of intelligent WAP systems.

ABSTRAK

Ketiadaan bekalan yang berlaku kebelakangan ini dikaitkan dengan kemusnahan teknikal dan ekonomi yang teruk menunjukkan perlindungan arus masih tidak mencapai keboleharapan yang mencukupi terutama apabila sistem kuasa berada di dalam keadaan kecemasan. Kajian ini bertujuan mengatasi isu tersebut dengan memperkenalkan pendekatan baru, bersepadu dan mengoptimumkan frekuensi pemodelan serta penggunaan Perlindungan Penyingkiran Beban Frekuensi (UFLS) bagi sistem kuasa elektrik. Sistem ini mampu untuk mempertimbangkan pelbagai aspek masalah yang berlaku secara serentak dalam sistem kuasa moden. Selain itu, kelebihan daripada penghasilan keputusan pelbagai objektif yang baru turut diambil kira bagi semua kriteria yang diperlukan dan petunjuk risiko berdasarkan kepada piawaian operasi sistem kuasa. Melalui pendekatan ini, gerak balas frekuensi sistem pemodelan yang baru, atau dikenali sebagai model Sistem Sambutan Frekuensi Lanjutan (ESFR) dan sistem pemodelan beban agregat dicadangkan. Pendekatan ini bukan sahaja mengambil kira semua faktor yang menyumbang kepada prestasi frekuensi sistem kuasa secara serentak, tetapi juga mampu untuk mempertimbangkan komponen terkini pada sistem kuasa elektrik. Pemodelan sistem ini turut direka selaras dengan sistem penyelakuan kuasa generasi baru yang canggih. Seterusnya, Algoritma Genetik (GA) yang dikenali sebagai Kecerdikan Buatan digunakan untuk mereka bentuk sistem UFLS optimum dan bersepadu. Pelaksanaan teknikal ini membawa kepada kewujudan satu kaedah baru untuk gandingan dua perisian penyelakuan. Pendekatan ini digunakan untuk mewujudkan hubungan antara penyelakuan sistem kuasa yang canggih dengan kaedah GA. Selain itu, kaedah ini bukan sahaja mengurangkan masa simulasi secara mendadak, ia turut membolehkan komunikasi secara jauh dilakukan diantara dua perisian atau lebih. Akhir sekali, sistem Kecerdikan Buatan (AI), yang dikenali sebagai Rangkaian Saraf Buatan (ANN) digunakan dalam struktur hibrid untuk melaksanakan reka bentuk sistem GA UFLS sebagai Kawasan Perlindungan Lebar (WAP) sistem yang dilaksanakan secara dalam talian. Keputusan awal menunjukkan keupayaan yang tinggi dalam kekerapan pemodelan sistem bagi tindak balas frekuensi yang dicadangkan. Pendekatan baru dalam reka bentuk sistem perlindungan frekuensi kurang turut menunjukkan kelebihan yang jelas berbanding dengan kaedah konvensional. Kesimpulannya, prestasi ANN mampu menjanjikan kelebihan yang ketara sebagai generasi baru sistem WAP yang pintar.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

UFLS	-	Under Frequency Load Shedding
AI	-	Artificial Intelligence
ROCOF	-	Rate Of Change Of Frequency
DG	-	Distributed Generation
SCADA	-	Supervisory Control And Data Acquisition
WAP	-	Wide Area Protection
WAMS	-	Wide Area Measurement System
HVDC	-	High Voltage Direct Current
FACTS	-	Flexible Alternating Current Transmission System
SFR	-	System Frequency Response
ESFR	-	Extended System Frequency Response
ANN	-	Artificial Neural Network
GA	-	Genetic Algorithm
AVR	-	Automatic Voltage Regulator
PSS	-	Power System Stabilizer
CRIEPI	-	Central Research Institute of Electric Power Industry
UCTE	-	Union for the Coordination of Transmission of Electricity
CE	-	Continent Europe
DPL	-	DIgSILENT Programming Language
SSE	-	Sum Squared Error
MSE	-	Mean Squared Error
APE	-	Absolute Percentage Error
MAPE	-	Mean Absolute Percentage Error
Mode	-	Most frequent value
$Risk_{Sys}$	-	Risk of the System
T.S.	-	Total Load Shed

M.D. - Magnitude of the Disturbance
B.F. - Base Fault
M.C. - Maximum Contingence
O.C. - Operating Condition
H.G. - Hydro Generation
B.C. - Base Condition
Hyd.Units - Hydro Units
Stea.Unts - Steam Units
Sc.+/- - Scenario of rising or falling value
DFIG - Double Fed Induction Generator
CB - Circuit Breaker
WTG - Wind Turbine Generator
CHP - Combined Heat and Power
CPU - Central Processing Unit
FRF - Frequency Regulation Factor
OBDD - Ordered Binary Decision Diagram
PO.L - Percentage of Active Power Over Load Indicator
AHP - Analytical Hierarchy Process
SPS - Special Protection Scheme
GPS - Global Positioning Satellite
PMU - Phasor Measurement Unit
TSO - Transmission System Operator
PV - Photo-Voltaic
ENTSOE - European Network of Transmission System Operators for Electricity
NNH - Number of Neuron in the Hidden layer

LIST OF SYMBOLS

T_R - Average Reheat Time Constant

H - Inertia Constant

R - Governor Regulation or Droop

D - Damping Factor

F_H - High Pressure Power Fraction of Reheat Turbine

K_m - Mechanical Gain

SR - Spinning Reserve

PF - Power Factor

ω_S - Synchronous Speed

J - Moment of Inertia

T_m - Accelerating Time Constant

T_W - Water Starting Time Constant

K - Effective Gain of Governing System

T_G - Governor Time Constant

Delta - Temporary Droop

Sigma - Permanent Droop

T_r - Hydro Governor Time Constant

T_P - Pilot Valve Time Constant

T_g - Gate Servo Time Constant

T - Turbine Time Constant

K - Turbine Factor

a - Water Hammer Factor

K_{Pf} - Load Active Power Frequency Dependency Factor

K_{qf} - Load Reactive Power Frequency Dependency Factor

K_{PV} - Load Active Power Voltage Dependency Factor

K_{qV} - Load Reactive Power Voltage Dependency Factor

Z - Constant Impedance

T_1 - Dynamic Load Time Constant
T_{Pf} - Transient Frequency Dependency of Load Active Power
T_{qf} - Transient Frequency Dependency of Load Reactive Power
T_{Pu} - Transient Voltage Dependency of Load Active Power
T_{qu} - Transient Voltage Dependency of Load Reactive Power
P - Active Power
S - Apparent Power
N - The Number of Steps in Load Shedding
P_{Step} - Load to be Shed in Each Step
T_{Step} - Time Delay of Each Step
f_{OS} - Frequency Over-Shoot
f_{US} - Frequency Under-Shoot
f_{ost} - Overshoot Threshold or the Maximum Instantaneous Frequency Permissible after loss of Load
f_{ust} - Undershoot Threshold or the Maximum Instantaneous Frequency Permissible after loss of Load
f_{SS} - Post-fault Steady State Frequency
f_{osdt} - Post-fault Steady State downer Threshold of Frequency or Minimum Quasy-Steady-State deviation of Frequency after Reference Incident
f_{osut} - Post-fault Steady State Upper Threshold of Frequency or Minimum Quasy-Steady-State deviation of Frequency after Reference Incident
ζ - Vector of Load Shedding
ξ - Vector of the Sequence of the Measurable
g - Gradient
$d\omega/dt$ - Frequency Gradient
ΔP_L - Active Power Load Changing
$P_{L\Delta}$ - Threshold value of active power mismatch
P_{tur} - Turbine-Governor reaction to Disturbance
f_{final} - Final Steady State Frequency
t_{off} - Non-permissible Off-nominal Frequency Duration
t_{fall} - Time of Frequency Fall

α - Factor Depicting Active Power Dependence of Load on Voltage Deviations

β - Factors Depicting Reactive Power Dependence of Load of Voltage Deviations

CHAPTER 1

INTRODUCTION

1.1 Background

Security is one of the most vital requirements in the operation of electric power systems. “Power system security” is the ability of the system to survive probable contingencies without interruption to customer service [1]. A set of imminent disturbance is referred to as contingencies. Power System Stability is also defined as the ability to regain an equilibrium state after being subjected to a physical disturbance [1]. Stability is an important factor of power system security, which is closely dependent on the value of system frequency. The deviation of frequency from its rated value is not only an indication of imbalance between real power generation and load demand, but also it is a reliable indicator for the instability condition of the given power system.

As power system load exceeds the maximum generation of power supply or large disturbance occur, such that system overload takes place due to governors being unable to react in time, system frequency will thus suffer a fast drop and in turn it can result in system collapse if appropriate preventive actions are not taken or functioning property.

Under Frequency Load Shedding (UFLS), as the only appropriate way to prevent an electric power system from collapsing, may lead to severe technical and economical damages, is of major importance. Load shedding schemes have become quite important in present day power systems, because they are operating at ever smaller capacity of the reserve and stability margins and have considerable connections with neighbour systems.

In other words, if the generation does not match the load in an interconnected power system (or in the isolated area) then an automatic load shedding scheme based on system frequency can be used to maintain system stability and provide a continuous supply for remaining loads and protecting for other equipment. Dynamic load shedding schemes have not been only suggested to stabilize the island following major disturbances but also define an appropriate analytic framework to enhance the dynamics of the islanding with the minimum load shedding effort. This problem is too complex to solve in real-time.

The major concern of UFLS design in modern power system operation is to take into account various influencing factors leading to the best load shedding scenario. Hence, fast calculation of optimal approaches for load shedding is one of the most important issues in planning, security, and operation of power systems. Recent advances in computer systems and Artificial Intelligence (AI) methods have provided golden opportunities leading to development an integrated UFLS system.

The first step in any electric power system dynamic study is choosing a proper mathematical model. Yet the selection of a power system model can be dissociated neither from the problem itself nor from the computing facilities and control techniques available. It is neither adequate, nor practical to devise a “universal model” for all power system dynamic problems. There are various kinds of power system dynamic problems, but there are only a limited number of system components which are important to the dynamic study. For each of them, several basic models are recommended by the professional societies, and can be adapted for the studies of specific problems.

Several UFLS schemes are also available that they can be categorised as traditional schemes, based only on frequency threshold, semi-adaptive schemes, based on frequency and Rate Of Change Of Frequency (ROCOF), adaptive schemes, based on frequency, and System Frequency Response (SFR) model [2].

Traditional load shedding schemes are designed by using a static model of power system which are set to disconnect fixed amounts of load using a predetermined fixed number of step sizes and usually do not provide optimized settings for different system conditions. These are conservative in the amount of load effectively shed and the frequency excursion ranges of UFLS schemes are too wide; because of neglecting the actual system state and magnitude of disturbance. In addition, it was found that the present schemes were not safe enough to maintain power system stability in the recent blackouts.

Studies have been conducted to determine the quantity of the load to be shed and to assess the system dynamic response following disturbances. However there is no representation that can effectively determine the settings of this protection. Several strategies used the frequency gradient to determine the initial active power deficit via a frequency response model. It has been shown that certain other factors also cannot be ignored or assumed to be constant. Otherwise, using frequency gradient as a sole indicator can give very misleading information about the active power deficit in the power system or an island. Additional information about the system such as voltage, spinning reserve, total system inertia, load characteristics are also required for designing an integrated UFLS system.

Previous researches assumed, in theory, that due to the slow response of the mechanical turbine valves controlled by the turbine governor, compared to the frequency decay rate, it can be concluded that the turbine output remains constant at the moment of disturbance and there is no turbine governor's reaction [3]. But this is not the case for load change. In the other words, load has a special position between various components in power systems which are affected by frequency deviations. Nevertheless, the major drawback of using the conventional frequency response model for UFLS purposes is the fact that the load's frequency and voltage dependence is not included in the model [3]. Generally, several load models are considered in power system dynamic analysis, such as constant power, constant impedance and constant model [4-6]. The above brief outline shows that having an integrated UFLS protection system is dependent on providing an integrated frequency response model of electric power systems.

1.2 Problem Statement

Modern power systems are operating at ever smaller capacity and stability margins due to limitations imposed by introducing of renewable energy resources and deregulation. In this situation, traditional schemes involved in securing the power system, such as UFLS scheme should be revised. The existing UFLS schemes are predominantly deterministic, neither taking into account the actual system state, topology and operating condition; nor include the nature and the characteristic of the disturbance. Recent blackouts confirm that current UFLS systems are not safe and reliable enough when power system is in an emergency condition.

If an emergency frequency condition occurs, not only the governor will regulate the mechanical output power by frequency variation but also the load will regulate its active power. Furthermore, despite the individual contribution provided by the DG may be low, the total sum of these producers is currently significant; as its characteristic will change the overall system performance among frequency response. Previous load shedding schemes were designed without taking into consideration this type of generation.

What's more, new types of controls involving a complex array of devices are widely used in the modern power systems, which should be taken into consideration when performing the frequency dynamics analysis. Advances have also been made in the control and operating systems which play significant roles in the system dynamic performance. Nowadays it is also evident that Wide Area Protection (WAP) is the most suitable system of UFLS which is a concept of using the Wide Area Measurement System (WAMS).

Discussing the importance of UFLS brings us to the conclusion that a high reliability level must be reached by implementing UFLS scheme, specially in modern power systems. It is desirable to use adaptive and integrated load shedding schemes disconnecting the minimum required system load at different conditions and maintain system stability. There are various modern components such as various DG resources accompanied by promoting the control and operating systems that they play a significant role in the dynamic performance and the frequency response of electrical power systems.

The integration of an adaptive UFLS strategy is dependent upon the integration of dynamic simulation arrangement and frequency response modelling. Such an integrated simulation should be more capable enough to consider the mentioned components and advances. The integrated UFLS system must also be able to take into account their effects on the system action and on stability indicators.

Moreover, it is necessary to have an adaptive, optimized and integrated UFLS system that would be able to consider these factors simultaneously to design the best UFLS strategy. In an advanced and novel approach, based on this proposal, UFLS scheme must take into account different influencing factors such as frequency variation, load characteristics, magnitude of disturbance, spinning reserve leading to define number of steps, the amount of load shed and delay time of each step. In this point of view, it is important that the scenario of protection system design should be capable enough to handle the new and integrated frequency model to plan the best UFLS system for operation condition. The proposed approach is a response to this serious request of the electric industry.

The proposed approach is a considerable step towards having a high security power grid with enhanced reliability indices; the power system operators by applying, such an integrated, optimized, fast and precise protection system would be presented with huge economical and technical benefits. Moreover, parallel to recent advances in management policies of electric power systems and with due attention to the development of WAM and WAP systems, it is a good background for fast and intelligence protection system with high compatibility with modern operating systems.

1.3 Research Objectives

The objectives of this research are:

i. To propose an integrated frequency response model of complex electric power systems for both generation side and consumption side.
ii. To design a new integrated and optimized under frequency load shedding system.
iii. To develop a new integrated and optimized online protection system using the hybrid artificial intelligence method.
iv. To develop an efficient protection system by reducing the risk of the system in emergencies.

1.4 Research Contributions

The significant contributions of this study can briefly be listed as follows:

i. Developing an Extended System Frequency Response (ESFR) model.

ii. Developing a new Aggregated Load Modelling system.

iii. Devised a new integrated and optimised approach for Under Frequency Load Shedding System (UFLS) design.

iv. Developing a fast and adaptive hybrid intelligence based UFLS protection system.

1.5 Scope of Research

The novel high-order multi-machine ESFR model, which is proposed and developed in this research, is implemented in the “IEEE 39-Bus” standard Dynamic Test System, which is also known by the name of “New England” test system. Validation step is performed via a comparative analysis of the results with the full system performance and with the traditional model. In the next step, the new integrated and optimized UFLS design system also established and developed using Genetic Algorithm (GA) for the test case.

In this approach, GA is assigned to identify the number of steps, the amount of load should be shed in each step and time of each step gained to protect the frequency response of the system, the risk of the system and power interruption. It can be implemented by using the integrated dynamic simulation of the test system which is prepared in the first step.

Finally, a new intelligence UFLS protection system is provided by hybridization of GA with ANN. In this approach, ANN is set to determine the GA output based on operating data. The results of this method are validated by comparing with the traditional UFLS system for the test grid.

It is assumed that the “ New England” test case is a complex power system with high penetration of renewable energy resources, especially hydro generation. Considering the technical aspects which exist in all power systems, there are limitations related to the maximum number of steps can be executed for UFLS protection and minimum discrimination required time between two steps. These limitations are considered in the approach as can be defined by the operators for each application.

1.6 Thesis Organization

The structure of this thesis is outlined to comprise five chapters as follows:

Chapter 2 is dedicated to review of the recent advances in the frequency response modelling approach of electrical power systems, load modelling, consideration of renewable energy resources and UFLS system improvement. The background of artificial intelligence applications in the field of study is also analysed. All the above have been done to find the main gap in this field and performing this idea to cover the requirements of the electric industry.

Chapter 3 is allocated firstly to outline the new Extended System Frequency Response (ESFR) and new aggregated load modelling approaches which are proposed by this research for complex power systems.

Chapter 4 is proposed a new approach to the design of UFLS protection system using the GA. In the next step, in a hybrid intelligence approach, ANN is used in an on-line WAP structure to execute the GA-UFLS design in complex power systems.

Chapter 5 presents the process of test and validation of the proposed approaches (in all three sections of the ESFR modelling system, GA-UFLS designer and ANN-GA wide area protection) and the related results considering the required analysis.

Chapter 6 contains a conclusion on the finding of the proposed approaches and requirements of this field leading to make recommendations for the future.

REFERENCES

[1] Jan Machowski, Janusz W. Bialek, and J. R. Bumby, *Power System Dynamics: Stability and Control*. Chippenham, Wiltshire, UK: John Wiley & Sons, Ltd., This edition first published 2008.

[2] B. Delfino, S. Massucco, A. Morini, P. Scalera, and F. Silvestro, "Implementation and comparison of different under frequency load-shedding schemes," in *Power Engineering Society Summer Meeting*, 2001, pp. pp. 307–312.

[3] U. Rudez and R. Mihalic, "Analysis of Underfrequency Load Shedding Using a Frequency Gradient," *Power Delivery, IEEE Transactions on*, vol. PP, pp. 1-1, 2009.

[4] "Load representation for dynamic performance analysis [of power systems]," *Power Systems, IEEE Transactions on*, vol. 8, pp. 472-482, 1993.

[5] I. A. Hiskens and J. V. Milanovic, "Load modelling in studies of power system damping," *Power Systems, IEEE Transactions on*, vol. 10, pp. 1781-1788, 1995.

[6] K. Yamashita, M. Asada, and K. Yoshimura, "A development of dynamic load model parameter derivation method," in *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, 2009, pp. 1-8.

[7] M. Sanaye-Pasand and M. Davarpanah, "A new adaptive multidimensioanal load shedding scheme using genetic algorithm," in *Electrical and Computer Engineering, 2005. Canadian Conference on*, 2005, pp. 1974-1977.

[8] M. T. Bishop and R. P. Jozwowski, "Frequency Sensing and Load Shedding Schemes," pp. 7-8, 1999.

[9] V. Chin, Z. Y. Dong, T. K. Saha, J. Ford, and Z. Jing, "Adaptive and optimal under frequency load shedding," in *Power Engineering Conference, 2008. AUPEC '08. Australasian Universities*, 2008, pp. 1-6.

[10] C. Concordia, L. H. Fink, and G. Poullikkas, "Load shedding on an isolated system," *Power Systems, IEEE Transactions on*, vol. 10, pp. 1467-1472, 1995.

[11] R. M. El Azab, E. H. S. Eldin, and M. M. Sallam, "Adaptive Under Frequency Load Shedding using PMU," in *Industrial Informatics, 2009. INDIN 2009. 7th IEEE International Conference on*, 2009, pp. 119-124.

[12] P. Du and J. K. Nelson, "Two-step solution to optimal load shedding in a micro-grid," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, 2009, pp. 1-9.

[13] E. E. Aponte and J. K. Nelson, "Time optimal load shedding for distributed power systems," *Power Systems, IEEE Transactions on,* vol. 21, pp. 269-277, 2006.

[14] Y. Halevi and D. Kottick, "Optimization of load shedding system," *Energy Conversion, IEEE Transactions on,* vol. 8, pp. 207-213, 1993.

[15] E. De Tuglie, M. Dicorato, M. La Scala, and P. Scarpellini, "A corrective control for angle and voltage stability enhancement on the transient time-scale," *Power Systems, IEEE Transactions on,* vol. 15, pp. 1345-1353, 2000.

[16] Y. Min, S.-B. Hong, Y.-D. Han, Y.-K. Gao, and Y. Wang, "Analysis of power-frequency dynamics and designation of under frequency load shedding scheme in large scale multi-machine power systems," in *Advances in Power System Control, Operation and Management, 1991. APSCOM-91., 1991 International Conference on*, 1991, pp. 871-876 vol.2.

[17] B. F. Rad and M. Abedi, "An optimal load-shedding scheme during contingency situations using meta-heuristics algorithms with application of AHP method," in *Optimization of Electrical and Electronic Equipment, 2008. OPTIM 2008. 11th International Conference on*, 2008, pp. 167-173.

[18] E. J. Thalassinakis, E. N. Dialynas, and D. Agoris, "Method Combining ANNs and Monte Carlo Simulation for the Selection of the Load Shedding Protection Strategies in Autonomous Power Systems," *Power Systems, IEEE Transactions on,* vol. 21, pp. 1574-1582, 2006.

[19] P. M. Anderson and M. Mirheydar, "A low-order system frequency response model," *Power Systems, IEEE Transactions on,* vol. 5, pp. 720-729, 1990.

[20] P. M. Anderson and M. Mirheydar, "An adaptive method for setting underfrequency load shedding relays," *Power Systems, IEEE Transactions on,* vol. 7, pp. 647-655, 1992.

[21] D. Kottick and O. Or, "Neural-networks for predicting the operation of an under-frequency load shedding system," *Power Systems, IEEE Transactions on,* vol. 11, pp. 1350-1358, 1996.

[22] A. Denis Lee Hau, "A general-order system frequency response model incorporating load shedding: analytic modeling and applications," *Power Systems, IEEE Transactions on,* vol. 21, pp. 709-717, 2006.

[23] M. Zima, M. Larsson, P. Korba, C. Rehtanz, and G. Andersson, "Design Aspects for Wide-Area Monitoring and Control Systems," *Proceedings of the IEEE,* vol. 93, pp. 980-996, 2005.

[24] U. Rudez and R. Mihalic, "Dynamic analysis of transition into island conditions of Slovenian power system applying underfrequency load shedding scheme," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1-6.

[25] S. J. Huang and C. C. Huang, "An adaptive load shedding method with time-based design for isolated power systems," *Int. J. Elect. Power & Energy Syst.*, vol. vol. 22, no. 1, pp. pp. 51–58, 2000.

[26] R. M. Maliszewski, R. D. Dunlop, and G. L. Wilson, "Frequency Actuated Load Shedding and Restoration Part I - Philosophy," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-90, pp. 1452-1459, 1971.

[27] H. You, V. Vittal, J. Jung, C.-C. Liu, M. Amin, and R. Adapa, "An intelligent adaptive load shedding scheme," presented at the 14 th PSCC, Sevilla, Spain, 2002.

[28] V. V. Terzija, "Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation," *Power Systems, IEEE Transactions on,* vol. 21, pp. 1260-1266, 2006.

[29] M. S. Pasand and H. Seyedi, "New Centralized Adaptive Under Frequency Load Shedding Algorithms," in *Power Engineering, 2007 Large Engineering Systems Conference on*, 2007, pp. 44-48.

[30] Y. Haibo, V. Vittal, and Y. Zhong, "Self-healing in power systems: an approach using islanding and rate of frequency decline-based load shedding," *Power Systems, IEEE Transactions on,* vol. 18, pp. 174-181, 2003.

[31] K. Seethalekshmi, S. N. Singh, and S. C. Srivastava, "WAMS assisted frequency and voltage stability based adaptive load shedding scheme," in *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, 2009, pp. 1-8.

[32] H. Cheng-Ting, C. Hui-Jen, and C. Chao-Shun, "Artificial Neural Network Based Adaptive Load Shedding for an Industrial Cogeneration Facility," in *Industry Applications Society Annual Meeting, 2008. IAS '08. IEEE,* 2008, pp. 1-8.

[33] L. Aimin and C. Zexiang, "A method for frequency dynamics analysis and load shedding assessment based on the trajectory of power system simulation," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*, 2008, pp. 1335-1339.

[34] X. Ding and A. A. Girgis, "Optimal load shedding strategy in power systems with distributed generation," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 788-793 vol.2.

[35] Z. X. Cai and Y. X. Ni, "A direct method for frequency stability assessment of power systems," in *Advances in Power System Control, Operation and Management, 2000. APSCOM-00. 2000 International Conference on*, 2000, pp. 285-289 vol.1.

[36] Y. Xue, "Fast analysis of stability using EEAC and simulation technologies," in *Power System Technology, 1998. Proceedings. POWERCON '98. 1998 International Conference on*, 1998, pp. 12-16 vol.1.

[37] D. Prasetijo, W. R. Lachs, and D. Sutanto, "A new load shedding scheme for limiting underfrequency," *Power Systems, IEEE Transactions on,* vol. 9, pp. 1371-1378, 1994.

[38] T. Wei, S. Chen, Z. Xuemin, and N. Jingmin, "A new under-frequency load shedding scheme based on OBDD," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on*, 2009, pp. 1-5.

[39] S. S. Ladhani and W. Rosehart, "Under voltage load shedding for voltage stability overview of concepts and principles," in *Power Engineering Society General Meeting, 2004. IEEE*, 2004, pp. 1597-1602 Vol.2.

[40] P. S. Kundur, *Power system stability and control*: Mc Grow-Hill, 1993.

[41] A. Saffarian, M. Sanaye-pasand, and H. Asadi, "Performance Investigation of New Combinational Load Shedding Schemes," in *Power System Technology and IEEE Power India Conference, 2008. POWERCON 2008. Joint International Conference on*, 2008, pp. 1-8.

[42] L. Ying, K. Wen-Shiow, and C. Yung-Tien, "Study of applying load shedding scheme with dynamic D-factor values of various dynamic load models to Taiwan power system," *Power Systems, IEEE Transactions on,* vol. 20, pp. 1976-1984, 2005.

[43] M. La Scala, M. Trovato, and C. Antonelli, "On-line dynamic preventive control: an algorithm for transient security dispatch," *Power Systems, IEEE Transactions on,* vol. 13, pp. 601-610, 1998.

[44] R. C. Dugan and S. K. Price, "Issues for distributed generation in the US," in *Power Engineering Society Winter Meeting, 2002. IEEE*, 2002, pp. 121-126 vol.1.

[45] W. Helmy, Y. G. Hegazy, M. A. Mostafa, and M. A. Badr, "Implementing distributed generation to mitigate under-frequency load shedding," in *Power System Conference, 2008. MEPCON 2008. 12th International Middle-East*, 2008, pp. 136-140.

[46] "IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," *IEEE Std 1547.2-2008,* pp. 1-207, 2009.

[47] "IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems," *IEEE Std 1547-2003,* pp. 0_1-16, 2003.

[48] K. A. Nigim and Y. G. Hegazy, "Intention islanding of distributed generation for reliability enhancement," in *Power Engineering Society General Meeting, 2003, IEEE*, 2003, p. 2451 Vol. 4.

[49] M. Mardaneh and G. B. Gharehpetian, "Siting and sizing of DG units using GA and OPF based technique," in *TENCON 2004. 2004 IEEE Region 10 Conference*, 2004, pp. 331-334 Vol. 3.

[50] A. R. Malekpour, A. R. Seifi, M. R. Hesamzadeh, and N. Hosseinzadeh, "An optimal load shedding approach for distribution networks with DGs considering capacity deficiency modelling of bulked power supply," in *Power Engineering Conference, 2008. AUPEC '08. Australasian Universities*, 2008, pp. 1-7.

[51] J. Ding and Z. Cai, "Mixed Measurements State Estimation Based on Wide-Area Measurement System and Analysis," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1-5.

[52] R. V. Fernandes, S. A. B. de Almeida, F. P. M. Barbosa, and R. Pestana, "Load shedding; Coordination between the Portuguese transmission grid and the Distribution grid with minimization of loss of Distributed Generation," in *PowerTech, 2009 IEEE Bucharest*, 2009, pp. 1-6.

[53] S. Hirodontis, H. Li, and P. A. Crossley, "Load shedding in a distribution network," in *Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference on*, 2009, pp. 1-6.

[54] K. Maslo and J. Andel, "Gas turbine model using in design of heat and power stations," in *Power Tech Proceedings, 2001 IEEE Porto*, 2001, p. 6 pp. vol.4.

[55] O. Anaya-Lara, F. M. Hughes, N. Jenkins, and G. Strbac, "Contribution of DFIG-based wind farms to power system short-term frequency regulation," *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 153, pp. 164-170, 2006.

[56] M. García-Gracia, M. P. Comech, J. Sallán, and A. Llombart, "Modelling wind farms for grid disturbance studies," *Renewable Energy*, vol. 33, pp. 2109-2121, 2008.

[57] M. Weixelbraun, H. Renner, R. Schmaranz, and M. Marketz, "Dynamic simulation of a 110-kV-network during grid restoration and in islanded operation," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[58] P. Mahat, C. Zhe, and B. Bak-Jensen, "Underfrequency Load Shedding for an Islanded Distribution System With Distributed Generators," *Power Delivery, IEEE Transactions on*, vol. 25, pp. 911-918, 2010.

[59] "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies," *IEEE Std 421.5-2005 (Revision of IEEE Std 421.5-1992)*, pp. 0_1-85, 2006.

[60] "Program Operation Manual," in *Power Technologies*, ed: Inc. New York.

[61] L. Poh Chiang, M. J. Newman, D. N. Zmood, and D. G. Holmes, "A comparative analysis of multiloop voltage regulation strategies for single and three-phase UPS systems," *Power Electronics, IEEE Transactions on,* vol. 18, pp. 1176-1185, 2003.

[62] P. Du, "Operation of power system with distributed generation," PhD, RENSSELAER POLYTECHNIC INSTITUTE, 2006.

[63] T. Jain, S. N. Singh, and S. C. Srivastava, "Dynamic available transfer capability computation using a hybrid approach," *Generation, Transmission & Distribution, IET,* vol. 2, pp. 775-788, 2008.

[64] "Dynamic Security Assessment for Power Systems: Research Plan," August 1987 1987.

[65] M. Aggoune, M. A. El-Sharkawa, D. C. Park, M. J. Damborg, and R. J. Marks, II, "Preliminary results on using artificial neural networks for security assessment [of power systems]," *Power Systems, IEEE Transactions on,* vol. 6, pp. 890-896, 1991.

[66] M. Aggoune, M. A. El-Sharkawi, D. C. Park, M. J. Damborg, and R. J. Marks, II, "Correction to `Preliminary results on using artificial neural networks for security assessment' (May 91 890-896)," *Power Systems, IEEE Transactions on,* vol. 6, pp. 1324-1325, 1991.

[67] D. J. Sobajic and Y. H. Pao, "Artificial neural-net based dynamic security assessment for electric power systems," *Power Systems, IEEE Transactions on,* vol. 4, pp. 220-228, 1989.

[68] M. Djukanovic, D. J. Sobajic, and Y. H. Pao, "Neural net based determination of generator-shedding requirements in electric power systems," *Generation, Transmission and Distribution, IEE Proceedings C,* vol. 139, pp. 427-436, 1992.

[69] E. J. Thalassinakis and E. N. Dialynas, "A Monte-Carlo simulation method for setting the underfrequency load shedding relays and selecting the spinning reserve policy in autonomous power systems," *Power Systems, IEEE Transactions on,* vol. 19, pp. 2044-2052, 2004.

[70] X. Xiaofu and L. Wenyuan, "A New Under-Frequency Load Shedding Scheme Considering Load Frequency Characteristics," in *Power System Technology, 2006. PowerCon 2006. International Conference on*, 2006, pp. 1-4.

[71] T. S. P. Fernandes, J. R. Lenzi, and M. A. Mikilita, "Load Shedding Strategies Using Optimal Load Flow With Relaxation of Restrictions," *Power Systems, IEEE Transactions on,* vol. 23, pp. 712-718, 2008.

[72] "IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration," *IEEE Std C37.117-2007,* pp. c1-43, 2007.

[73] S. Bonian, X. Xiaorong, and H. Yingduo, "WAMS-based Load Shedding for Systems Suffering Power Deficit," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1-6.

[74] M. Etezadi-Amoli, "On underfrequency load shedding schemes," in *Power Symposium, 1990. Proceedings of the Twenty-Second Annual North American*, 1990, pp. 172-180.

[75] J. Bertsch, C. Carnal, D. Karlson, J. McDaniel, and K. Vu, "Wide-Area Protection and Power System Utilization," *Proceedings of the IEEE*, vol. 93, pp. 997-1003, 2005.

[76] C. R. Rowland, D. W. Smaha, and J. W. Pope, "Coordination of Load Conservation with Turbine-Generator Underfrequency Protection," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-99, pp. 1137-1150, 1980.

[77] V. V. Terzija and H. J. Koglin, "Adaptive underfrequency load shedding integrated with a frequency estimation numerical algorithm," *Generation, Transmission and Distribution, IEE Proceedings-,* vol. 149, pp. 713-718, 2002.

[78] M. Parniani and A. Nasri, "SCADA based under frequency load shedding integrated with rate of frequency decline," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 6 pp.

[79] M. Larsson and C. Rehtanz, "Predictive frequency stability control based on wide-area phasor measurements," in *Power Engineering Society Summer Meeting, 2002 IEEE*, 2002, pp. 233-238 vol.1.

[80] V. N. Chuvychin, N. S. Gurov, S. S. Venkata, and R. E. Brown, "An adaptive approach to load shedding and spinning reserve control during underfrequency conditions," *Power Systems, IEEE Transactions on,* vol. 11, pp. 1805-1810, 1996.

[81] M. Lukic, I. Kuzle, and S. Tesnjak, "An adaptive approach to setting underfrequency load shedding relays for an isolated power system with private generation," in *Electrotechnical Conference, 1998. MELECON 98., 9th Mediterranean*, 1998, pp. 1122-1125 vol.2.

[82] Z. Salcic, Z. Li, U. D. Annakkage, and N. Pahalawaththa, "A comparison of frequency measurement methods for underfrequency load shedding," *Electric Power Systems Research,* vol. 45, pp. 209-219, 1998.

[83] A. A. M. Zin, H. M. Hafiz, and W. K. Wong, "Static and dynamic under-frequency load shedding: a comparison," in *Power System Technology, 2004. PowerCon 2004. 2004 International Conference on*, 2004, pp. 941-945 Vol.1.

[84] A. M. Leite da Silva, A. M. Cassula, R. Billinton, and L. A. F. Manso, "Optimum load shedding strategies in distribution systems," in *Power Tech Proceedings, 2001 IEEE Porto*, 2001, p. 6 pp. vol.2.

[85] H. M. Dola and B. H. Chowdhury, "Intentional islanding and adaptive load shedding to avoid cascading outages," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 8 pp.

[86] M. Begovic and D. Novosel, "On Wide Area Protection," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-5.

[87] E. Price, "Practical considerations for implementing wide area monitoring, protection and control," in *Protective Relay Engineers, 2006. 59th Annual Conference for*, 2006, p. 12 pp.

[88] M. A. El-Hadidy, D. H. Helmi, H. G. Negm, and H. M. El-Shaer, "Starting Synchrophasor measurements in Egypt: A pilot project using fault recorders," in *Power System Conference, 2008. MEPCON 2008. 12th International Middle-East*, 2008, pp. 157-161.

[89] J. G. Thompson and B. Fox, "Adaptive load shedding for isolated power systems," *Generation, Transmission and Distribution, IEE Proceedings-*, vol. 141, pp. 491-496, 1994.

[90] S. A. Nirenberg, D. A. McInnis, and K. D. Sparks, "Fast acting load shedding," *Power Systems, IEEE Transactions on*, vol. 7, pp. 873-877, 1992.

[91] K. Abdel-Rahman, L. Mill, A. Phadke, J. De La Ree, and L. Yilu, "Internet based wide area information sharing and its roles in power system state estimation," in *Power Engineering Society Winter Meeting, 2001. IEEE*, 2001, pp. 470-475 vol.2.

[92] A. Mao, J. Yu, and Z. Guo, "PMU placement and data processing in WAMS that complements SCADA," in *Power Engineering Society General Meeting, 2005. IEEE*, 2005, pp. 780-783 Vol. 1.

[93] A. G. Phadke and J. S. Thorp, "HISTORY AND APPLICATIONS OF PHASOR MEASUREMENTS," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 331-335.

[94] "IEEE Standard for Synchrophasors for Power Systems," *IEEE Std C37.118-2005 (Revision of IEEE Std 1344-1995)*, pp. 0_1-57, 2006.

[95] Z. Li and Z. Jin, "UFLS Design by Using f and Integrating df/dt," in *Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES*, 2006, pp. 1840-1844.

[96] (2013). *Load-Frequency Control and Performance*. Available: https://www.entsoe.eu/

[97] S. H. Horowitz, A. Politis, and A. F. Gabrielle, "Frequency Actuated Load Shedding and Restoration Part II - Implementation," *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-90, pp. 1460-1468, 1971.

[98] C.-C. Huang and S.-J. Huang, "A time-based load shedding protection for isolated power systems," *Electric Power Systems Research*, vol. 52, pp. 161-169, 1999.

[99] T. K. P. Medicherla, R. Billinton, and M. S. Sachdev, "Generation Rescheduling and Load Shedding to Alleviate Line Overloads-Analysis," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-98, pp. 1876-1884, 1979.

[100] T. K. P. Medicherla, R. Billinton, and M. S. Sachdev, "Generation Rescheduling and Load Shedding to Alleviate Line Overloads-System Studies," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-100, pp. 36-42, 1981.

[101] A. Shandilya, H. Gupta, and J. Sharma, "Method for generation rescheduling and load shedding to alleviate line overloads using local optimisation," *Generation, Transmission and Distribution, IEE Proceedings C,* vol. 140, pp. 337-342, 1993.

[102] entsoe. (2013). *Load-Frequency Control and Performance*. Available: https://www.entsoe.eu/

[103] P. Djapic, C. Ramsay, D. Pudjianto, G. Strbac, J. Mutale, N. Jenkins*, et al.*, "Taking an active approach," *Power and Energy Magazine, IEEE,* vol. 5, pp. 68-77, 2007.

[104] "IEEE Recommended Practice for Utility Interface of Residential and Intermediate Photovoltaic (PV) Systems," *ANSI/IEEE Std 929-1988,* p. 0_1, 1987.

[105] C. T. Hsu, M. S. Kang, and C. S. Chen, "Design of adaptive load shedding by artificial neural networks," *Generation, Transmission and Distribution, IEE Proceedings-,* vol. 152, pp. 415-421, 2005.

[106] M. A. Mitchell, J. A. P. Lopes, J. N. Fidalgo, and J. D. McCalley, "Using a neural network to predict the dynamic frequency response of a power system to an under-frequency load shedding scenario," in *Power Engineering Society Summer Meeting, 2000. IEEE,* 2000, pp. 346-351 vol. 1.

[107] M.A. Pai, *Energy Function Analysis for Power System Stability,*: Kluwer Academic Publishers, 1989.

[108] P. M. Anderson and A. A. Fouad, *POWER SYSTEM CONTROL AND STABILITY, 2ND ED*: Wiley India Pvt. Limited, 2008.

[109] M. R. Aghamohammadi, "Iran Grid Frequency Studies (Winter & Summer 2012)," Iran Dynamic Research Center (IDRC), Tehran, Iran.

[110] J. Machowski, J. Bialek, and J. J. R. Bumby, *Power System Dynamics (Stability and Control),* Second Edition ed.: Wiley, 2008.

[111] A. R. Bergen and V. Vittal, *Power Systems Analysis*: Prentice Hall, 2000.

[112] I. C. Report, "Dynamic Models for Steam and Hydro Turbines in Power System Studies," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-92, pp. 1904-1915, 1973.

[113] P. M. Anderson, A. A. A. Fouad, I. o. Electrical, and E. Engineers, *Power system control and stability*: IEEE Press, 2003.

[114] K. Inc., "Impact of Large-Scale Distributed Generation Penetration on Power System Stability " 2006.

[115] D. GmbH, "DIgSILENT Power Factory/Library/Models/IEEE/Frames/IEEE-frame no droop," 14.0 ed, 2010.

[116] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*: Wiley, 2012.

[117] I. C. Report, "Computer representation of excitation systems," *Power Apparatus and Systems, IEEE Transactions on,* vol. PAS-87, pp. 1460-1464, 1968.

[118] "General Load Model " DIgSILENT GmbH Germany, 2008.

[119] J. A. P. Lopes, W. Wong Chan, and L. M. Proenca, "Genetic algorithms in the definition of optimal load shedding strategies," in *Electric Power Engineering, 1999. PowerTech Budapest 99. International Conference on*, 1999, p. 154.

[120] Y. Shu-Xia, "Neural network forecast under the organic hybrid model of genetic algorithm and particle swarm algorithm," in *Wavelet Analysis and Pattern Recognition, 2008. ICWAPR '08. International Conference on*, 2008, pp. 254-258.

[121] D. E. Goldberg, *Genetic Algorithms In Search, Optimization and Machine Learning.*: MA: Addison-Wesley, 1989.

[122] J. Holland, *Adaptation In Natural And Artificial Systems*: MI: University of Michigan Press,, 1975.

[123] J. J. Grefenstette, "Optimization of Control Parameters for Genetic Algorithms," *Systems, Man and Cybernetics, IEEE Transactions on,* vol. 16, pp. 122-128, 1986.

[124] A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis, "Optimal power flow by enhanced genetic algorithm," *Power Systems, IEEE Transactions on,* vol. 17, pp. 229-236, 2002.

[125] F. Oliveira, S. Hamacher, and M. Almeida, "Process industry scheduling optimization using genetic algorithm and mathematical programming," *Journal of Intelligent Manufacturing,* vol. 22, pp. 801-813, 2011.

[126] W. Shouchun and D. Xiucheng, "Predicting China's Energy Consumption Using Artificial Neural Networks and Genetic Algorithms," in *Business Intelligence and Financial Engineering, 2009. BIFE '09. International Conference on*, 2009, pp. 8-11.

[127] A. A. Abou El Ela, A. Z. El-Din, and S. R. Spea, "Optimal corrective actions for power systems using multiobjective genetic algorithms," in *Universities Power Engineering Conference, 2007. UPEC 2007. 42nd International*, 2007, pp. 365-376.

[128] S. K. Jain, P. C. Nayak, and K. P. Sudheer, "Models for estimating evapotranspiration using artificial neural networks, and their physical interpretation," *Hydrological Processes*, vol. 22, pp. 2225-2234, 2008.

[129] D. Marquardt, " An Algorithm for Least-Squares Estimation of Nonlinear Parameters," *SIAM J. Appl. Math.* , vol. Vol. 11, pp. pp 431-441, 1963.

[130] K. Levenberg, " A Method for the Solution of Certain Problems in Least Squares," *Quart. Appl. Math.* , vol. Vol. 2,, pp. pp 164-168, , 1944.

[131] A. U. Khan, T. K. Bandopadhyaya, and S. Sharma, "Comparisons of Stock Rates Prediction Accuracy Using Different Technical Indicators with Backpropagation Neural Network and Genetic Algorithm Based Backpropagation Neural Network," in *Emerging Trends in Engineering and Technology, 2008. ICETET '08. First International Conference on*, 2008, pp. 575-580.