UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A MODIFIED ADAPTIVE PROTECTION SCHEME USING MACHINE LEARNING TECHNIQUE FOR FAULT CLASSIFICATION IN RENEWABLE ENERGY PENETRATED TRANSMISSION LINE

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By

OSAJI EMMANUEL OLUFEMI

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

September 2020

DEDICATION

This thesis is dedicated to God for His infinite mercies, provisions and guidance all through the research period. To God, be all glory. (amen)

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

DEVELOPMENT OF A MODIFIED ADAPTIVE PROTECTION SCHEME USING MACHINE LEARNING TECHNIQUE FOR FAULT CLASSIFICATION IN RENEWABLE ENERGY PENETRATED TRANSMISSION LINE

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Chair : Mohammad Lutfi Othman, PhD PEng
Faculty : Engineering

The conventional utility grid-protection scheme is predesigned at the network's early planning stage with consideration to the high short circuit fault current magnitude contribution level from the Synchronous Generators (SG) to prevent the mal-operation of the relaying scheme. In the modern power system grid, the integration of the Renewable Energy Resources (RER) from Windfarms (WF) or Photovoltaic (PV) generation sources focused on addressing the climate change environmental issues and solving the impending future energy sustainability challenges. In compliance with the new grid code requirement of permanently integrating RER with the conventional SG sources during grid short circuit faults, also known as the low voltage fault ride-through (LVFRT). Such RERs integration phenomenon compromised the existing protection relaying scheme operation settings due to the power grid system topology changes. The added infeed current penetration from integrated RERs impacted adversely on the existing protective relay operation setting compromise. The relay operation setting compromise is due to the wrong estimated impedance seen by the relay leading to overreach or underreach mal-operation. The current Adaptive Protection Scheme (APS) motivation focused on the accurate relay operation setting changes based on the prevailing grid system configuration variations. Hence, eliminate the utility grid relay operation setting compromise. The lack of healthy lines detailed protection useful information knowledge has limited the existing APS performance, as only faulty lines' measured parameters (voltage, current, and phase angle) are mostly used in the relaying protection scheme design. The high-cost of implementations, cyber-attack, and latency concerns from the adopted communication channels for the standard APS relay characteristic setting and selection is another drawback identified. This study proposed a modified standalone Machine Learning-based Adaptive Protection Scheme (ML-APS) relay' fault classifier

model using novel useful hidden Knowledge Discovery from historical fault events Dataset (KDD) from healthy and faulty lines. The healthy lines extracted fault signals' functional signature are added to the earlier deployed faulty-line decomposed dataset, operation parameters, and changing network topology information from the SCADA logged reports without communication channel use. The hybrid Wavelet Multiresolution Analysis and Machine learning algorithm (WMRA-ML) is used to extracts the useful hidden knowledge from decomposed one-cycle fault transient signals (voltage & current) from four Matlab/Simulink CIGRE models. Consideration was given to different RER penetration levels based on the changing network topologies subjected to twelve different short circuit fault scenarios.The selected 29 unique feature attributes across 15,120 historical faults dataset deployed as the input-output training dataset for the ML-APS relay classifier model development in Waikato Environment of Knowledge Analysis Software (WEKA). The obtained result from the twelve deployed ML algorithms for the standalone intelligent ML-APS relay classifier modification without communication medium adoption for transmitting and receiving the updated relay operation settings during network configuration changes. The RandomTree standalone ML-AP relay model presented the best performing models from the ML-APS relay model with the best average performance for the correctly classified fault types of 97.61 % at 5 % significance level above other ML algorithms. The recorded kappa statistic value of 0.9802, and the Receiver Operating Curve (ROC) area of 98.73 %. The RandomTree relay algorithm model presented an improved average trip decision time of 18 ms compared with the standard minimum value of 20 ms recorded for the conventional relay due to eliminated communication channels. The ML-AP relay model addressed the cyber-attack and latency compromises in the earlier APS relay for the modern power system network. The obtained result demonstrated useful hidden knowledge in the healthy line sections that have contributed valuable information for improved ML-APS relay model for the faults detection, discrimination, and decision trip improvement during the grid short circuit faults.

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

PEMBANGUNAN SKIM PERLINDUNGAN ADAPTIF TERUBAH SUAI MENGGUNAKAN TEKNIK PEMBELAJARAN MESIN UNTUK PENGKLASIFIKASIAN KEROSAKAN DALAM TALIAN PENGHANTARAN YANG TERTEMBUS TENAGA BOLEH DIPERBAHARUI

Oleh

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Skim perlindungan jaringan (grid) utiliti konvensional telah diprareka bentuk lebih awal pada peringkat perancangan awal jaringan dengan mempertimbangkan tahap sumbangan magnitud arus rosak litar pintas yang tinggi dari penjana segerak (synchronous generators, SG) untuk mengelakkan ketidak-operasian skim penggegantian. Dalam jaringan sistem kuasa moden, penyepaduan Sumber Tenaga Boleh Diperbaharui (Renewable Energy Resources, RER) dari sumber penjanaan Ladang Angin (Windfarms,WF) atau Photovolta (Photovoltaic, PV) menjurus kepada menangani isu persekitaran perubahan iklim dan mengatasi cabaran-cabaran kelestarian tenaga masa hadapan. Bagi mematuhi kehendak kod grid baru yang menyepadukan RER secara kekal dengan sumber SG konvensyional semasa kerosakan litar pintas grid, ianya juga dikenali sebagai pacu-lalu kerosakan voltan rendah (low voltage fault ride-through, LVFRT). Penyepaduan RER seperti ini telah mengkompromi pengesetan operasi skim penggegantian perlindungan sedia ada berikutan perubahan dalam topologi sistem jaringan kuasa. Penetrasi arus masukan tambahan dari penyepaduan RER telah memberi kesan buruk ke atas kompromi sedia ada pengesetan operasi skim geganti perlindungan. Kompromi pengesetan operasi geganti ini disebabkan oleh anggaran galangan yang salah yang dilihat oleh geganti yang membawa kepada ketidak-operasian lebih-jangkauan atau kurang-jangkauan. Motivasi terkini Skim Perlindungan Ubah Suai (Adaptive Protection Scheme, APS) memfokus kepada perubahan pengesetan operasi geganti yang tepat berdasarkan kepada variasi konfigurasi sistem jaringan yang lazim. Oleh itu, hapuskan kompromi pengesetan operasi skim geganti perlindungan utiliti berkenaan. Kurangnya pengetahuan informasi perlindungan berguna talian sihat telah menghadkan prestasi APS sedia ada, kerana hanya parameter terukur talian rosak (voltan, arus dan sudut fasa) yang banyak digunakan dalam reka bentuk skim perlindungan penggegantian. Kos pelaksanaannya yang tinggi, serangan siber, dan kerisauan kependaman dari saluran komunikasi yang digunakan untuk pengesetan dan pemilihan ciri geganti APS piawai adalah satu lagi kelemahan yang dikenalpasti. Kajian ini mencadangkan satu model pengklasifikasian kerosakan geganti Skim Perlindungan Ubah Suai berasaskan Pembelajaran Mesin (Machine Learning-based Adaptive Protection Scheme, ML-APS) kendiri terubahsuai dengan menggunakan Penemuan Pengetahuan yang berguna tersembunyi dari set data sejarah peristiwa kerosakan (Knowledge Discovery from Database, KDD) talian yang sihat dan rosak. Tanda kenal fungsian isyarat kerosakan tersari talian sihat ditambah kepada set data terurai talian rosak yang teratur sebelumnya, parameter operasi, dan maklumat topologi jaringan yang berubah dari laporan log SCADA tanpa penggunaan saluran komunikasi. Algoritma Analisa Berbilang Leraian Gelombang Kecil dan Pembelajaran Mesin (Wavelet Multiresolution Analysis and Machine learning, WMRA-ML) hibrid digunakan untuk mengestrak pengetahuan tersembunyi berguna dari isyarat transien rosak satu-kitaran terurai (voltan dan arus) dari empat model Matlab/Simulink CIGRE. Pertimbangan diberikan kepada tahap penetrasi RER berbeza berdasarkan topologi jaringan yang berubah terdedah kepada dua belas senario kerosakan litar pintas yang berbeza. 29 atribut ciri unik merentasi 15,120 data set sejarah kerosakan digunakan sebagai set data latihan input-output untuk pembangunan model pengklasifikasi geganti ML-APS dalam Waikato Environment of Knowledge Analysis Software (WEKA). Keputusan yang diperolehi daripada dua belas algoritma ML yang digunakan untuk modifikasi pengklasifikasi geganti ML-APS pintar kendiri tanpa penggunaan media komunikasi untuk menghantar dan menerima pengesetan operasi geganti yang terkini ketika perubahan konfigurasi jaringan. Model geganti ML-AP kendiri Pohon Rawak (Random Tree) mengemukakan model persembahan yang terbaik dengan prestasi purata terbaik untuk jenis kerosakan yang betul diklasifikasi 97.61 % pada aras signifikan 5 % melebihi algoritma ML lain. Nilai statistik kappa yang direkodkan adalah 0.9802 dan keluasan Lengkuk Operasi Penerima (Receiver Operating Curve, ROC) adalah 98.73 %. Model algoritma geganti Pohon Rawak (Random Tree) menghasilkan masa keputusan pelantik purata yang lebih baik iaitu 18 ms berbanding dengan nilai minima piawai 20 ms yang direkodkan untuk geganti konvensiional disebabkan saluran komunikasi yang dihapuskan. Model geganti ML-AP ini dapat mengatasi kompromi kepada serangan siber dan kependaman yang didapati dalam geganti APS terdahulu untuk jaringan sistem kuasa yang moden. Keputusan yang diperolehi menunjukkan bahawa pengetahuan tersembunyi yang berguna dalam bahagian talian yang sihat telah menyumbang maklumat berguna untuk model geganti ML-APS yang lebih baik untuk pengesanan kerosakan, diskriminasi, dan penambahbaikan pelantik keputusan ketika kerosakan litar pintas jaringan.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AP	adaptive protection
APS	adaptive protection scheme
ARFF	attribute relation file format
AWDA	adaptive weather data acquisition
CA	approximate coefficient
CB	circuit breaker
CD	detailed coefficient
CSV	comma separated value
CT	current transformer
DER	distributed energy resources
DFIG	doubly-fed induction generation
DLG	double-line-to-ground
EE	entropy energy
GHG	greenhouse gas
HP	high-pass
Imp	maximum current power
KDD	knowledge discovery from historical fault events dataset
LP	low-pass
LVFRT	low voltage fault ride-through
ML	machine learning
ML-APS	machine-learning adaptive protection
MPPT	maximum power point tracker
Ncell	cell per module
PCC	point of common coupling
PMU	phasor measurement unit
PT	potential transformer
PV	photovoltaic
Rsh	shunt resistance
Rs	Series resistance
RER	renewable energy resources
ROC	receiver operating curve
SCADA	supervisory control and data acquisition
SG	synchronous generator
SLG	single line-ground
STD	standard deviation
Vmp	maximum power voltage
Voc	open circuit voltage
VPP	virtual power plant
VSC	voltage source converter
WEKA	waikato environment of knowledge analysis
WF	windfarm
WMRA	wavelet multiresolution analysis
WMRA-ML	wavelet multiresolution analysis and machine learning

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The electrical power utility grid protective relaying scheme depends on some preset system operation parameter measurements such as the line voltage, current, and phase angle displacement [1]. These parameters assist in the line impedance estimation for effective fault detection, location, and decision trip initiation for any power system contingencies/disturbances [2]. The need to quickly isolate any system contingencies due to power system configuration changes is to restore power system stability [3, 4]. The energy sustainability challenges and the quest for alternative environmentally-friendly power generating sources have necessitated the current demand for the massive integration of renewable energy resources (RER) from Windfarm (WF) and Photovoltaic (PV) systems into the existing utility grid system [5, 6]. The RER's choices are encouraged by the reduced greenhouse gas emissions (GHG) and the replenishing capacity of both sources in addressing the global energy demand sustainability challenges [7]. The new code requirement's emergence enables continuous integration of the Doubly-Fed Induction Generator (DFIG) based WF [8, 9] and large megawatts rated PV modules system [10, 11] on the same utility grid network during the grid short circuit fault. The phenomenon is known as the low voltage fault ride-through (LVFRT) [12, 13].

The modern power grid system has large integrated RERs expected to provide full dynamic voltage stability support through reactive current injection into the grid [14]. This approach maintains system stability without disconnecting the alternative RER sources from the grid to prevent the power system from collapse during short circuit faults [15-17]. On the contrary, the new RER integration paradigm shift has introduced some power system protection-related problem [18] and other system contingencies due to reduced system inertial support mostly produced from the conventional Synchronous Generator (SG) sources. The large RER integration on the existing utility grid is accompanied by several technical issues that must be addressed like: the power system security, system stability/frequency deviation, power quality [19-21], and protection scheme compromise challenges [22] for the smooth coexistence of both conventional Synchronous Generators (SG) and RER. The large short circuit current infeeds from these coexisting sources on the same networks into the faulty section of the line has introduced some protection challenges due to the new grid code implementation [13, 23]. This study focuses on the protection relay operation setting compromise challenges based on the changes in the network configurations due to the short circuit fault current penetration impact on the protective relay operation setting during grid fault

1.2 Problem Statement

In a quest to address the impending conventional protective relay operation setting compromise due to network configuration changes resulting from additional infeed current penetrations from RER into the faulty line section in the modern power grid system. Earlier relaying scheme deployed fixed system short circuit level mainly from only synchronous Generators (SG) for the fixed preset characteristic selection for enhanced system safety and protection reliability. The need for constant changes in the relay operation parameter setting has necessitated introducing the Adaptive Protection Scheme (APS) to improve modern power system protection [24]. The adaptive protection (AP) relay changes its operational parameters based on the system operating parameter's prevailing changes to maintain adequate safety, as seen in the distance relay APS [25]. The infeed penetrations impact the APS relay operation characteristic updates adversely at regular intervals varying from 1-10 minutes through the advanced telecommunication channel [26]. The short circuit fault current infeed penetration from the RER integration on the existing utility grid system compromises the relay operation parameter settings updating due to the network topology changes. If not addressed within reasonable trip operation time, such safety compromise may lead to undesirable damages to equipment installations and personnel lives and may cause power system outages. The need for an improved trip decision time better than the current existing 20 ms of the existing numerical APS is also a motivation for this present study.

The existing APS for the transmission line protection uses digital relay and advance communication technology to provide the dynamic protection scheme for a transmission line system [27]. APS operation is based on a centralized protection scheme that updates the relay operation parameter settings using a look-up characteristic table at the substation to adjust the operating parameters based on the network topology changes [28]. The bidirectional communication medium between the relay location and the substation computer database is costly to implement and may be subjected to cyber-attack challenges. Besides, current APS uses sampled information from the faulted lines' voltage, current, and phase angle parameters to estimate the new operation characteristic selection based on the prevailing network topology changes at equal time intervals. There is a need to modify the existing APS relay operation using discovered hidden knowledge from historical fault data records from both healthy and faulty lines for the intelligently modified APS using the Machine learning (ML) algorithm-based fault classier model. This study is focused on building a standalone ML-APS relay model that will address the preset relay operation compromise resulting from the network configuration changes due to short circuit fault current penetrations from the RERs during grid faults [29]. The modified standalone ML-APS will eliminate a communication channel for updating the operation characteristic selection and trip decision transmission. Hence, addressing the cyber-attack tendencies. It will also reduce decision trip time for the short circuit fault detection and classification without a communication channel.

1.3 Research Objectives

The main aim is to develop a modified Machine Learning (ML) Adaptive Protection Scheme (ML-APS) relay model for short circuit fault classification during system network configuration changes due to additional infeed current penetrations from the integrated RERs sources during grid faults. The modified ML-APS relay will eliminate existing relay compromise, fast decision trip time, and eliminate the cyber-attack challenges under different prevailing network configuration changes. The proposed ML-APS model with the new grid code implementation will encourage RER and SG sources networks' coexistence as an interconnected system. The study comprised the following three-pronged sub-objectives.

i. To discover hidden knowledge from historical fault database (KDD) extracted records from healthy and faulty lines using Wavelet Multi-Resolution Analysis (WMRA) of one-cycle transient fault voltage and current signals.
ii. To develop a modified APS relay model using Machine Learning (ML) algorithm (ML-APS) under different network configuration changes for faults detection, classification, and fast tripping on integrated RERs grid networks
iii. To validate the modified ML-APS relay classifier model performance using new fault dataset for model generalization based on selectivity, reliability, and improve trip-decision time.

When these objectives are achieved, the modified ML-APS relay model should eliminate the impending operation setting compromise with fast tripping speed. The study help reduce the damaging impact of the short circuit fault current infeed penetration on the equipment installation and personnel safety. Furthermore, the standalone modified APS without communication link eliminates the cyber-attack tendencies on the system network.

1.4 Research Hypothesis

A modified APS relay model based on Machine Learning (ML) algorithm will eliminate the relay mal-operation compromise with an improved fault trip time due to current infeed contribution from integrated renewable energy resources (RER) during grid faults.

1.5 Research Scope and Limitation

This study's scope is focused on testing the formulated hypothesis towards achieving all proposed objectives for the modified ML-APS relay classifier model development. The study divulged the information on short circuit historical fault database records from both faulty and healthy lines combined with other network topology variation data and system operation parameter changes beginning from 15 km fault location due to Matlab/Simulink software limitations to conduct fault scenario at a much lower distance. The scope of the current study involves

i. Modification of the typical Matlab/Simulink CIGRE model of 120 kV double-ends sources, 50 Hz utility transmission line network with two penetrated RER from Windfarm (WF), and Photovoltaic (PV) system.
ii. The historical fault event recording during grid short circuit fault transient event simulations, and extraction of one-cycle transient voltage and current signals from both healthy/ faulty lines at the Point of Common Coupling (PCC).
iii. The study extracted hidden knowledge discovered from the historical fault database (KDD) by mining unique, useful feature coefficients from decomposed voltage and current signals from the healthy and faulty line using the WMRA toolbox in Matlab.
iv. The deployment of the extracted 29 useful feature coefficients as inputs for the modified ML-APS relay classifier model's training using supervised learning in WEKA software.
v. Testing trained ML-APS relay models on discrimination of ten different fault types under various network configuration changes, due to different fault current penetration levels from both RERs and SG without compromise at rapid trip decision time.
vi. Validation of the modified ML-APS relay model for generalizations performance test on new fault records from a different location and current penetration levels.
vii. Modify existing APS relay with the integration of the extracted generated code from the ML-APS relay model.

The current research is limited to the offline deployment of modified ML-APS relay fault classifier model without the real-time sensors data acquisition deployments from the Adaptive Weather Data Acquisition (AWDA) and Supervisory Control and Data Acquisition (SCADA) units [30].

1.6 Research Contributions

This research study on the modified ML-APS relay fault classifier model eliminates impending short circuit fault current infeed penetration impact on protection relay operation compromise on RER integrated transmission line. This relay operation compromise prevented the smooth coexistence of both conventions SGs and RERs on the utility grid network as the future energy sustainable solution. The following are the contributions to the existing body of knowledge in this area of power system protection analysis.

i. The novel adoption of discovered useful hidden knowledge from the healthy lines transient signals added to the usual faulty line parameters, network topologies variation data, and system operation parameters improved the intelligent modified ML-APS relay model.

ii. The modified ML-APS relay algorithm-code modification improved the relay decision trip-time with a minimum value of 0.18 ms below the conventional minimum recorded 20 ms.
iii. The ML-APS relay selectivity is enhanced by isolating only the affected line through practical fault discrimination under different power system configuration changes without compromise.
iv. The standalone ML-APS relay model has prevented cyber-attack tendencies by eliminating communication lines for relay operation parameter setting, characteristic selection, and trip decision code transmission.

1.7 The layout of the Thesis

Chapter 1 is the introduction section with insight into the background on adaptive protection scheme (APS), associated problem to the existing APS scheme on a transmission line with integrated RERs. The objectives for solving the discovered gap, scope, and limitations of the current study are divulged.

Chapter 2 (Literature Review) discusses the impact of renewable energy choices on the existing protective relay compromise. Literature reviews on the existing APS relay algorithm models, the parameters used for the APS execution, performance challenges, and the limitations from each approach identified. The discovered gap to be addressed by modifying the existing APS relay approach highlighted for integrated RERs during grid faults.

Chapter 3 (Methodology and Procedures) elaborates steps in achieving the proposed research objectives based on the formulated hypothesis for the modified ML-APS relay classifier model actualization. Deep insight into the sequential steps adopted for hybrid WMRA and data mining algorithms deployment for the modified ML-APS relay model realization under changing network configuration based on different short circuit penetration infeeds from RERs from WF, PV and SG system presented.

Chapter 4 (Results and Discussions) presented detailed discussions on obtained ML-APS relay model results under different network topologies changes based on various infeed current penetrations from both RERs and SG during utility grid faults. The best intelligent computational algorithm model selection was conducted based on the performance comparison and computation time constraints satisfaction. The final validation of the build ML-APS relay fault classifier model demonstrated.

Chapter 5 (Conclusion and Recommendations) presents the modified ML-APS relay models' implication in addressing the projected objectives in Chapter 1 and future recommendations.

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