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MACHINE-LEARNING-BASED ADAPTIVE DISTANCE PROTECTION RELAY TO ELIMINATE ZONE-3 PROTECTION UNDER-REACH PROBLEM ON STATCOM-COMPENSATED TRANSMISSION LINES

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FK 2021 11

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By

AKER ELHADI EMHEMED ALHAAJ AMMAR

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

November 2020

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DEDICATION

I would like to thank my supervisors for their guidance and invaluable advice, alongside my deepest gratitude to my lovely wife and dear children. You are the best gift in my life.

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

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November 2020

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There is impending distance relay (DR) zone-3 backup protection element safety compromise in a midpoint integrated STATCOM on the utility grid system. This impending protection limitation is due to the relay under-reach effect due to the infeed reactive current injection into the grid from the midpoint integrated STATCOM device during the far-end short circuit fault at the zone-3 element protection coverage boundary. The infeed injected current led to the wrong line impedance estimation from the relay location to the faulty line section. Such compensated power grid protection actualization is a critical concern to the power system protection engineer due to the involvement of the injected reactive current from the STATCOM in the apparent impedance fault loop used seen by the relay for every fault beyond the DR midpoint location for effective short circuit fault isolation. This nuisance current contribution from the midpoint integrated STATCOM device assists in the power system voltage stability but causes a protection compromise for the backup zone-3 protection element during the far-end short circuit faults at the relay protection boundary. The estimated fault impedance value by the zone-3 elements is slightly higher than the actual pre-fault estimated threshold value under normal operating conditions. Thereby locating the apparent impedance trajectory outside the preset protection coverage as if there was no fault in the system, leading to protection safety compromise. Several conventional adaptive distance relay (ADR) and computational based intelligent modifications presented to solve the impending compromise by using faulted line voltage and current parameters for the various protection relay controller modification, optimizing synchronized measurement to block or limit the fault current penetration into the grid. The computational complexity and mathematical formulation solutions are some limitations in optimizing the relay characteristic changes with changes in the system reactive power penetration for effective fault detection and isolations. The ADR schemes also presented high computational time due to communication channel breakdown, latency, and susceptibility to the cyber-attack since the communication channel is used for the trip command transmission and considering the high cost of communication medium. The earlier intelligent approach presented an offline approach using only faulty line parameters for intelligent classifier model training to detect, classify and locate faults. The model limitation is in retraining for new knowledge with changes in the power system network topology and lacks robustness. This current study proposes an intelligent data mining approach for the Machine Learning-Adaptive Distance Relay (ML-ADR) fault classification model using novel extracted 1-cycle transient voltage and current signals hidden knowledge from both healthy and faulty lines parameters. The hybrid discrete wavelet multiresolution analyses and machine learning (DWMRA-ML) algorithm is deployed to discover the hidden useful knowledge extraction from the 1-cycle short circuit transient fault signals (voltage and current) from healthy and fault lines section. These parameters are used to develop a standalone intelligently machine learning adaptive distance relay (ML-ADR) modification. The intelligent algorithm ML-ADR fault classifier model could discriminate 10 different far-end short circuit fault types from two network topology changes with and without midpoint integrated STATCOM on the Matlab/Simulink power grid system model. Other system parameter variations are 4 different fault resistances (0.001 Ω, 10 Ω, 50 Ω, 100 Ω), and two inception angles (0 °C and 30 °C). The prior result from the Matlab model of the adaptive numerical distance relay connected on midpoint integrated STATCOM power grid system indeed establish the existence of the under-reach effect for the relay zone-3 elements ing far-end short circuit fault at the coverage boundary leading to wrong impedance estimation. The BayesNet provides the best integrated ML-ADR fault classifier model better at a 5 % significance level than other deployed algorithms in the intelligent supervised learning model realization. The BayesNet ML-ADR classifier model performance evaluation with the highest kappa statistic value of 0.991, the lowest mean absolute error value of 0.0009, weighted average precision values of 99.2 %, ROC area coverage of 100 %, the most down trip decision time of 10 ms better than the existing 20 ms for conventional ADR. The integrated BayesNet ML-ADR fault classifier model eliminates the under-reach effect compromise on the zone-3 backup protection element for accurate fault detection, classification, and trip decision time reduction during far-end boundary faults. This model satisfied and finally met the objectives of the desired ADR.

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

GEGANTI PERLINDUNGAN JARAK ADAPTIF BERDASARKAN PEMBELAJARAN MESIN UNTUK MENGATASI MASALAH BAWAH JANGKAUAN PERLINDUNGAN ZON-3 PADA TALIAN PENGHANTARAN TERPAMPAS STATCOM

Oleh

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Pada sistem grid utiliti terdapat kompromi keselamatan dalam elemen perlindungan sandaran jarak jauh geganti (DR) zon-3 dalam STATCOM bersepadu titik tengah. Batasan perlindungan yang berlaku ini disebabkan oleh kesan geganti di bawah jangkauan kerana penyuntikan arus reaktif masuk ke dalam grid dari peranti STATCOM bersepadu titik tengah semasa kesalahan litar pintas di sempadan perlindungan elemen zon-3. Arus yang disuntikkan menyebabkan anggaran galangan talian yang salah dari lokasi geganti ke bahagian talian yang rosak. Perlindungan grid kuasa yang dikompromi seperti ini memerlukan perhatian yang serius dari jurutera perlindungan sistem kuasa kerana penglibatan arus reaktif yang disuntikkan oleh STATCOM dalam gelung kerosakan impedans yang jelas dilihat oleh geganti untuk setiap kesalahan di luar lokasi titik tengah DR untuk jangka pendek yang berkesan bagi pengasingan kerosakan litar. Gangguan arus dari peranti STATCOM bersepadu titik tengah membantu dalam menstabilkan voltan sistem kuasa tetapi menyebabkan kompromi perlindungan elemen sandaran zon-3 semasa kerosakan litar pintas pada batasan perlindungan geganti. Nilai anggaran impedansi kesalahan oleh elemen zon-3 lebih tinggi sedikit daripada nilai anggaran pra-kesalahan sebenar dalam keadaan pengoperasian biasa. Dengan itu, mencari lintasan impedans yang jelas di luar liputan perlindungan yang telah ditetapkan seolah-olah tidak ada kesalahan dalam sistem menyebabkan kompromi perlindungan keselamatan. Beberapa geganti jarak adaptif konvensional (ADR) dan modifikasi pintar berdasarkan komputasi yang digunakan untuk menyelesaikan kompromi yang akan berlaku dengan menggunakan voltan talian yang rosak dan parameter arus untuk pelbagai modifikasi kawalan geganti perlindungan, mengoptimumkan pengukuran yang diselaraskan untuk menyekat atau membatasi penembusan arus rosak ke dalam grid. Kerumitan komputasi dan penyelesaian rumusan matematik adalah beberapa batasan dalam mengoptimumkan perubahan ciri geganti dengan perubahan penembusan daya reaktif sistem untuk mengesan dan mengasingkan kesalahan dengan berkesan. Skema ADR juga memperlihatkan waktu komputasi yang tinggi kerana kerosakan saluran komunikasi, terancam dan terdedah kepada serangan siber kerana saluran komunikasi digunakan untuk penghantaran arahan trip serta pertimbang atas kos komunikasi yang tinggi. Pendekatan pintar yang awal menggunakan pendekatan luar talian yang hanya menggunakan parameter arus yang salah untuk membangunkan model latihan pengkelasan pintar untuk mengesan, mengklasifikasikan dan mencari kesalahan. Batasan model ini adalah keperluan untuk menjalani latihan semula bagi pengetahuan baru disebabkan perubahan topologi rangkaian sistem kuasa dan ianya kurang mantap. Kajian semasa ini mencadangkan pendekatan perlombongan data pintar untuk model klasifikasi kesalahan Machine Learning-Adaptive Distance Relay (ML-ADR) menggunakan voltan sementara 1 kitaran yang diekstrak dan isyarat semasa yang tersembunyi dari kedua-dua parameter talian sihat dan rosak. Analisis multiresolusi wavelet diskrit hibrid dan algoritma pembelajaran mesin (DWMRA-ML) digunakan untuk pengekstrakan pengetahuan berguna yang tersembunyi dalam isyarat kerosakan sementara litar pintas 1 voltan (voltan dan arus) dari bahagian talian sihat dan rosak. Parameter ini digunakan untuk membangunkan modifikasi jarak jauh adaptif pembelajaran geganti jarak jauh (ML-ADR). Model pengkelasan kesalahan algoritma ML-ADR pintar dapat membezakan 10 jenis kesalahan litar pintas jarak jauh yang berbeza dari dua perubahan topologi rangkaian dengan dan tanpa STATCOM bersepadu titik tengah pada model sistem grid kuasa Matlab / Simulink. Variasi parameter sistem lain adalah 4 rintangan kesalahan yang berbeza (0,001 Ω, 10 Ω, 50 Ω, 100 Ω), dan dua sudut permulaan (0 oC dan 30 oC). Hasil sebelumnya dari model Matlab dari geganti jarak berangka adaptif yang disambungkan pada sistem grid kuasa STATCOM bersepadu titik tengah sememangnya membuktikan wujudnya kesan di bawah jangkauan untuk elemen geganti zon-3 dengan kesalahan litar pintas pada batas liputan kepada anggaran impedans yang salah. BayesNet menyediakan model pengkelasan kesalahan ML-ADR terpadu yang lebih baik pada tahap kepentingan 5% daripada algoritma lain yang digunakan dalam merealisasikan model pembelajaran yang diselia pintar. Penilaian prestasi model pengkelasan BayesNet ML-ADR dengan nilai statistik kappa tertinggi 0.991, nilai ralat mutlak min terendah 0.0009, nilai ketepatan purata berwajaran 99.2%, liputan kawasan ROC 100%, masa keputusan perjalanan paling rendah 10 ms lebih baik daripada 20 ms yang ada untuk ADR konvensional. Model pengkelasan kesalahan BayesNet ML-ADR yang terintegrasi menghilangkan kompromi kesan di bawah elemen perlindungan sandaran zon-3 untuk pengesanan kesalahan, klasifikasi, dan pengurangan masa perjalanan yang tepat semasa kesalahan sempadan jarak jauh. Model ini menepati dan memenuhi objektif ADR yang diinginkan..

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LIST OF ABBREVIATIONS

A	approximate coefficient
ANFIS	adaptive neuro-fuzzy inferencing system
ANN	artificial neural network
ARFF	attribute related file format
CB	circuit breaker
CSV	comma-separated format
CT	current transformers
D	detail coefficient
DWT	discrete wavelet transform
EE	entropy energy
FACTS	flexible alternating current transmission system
GPS	global position system
GUI	graphical user interface
HPF	high pass-filters
HST	hyperbolic s-transform
IPA	improved prony analysis
LLG	line to line to ground
LLLG	three-phase to ground
LPF	low pass filter
ML	machine learning
MLP	multi-layer perceptron
NN	neural network
PMU	phasor measurement unit

PST	phase-shifting transformers
PV	photovoltaic
RER	renewable energy resources
RMS	root mean square error
ROC	receiver operating curve
SLG	single line to ground
SSSC	static synchronous series compensator
STATCOM	static synchronous compensators
Std	standard deviation
SVC	static var compensator
SVM	support vector machines
UPFC	unified power flow controller
VSC	voltage sourced converter
VT	voltage transformers
WEKA	waikato environment for knowledge analysis
WF	wind farm
WMRA	wavelet multiresolution analyses
WMRA-ML	wavelet multiresolution analyses signal processing and machine learning
WPD	wavelet packet decomposition

CHAPTER 1

INTRODUCTION

1.1 Background

There has been a constant global increase in global electric power energy demands in recent years [1, 2]. These have necessitated the commissioning of new power generation stations, alongside the expansion of the transmission and distribution network grid to meet these new trends [3, 4]. The concern on the successful evacuation of generated power from different energy sources to the end load terminals with minimum losses through the transmission network is also important [5]. There are drops in the voltage values (voltage-sag) at the midpoint of the long-distance transmission lines system [6, 7]. This limitation encourages the introduction of Flexible Alternating Current Transmission System (FACTS) devices [8], like the Static Synchronous Series Compensator (SSSC) [9], Static VAR compensator (SVC) [10], Static Synchronous Compensators (STATCOM) [11], and composite compensator like the unified power flow controller (UPFC) [12]. The FACTS devices facilitate the maximum electric power delivery from the generation source to the end-terminal substations at a high voltage level with minimal power losses and voltage variation [13]. The FACTS devices' presence changes the transmission lines parameters in the event of a fault affecting the measured impedance value compared to the pre-fault estimated value [14, 15]. This problem highlights the importance of studying and analyzing the effects of the STATCOM device on the distance relay protection operation on a high voltage transmission line [16-18]. The STATCOM device absorbs or injects current into the connecting buses, affecting the distance relay protection device's operation performance during short circuit fault scenarios on the compensated grid system. This injected infeed penetrations led to the protection relay under-reach or over-reach effect when connected between the distance protective relay location and the faulty point [19-21]. Hence, an equivalent apparent impedance is injected into the fault loop, which prevented the accurate fault impedance estimation by the distance relay, thereby compromising the relay safety operation compromise at zone-3 backup operation [22, 23].

The midpoint integration of the STATCOM FACTS device on the transmission lines enables power transfer capability and optimum power system infrastructure utilization. Albeit being very useful, the shunt FACT device causes misoperation of the distance relay due to wrong faults impedance estimations due to the constant current penetrations from the connected STATCOM at the mid-point of connection to the utility grid [24, 25]. Some of the challenges encountered by the protection relay on such a compensated high voltage transmission line include false detection of faults, wrong fault zone identification, incorrect fault types classification, and inaccurate fault location estimation on the line [26-28].

1.2 Problem Statement

A power system utility grid with midpoint integrated STATCOM compensation device compromising the estimated apparent impedance seen by the distance protection relay. The distance relay estimated voltage and current signals are affected by the STATCOM penetration impact within the fault loop for far-end faults (zone-3) beyond the compensator location [29, 30]. Hence, impact the wrong trip command initiation (no-trip) based on the underreach effect in zones-3 backup protection element coverage [31, 32]. For a short circuit fault beyond the STATCOM midpoint location, the STATCOM contributes a reactive component into the utility grid leading to a slight increment in the estimated apparent impedance above the pre-set reference value. The estimated impedance increment is due to the additional STATCOM reactive current injection impact within the fault loop, resulting in the zone-3 protection element compromise (under-reaching effect). The relay initiated a no-trip command as the estimated impedance locate fault outside the zone-3 protection element coverage. Several Adaptive Distance Relay protection (ADR) schemes modifications were presented to address this safety compromise considering the high-risk involvement to equipment installation and personnel. Different adaptation levels on the relay operational setting characteristic changes in line with variation in the injected reactive current from the STATCOM into the grid. The earlier presented ADR schemes challenged have computational complexity in optimizing the relay operational characteristic changes in line with the system reactive current penetration changes for effective fault detection and classification. The possibility of cyber-attack compromises on the introduced communication link adoption for the adaptive characteristic setting changes and data transmission between the relay location and the sub-station is also a matter of concern.

Given all these challenges, this study proposed an intelligent Machine Learning (ML) algorithm-based ADR (ML-ADR) to eradicate the zone-3 backup protection element trip compromise on the midpoint STATCOM compensated transmission line. The current study proposes an intelligent standalone machine learning algorithm (ML) adaptive distance relay (ML-ADR) modification model for effective elimination of zone-3 backup protection element compromise due to under-reach effect from midpoint integrated STATCOM during far-end fault at the relay zone-3 coverage boundary. Adopting intelligent computational algorithms to deploy artificially intelligent algorithms for the ADR modification will address the conventional distance relay protection compromise limitation. The proposed ML-ADR scheme will improve the detection of the zone-3 under-reach effect on fault classification, cyber-attack elimination, and fast trip decision algorithm generation that will isolate the relay far-end zone-3 backup protection trip compromise.

1.3 Research Objectives

The main aim is to develop an intelligent standalone Machine Learning (ML) algorithm based Adaptive Distance Relay (ML-ADR) Protection Scheme. The ML-ADR addresses the midpoint integrated STATCOM compensating device's impact on the distance relay zone-3 element compromise on the grid transmission lines during the far-end short circuit fault. The proposed ML-ADR scheme will improve on the detection of the zone-3 under-reach effect on fault classification, cyber-attack elimination, and fast trip decision algorithm generation using the following specific objectives:

i. To model a Matlab/Simulink distance relay with the midpoint integrated STATCOM utility transmission grid system to demonstrate the impending zone-3 under-reach effect from STATCOM injected current impact on the distance relay zone-3 backup protection element compromise during the far-end short circuit.

ii. To discover knowledge from the extracted 1-cycle fault data from midpoint STATCOM integrated and non-integrated models during far-end zone-3 faults, using hybrid Discrete Wavelet Multiresolution Analysis and ML for the intelligent ML-ADR model development.

iii. To validate the standalone intelligent ML-ADR trip decision algorithm performance using a new fault dataset for fault detection, classification, and fast trip decision command.

1.4 Research Hypothesis

An intelligent machine learning adaptive distance relay (ML-ADR) algorithm model will eliminate the distance relay zone-3 protective element compromise due to infeed current contribution from midpoint integrated STATCOM during a far-end fault.

1.5 Research Scope and Limitation

This research study focuses mainly on testing the formulated hypothesis to achieve the stated objectives to improve the existing ADR zone-3 backup protection element compromise and operational efficiency during the far-end fault from the integrated STATCOM under-reach effects. The study presented the midpoint STATCOM integration grid system's impact on the distance relay protection scheme by focusing only on the distance relay zone-3 fault misdiagnosis and subsequent relay maloperation. The relay operation compromise is due to the wrong estimated fault impedance based on the under-reach effect from the capacitive operation mode of the STATCOM for far-end faults. The scope of the current study involves

i. MATLAB/Simulink software modeling of the distance relay demonstrates the under-reaching effect on the relay zone-3 element compromise for far-end faults.

ii. Matlab/Simulink modeling of the 400 kV, 60 Hz modified Libya double circuits power transmission model with midpoint integrated STATCOM.

iii. Conducting the far-end short circuit fault simulation and 1-cycle transient fault signals (voltage and current) extraction from STATCOM integrated and non-integrated networks topologies.

iv. Knowledge extraction from transient signal logged data using hybrid DWML-ML algorithm for the extraction of useful unique signatures adoption for the intelligent ML-ADR model development in WEKA data mining software platform.

v. Testing trained ML-ADR models to classify far-end short circuit fault with and without integrated STATCOM models with varying current injection into the grid to eliminate zone-3 element compromise.

vi. Validate the modified ML-ADR for generalization based on the characteristic operating performance of the zone-3 backup protection element coverage with and without the presence of the STATCOM under constant loading and various far end-fault locations scenarios.

vii. Modify the existing ADR scheme with the extracted generated code from the ML-ADR model.

The study does not cover other FACTS devices' impact on the distance relay zone-3 protection coverage compromise. It does not address the over-reach effect during the inductive operational mode of the STATCOM, where the STATCOM absorbs the inductive current from the utility grid system. The estimated apparent impedance falls within the protection coverage zone and does not compromise the protection elements. Also, the distance relay's instantaneous primary operation in instantaneous zone-1 and backup zone-2 protection coverage are not covered under this current study because they are not affected by this under-reach phenomenon. The present research is limited to the offline deployment of modified ML-ADR fault classifier model without the real-time sensors data acquisition deployments.

1.6 Research Contributions

This research study Addressed the impending challenges of distance relay misdiagnosis of faults based on the wrong estimation of apparent line impedance during the under-reach effect caused by STATCOM connected at the midpoint of the utility line during the far-end zone-3 short circuit faults. The wrong estimation of the distance relay located fault impedance trajectory barely outside the zone-3 backup coverage is the primary reason for the relay maloperation in the zone-3 element. This phenomenon indicates no-fault conditions on the transmission line system, and the relay will not initiate any trip command to all associated breakers under such conditions. Hence, this is a major safety compromise that must be urgently addressed in the primary protection relay's failure for the next adjacent line sections. The following are the contributions to the existing body of knowledge in this area of power system protection analysis.

i. Improvement on the existing ADR operational efficiency with the new modified ML-ADR decision algorithm for the capacitive operation mode of zone-3 backup protection element compromise from the integrated STATCOM under-reach effects during the far-end short circuit faults.

ii. Improved power system safety, reliability, and dependability with the self-automated intelligent ML-ADR protection model effectively discriminate several fault types, using faulty and healthy line hidden signatures for informed decision trip to eliminate the impending STATCOM under-reach effect.

iii. Provide a teaching aid through the Matlab/Simulink model of the distance relay with the STATCOM connected to the transmission line midpoint to demonstrate the impact of shunt FACTS devices on distance relay zone-3 elements protection coverage operation.

iv. The modified ML-ADR algorithm-code modification improved the relay decision trip-time with a minimum value below the conventional minimum recorded 20 ms.

1.7 The layout of the thesis

Chapter 1 (Introduction) contains the introduction section of the research study, the background information on the distance relay protection zone-3 element compromise drawbacks' effect during the far-end short circuit fault from the midpoint integrated STATCOM device. Highlights on the significance of solving the problems associated with the distance relay misoperation presented. The study's formulated hypothesis, objectives, and research scope/limitations divulged.

Chapter 2 (Literature Review) enumerates details FACTS configurations with much emphasis on STATCOM devices, the operational principles, and under-reach effects on the distance relay backup protection element performance for the zone-3 far-end fault. A detailed review of recent related published literature on the adverse under-reach effect of STATCOM during capacitive operation mode on the distance relay accurate estimation of the line apparent impedance between the relay location and the faulty point under-connected large loads presented. Several methods were adopted in earlier studies to eliminate wrong impedance estimation on STATCOM integrated transmission line for zone-3 backup protection coverage zone divulged in detail.

Chapter 3 (Methodology) presents the proposed method for the research procedures, starting from the proposed modeling of the distance relay using Matlab/Simulink software to mimic the actual distance relay operation scheme and trip signal decision generation. The model demonstrates the under-reach effect from the midpoint integrated STACOM on the distance relay zone 3 elements backup protection comprise during far-end short circuit faults. The modeling of intelligent standalone ML-ADR model that could address the impending zone-3 element compromise presented. The useful adoption of hidden knowledge extraction from the one-cycle fault transient signals (voltage and current) from integrated and non-integrated STATCOM simulation models during far-end short circuit faults using DWMRA-ML.

Chapter 4 (Results and Discussions) presents a detailed analysis of the results from all propose objective execution in chapter 3 for a detailed discussion. The best intelligent standalone ML-ADR model selection conducted using operation performance comparison and trip-decision time reduction constraints. The ML-ADR model validation demonstrated.

Chapter 5 (Conclusion and Recommendations) summarises results implications based on achieved objectives and the future recommendations for further studies in the same research area.

REFERENCES

[1] M. Bilgili, A. Ozbek, B. Sahin, and A. Kahraman, "An overview of renewable electric power capacity and progress in new technologies in the world," *Renewable and Sustainable Energy Reviews,* vol. 49, pp. 323-334, 2015.

[2] M. Asif and T. Muneer, "Energy supply, its demand and security issues for developed and emerging economies," *Renewable and sustainable energy reviews,* vol. 11, no. 7, pp. 1388-1413, 2007.

[3] J. Petinrin and M. Shaabanb, "Impact of renewable generation on voltage control in distribution systems," *Renewable and Sustainable Energy Reviews,* vol. 65, pp. 770-783, 2016.

[4] I. Hadjipaschalis, A. Poullikkas, and V. Efthimiou, "Overview of current and future energy storage technologies for electric power applications," *Renewable and sustainable energy reviews,* vol. 13, no. 6-7, pp. 1513-1522, 2009.

[5] M. Z. Jacobson and M. A. Delucchi, "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials," *Energy policy,* vol. 39, no. 3, pp. 1154-1169, 2011.

[6] A. K. Pradhan and A. Routray, "Applying distance relay for voltage sag source detection," *IEEE Transactions on Power Delivery,* vol. 20, no. 1, pp. 529-531, 2005.

[7] R. Naidoo and P. Pillay, "A new method of voltage sag and swell detection," *IEEE Transactions on power delivery,* vol. 22, no. 2, pp. 1056-1063, 2007.

[8] K. Habur and D. O'Leary, "FACTS-flexible alternating current transmission systems: for cost effective and reliable transmission of electrical energy," *Siemens-World Bank document–Final Draft Report, Erlangen,* p. 46, 2004.

[9] M. Faridi, H. Maeiiat, M. Karimi, P. Farhadi, and H. Mosleh, "Power system stability enhancement using static synchronous series compensator (SSSC)," in *2011 3rd International Conference on Computer Research and Development*, 2011, vol. 3: IEEE, pp. 387-391.

[10] M. M. Biswas and K. K. Das, "Voltage level improving by using static VAR compensator (SVC)," *Global Journal of researches in engineering: J General Engineering,* vol. 11, no. 5, pp. 13-18, 2011.

[11] M. Castilla, J. Miret, A. Camacho, J. Matas, and L. G. de Vicuña, "Voltage support control strategies for static synchronous compensators under unbalanced voltage sags," *IEEE transactions on industrial electronics,* vol. 61, no. 2, pp. 808-820, 2013.

[12] N. Sharma and P. Jagtap, "Modelling and application of unified power flow controller (UPFC)," in *2010 3rd International Conference on Emerging Trends in Engineering and Technology*, 2010: IEEE, pp. 350-355.

[13] D. Murali and M. Rajaram, "Active and reactive power flow control using FACTS devices," *International Journal of Computer Applications,* vol. 9, no. 8, pp. 45-50, 2010.

[14] M. Zellagui and A. Chaghi, "Effects of shunt FACTS devices on MHO distance protection setting in 400 kV transmission line," *Electrical and Electronic Engineering,* vol. 2, no. 3, pp. 164-169, 2012.

[15] G. B. Abande, M. Satarkar, M. H. Rawoot, M. Thakre, and V. Kale, "Impact of STATCOM on distance relay," in *2014 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2014]*, 2014: IEEE, pp. 809-813.

[16] M. Allehyani, H. Samkari, and B. K. Johnson, "Modeling and simulation of the impacts of STATCOM control schemes on distance elements," in *2016 North American Power Symposium (NAPS)*, 2016: IEEE, pp. 1-6.

[17] M. A. T. Chandan, M. K. V. R. Mohan, M. S. Kompelli, and M. A. R. Singh, "Advance Distance Protection of Transmission Line in Presence of Shunt Compensator," *International Research Journal of Engineering and Technology (IRJET),* pp. 751-757, 2015.

[18] M. Purohit and V. Gohokar, "Effects of series compensation on distance protection of high voltage transmission lines under fault conditions," *International Journal of Electrical Engineering & Technology (IJEET) Volume,* vol. 9, pp. 57-66.

[19] M. Khederzadeh and A. Ghorbani, "STATCOM modeling impacts on performance evaluation of distance protection of transmission lines," *European Transactions on Electrical Power,* vol. 21, no. 8, pp. 2063-2079, 2011.

[20] M. Khederzadeh and A. Ghorbani, "STATCOM/SVC impact on the performance of transmission line distance protection," *IEEJ transactions on electrical and electronic engineering,* vol. 6, no. 6, pp. 525-533, 2011.

[21] A. R. Singh, A. Ahmed, and S. Dambhare, "Robust distance protection of mid-point shunt compensated transmission line," in *2012 IEEE Fifth Power India Conference*, 2012: IEEE, pp. 1-5.

[22] B. Sahoo and S. R. Samantaray, "System integrity protection scheme for enhancing backup protection of transmission lines," *IEEE Systems Journal,* 2020.

[23] V. H. Makwana and B. R. Bhalja, "A new digital distance relaying scheme for series-compensated double-circuit line during open conductor and ground fault," *IEEE transactions on power delivery,* vol. 27, no. 2, pp. 910-917, 2012.

[24] A. R. Singh, N. R. Patne, and V. S. Kale, "Adaptive distance protection setting in presence of mid-point STATCOM using synchronized measurement," *International Journal of Electrical Power & Energy Systems,* vol. 67, pp. 252-260, 2015.

[25] N. Aly and A. Ewais, "The Impact of STATCOM on Power Systems Protection Devices," *ERJ. Engineering Research Journal,* vol. 42, no. 4, pp. 249-253, 2019.

[26] D. Hemasundar, M. Thakre, and V. Kale, "Impact of STATCOM on distance relay-Modeling and simulation using PSCAD/EMTDC," in *2014 IEEE Students' Conference on Electrical, Electronics and Computer Science*, 2014: IEEE, pp. 1-6.

[27] R. Guan, Y. Xue, and X.-P. Zhang, "Advanced RTDS-based studies of the impact of STATCOM on feeder distance protection," *The Journal of Engineering,* vol. 2018, no. 15, pp. 1038-1042, 2018.

[28] O. H. Gupta and M. Tripathy, "Relaying scheme for STATCOM compensated transmission line," in *2016 IEEE 6th international conference on power systems (ICPS)*, 2016: IEEE, pp. 1-6.

[29] M. Alizadeh, N. Khodabakhshi-Javinani, G. Gharehpetian, and H. Askarian-Abyaneh, "Performance analysis of distance relay in presence of unified interphase power controller and voltage-source converters-based interphase power controller," *IET Generation, Transmission & Distribution,* vol. 9, no. 13, pp. 1642-1651, 2015.

[30] W.-H. Zhang, S.-J. Lee, M.-S. Choi, and S. Oda, "Considerations on distance relay setting for transmission line with STATCOM," in *IEEE PES General Meeting*, 2010: IEEE, pp. 1-5.

[31] P. Sonawane and P. Shembekar, "Impact analysis of statcom on distance relay performance," *International Journal of Advance Engineering and Research Development (IJAERD),* vol. 3, no. 6, pp. 210-214, 2016.

[32] A. Y. M. Abbas, G. O. A. Kalcon, and A. H. Sidahmed, "Impact of Static Synchronous Compensatoron Performance of Distance Protection of Transmission Lines," 2014.

[33] H. Thomas, A. Marian, A. Chervyakov, S. Stückrad, D. Salmieri, and C. Rubbia, "Superconducting transmission lines–Sustainable electric energy transfer with higher public acceptance?," *Renewable and Sustainable Energy Reviews,* vol. 55, pp. 59-72, 2016.

[34] B. F. Hobbs *et al.*, "Adaptive transmission planning: implementing a new paradigm for managing economic risks in grid expansion," *IEEE Power and Energy Magazine,* vol. 14, no. 4, pp. 30-40, 2016.

[35] S. Lumbreras and A. Ramos, "The new challenges to transmission expansion planning. Survey of recent practice and literature review," *Electric Power Systems Research,* vol. 134, pp. 19-29, 2016.

[36] Y. Li, Z. Lukszo, and M. Weijnen, "The impact of inter-regional transmission grid expansion on China’s power sector decarbonization," *Applied energy,* vol. 183, pp. 853-873, 2016.

[37] W. DOŁęGA, "National grid electrical power infrastructure–threats and challenges," *Polityka Energetyczna,* vol. 21, 2018.

[38] A. Abu-Siada and C. Karunar, "Improvement of Transmission Line Power Transfer Capability, Case Study," *system,* vol. 5, p. 6, 2012.

[39] H. Yu, C. Chung, and K. Wong, "Robust transmission network expansion planning method with Taguchi's orthogonal array testing," *IEEE Transactions on Power Systems,* vol. 26, no. 3, pp. 1573-1580, 2010.

[40] Q. Yu, "Applications of flexible AC transmissions system (FACTS) technology in SmartGrid and its EMC impact," in *2014 IEEE International Symposium on Electromagnetic Compatibility (EMC)*, 2014: IEEE, pp. 392-397.

[41] F. H. Gandoman *et al.*, "Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems," *Renewable and sustainable energy reviews,* vol. 82, pp. 502-514, 2018.

[42] A. Purohit and V. Gohokar, "Recent developments in distance protection of compensated transmission lines," in *2015 International Conference on Pervasive Computing (ICPC)*, 2015: IEEE, pp. 1-6.

[43] R. K. Bindal, "A Review of Benefits of FACTS Devices in Power system," *International Journal of Engineering and Advanced Technology (IJEAT),* vol. 3, no. 4, pp. 105-108, 2014.

[44] S. Manoj and P. Puttaswamy, "Importance of FACTS controllers in power systems," *International Journal of Advanced Engineering Technology,* vol. 2, no. 3, pp. 207-212, 2011.

[45] M. S. K. Elsamahy, "Impacts of midpoint FACTS controllers on the coordiantion between generator phase backup protection and generator capability limits," University of Saskatchewan, 2011.

[46] A. K. L. Al-Behadili, "Performance Analysis of Distance Relay on Shunt/Series Facts-Compensated Transmission Line," 2015.

[47] X. Kong *et al.*, "A three-zone distance protection scheme capable to cope with the impact of UPFC," *IEEE Transactions on Power Delivery,* vol. 33, no. 2, pp. 949-959, 2017.

[48] Z. Moravej, M. Pazoki, and M. Khederzadeh, "New smart fault locator in compensated line with UPFC," *International Journal of Electrical Power & Energy Systems,* vol. 92, pp. 125-135, 2017.

[49] S. Gawande and M. Ramteke, "Three-level NPC inverter based new DSTATCOM topologies and their performance evaluation for load compensation," *International Journal of Electrical Power & Energy Systems,* vol. 61, pp. 576-584, 2014.

[50] M. Elsamahy, S. O. Faried, and T. Sidhu, "Impact of midpoint STATCOM on generator loss of excitation protection," *IEEE Transactions on power delivery,* vol. 29, no. 2, pp. 724-732, 2013.

[51] A. Yadav and Y. Dash, "An overview of transmission line protection by artificial neural network: fault detection, fault classification, fault location, and fault direction discrimination," *Advances in Artificial Neural Systems,* vol. 2014, 2014.

[52] A. Ghorbani, B. Mozafari, and A. M. Ranjbar, "Digital distance protection of transmission lines in the presence of SSSC," *International Journal of Electrical Power & Energy Systems,* vol. 43, no. 1, pp. 712-719, 2012.

[53] R. Ilango and T. S. R. Raja, "Impact Analysis of midpoint Connected STATCOM on Distance Relay Performance," *TELKOMNIKA Indonesian Journal of Electrical Engineering,* vol. 13, no. 2, pp. 257-263, 2015.

[54] Q. Liu, Z.-p. Wang, and Y. Zhang, "Study on a novel method of distance protection in transmission line with STATCOM," in *2010 Asia-Pacific Power and Energy Engineering Conference*, 2010: IEEE, pp. 1-5.

[55] A. Albehadili and I. Abdul-Qader, "Analysis of distance relay performance on shunt FACTS-compensated transmission lines," in *2015 IEEE International Conference on Electro/Information Technology (EIT)*, 2015: IEEE, pp. 188-193.

[56] K. R. Dhenuvakonda, A. R. Singh, M. P. Thakre, B. S. Umre, A. Kumar, and R. C. Bansal, "Effect of SSSC-based SSR controller on the performance of distance relay and adaptive approach using synchronized measurement," *International Transactions on Electrical Energy Systems,* vol. 28, no. 11, p. e2620, 2018.

[57] S. Behera, P. Raja, and S. Moorthi, "Modelling and simulation of the impact of SVC on existing distance relay for transmission line protection," in *2015 International Conference on Condition Assessment Techniques in Electrical Systems (CATCON)*, 2015: IEEE, pp. 151-156.

[58] S. Biswal and M. Biswal, "Adaptive distance relay algorithm for shunt compensated transmission line," in *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, 2016: IEEE, pp. 426-431.

[59] O. H. Gupta and M. Tripathy, "An innovative pilot relaying scheme for shunt-compensated line," *IEEE Transactions on Power Delivery,* vol. 30, no. 3, pp. 1439-1448, 2015.

[60] B. Kumar, A. Yadav, and A. Y. Abdelaziz, "Synchrophasors assisted protection scheme for the shunt-compensated transmission line," *IET Generation, Transmission & Distribution,* vol. 11, no. 13, pp. 3406-3416, 2017.

[61] P. K. Dash, S. Das, and J. Moirangthem, "Distance protection of shunt compensated transmission line using a sparse S-transform," *IET Generation, Transmission & Distribution,* vol. 9, no. 12, pp. 1264-1274, 2015.

[62] J.-H. Lee, Y.-B. Yoon, S.-T. Cha, J. Lee, and J.-W. Choe, "Development of distance relay models for real time digital simulator," *IFAC Proceedings Volumes,* vol. 36, no. 20, pp. 979-984, 2003.

[63] H. Samkari, M. Allehyani, and B. K. Johnson, "Modeling and simulation the impacts of STATCOMs on distance protection," in *2015 North American Power Symposium (NAPS)*, 2015: IEEE, pp. 1-5.

[64] B. Singh, R. Saha, A. Chandra, and K. Al-Haddad, "Static synchronous compensators (STATCOM): a review," *IET Power Electronics,* vol. 2, no. 4, pp. 297-324, 2009.

[65] R. K. Sampath and C. Kumar, "Dynamic Performance of STATCOM Under Various Faults in Power System," *International Journal of Advanced Computer Research,* vol. 2, no. 4, p. 334, 2012.

[66] R. Sampath and C. Kumar, "Dynamic compensation of reactive power in Various Faults in Power System," *Joumal of Electrical and Electronics Engineering,* vol. 3, no. 3, pp. 01-07, 2012.

[67] M. K. Rao, T. Ganeshkumar, and P. Puthra, "Mitigation of voltage sag and voltage swell by using D-STATCOM and PWM switched autotransformer," *International Journal of Emerging Trends in Electrical and Electronics,* vol. 7, no. 1, 2013.

[68] Y. Zhang, Y. Zhang, B. Wu, and J. Zhou, "Power injection model of STATCOM with control and operating limit for power flow and voltage stability analysis," *Electric Power Systems Research,* vol. 76, no. 12, pp. 1003-1010, 2006.

[69] M. El-Moursi and A. Sharaf, "Novel reactive power controllers for the STATCOM and SSSC," *Electric Power Systems Research,* vol. 76, no. 4, pp. 228-241, 2006.

[70] M. El-Moursi and A. Sharaf, "Novel controllers for the 48-pulse VSC STATCOM and SSSC for voltage regulation and reactive power compensation," *IEEE Transactions on Power systems,* vol. 20, no. 4, pp. 1985-1997, 2005.

[71] X. Luo, Z. Akhtar, C. K. Lee, B. Chaudhuri, S.-C. Tan, and S. Y. R. Hui, "Distributed voltage control with electric springs: Comparison with STATCOM," *IEEE Transactions on Smart Grid,* vol. 6, no. 1, pp. 209-219, 2014.

[72] Y. Xu and F. Li, "Adaptive PI control of STATCOM for voltage regulation," *IEEE transactions on power delivery,* vol. 29, no. 3, pp. 1002-1011, 2014.

[73] N. Cherkaoui, T. Haidi, A. Belfqih, F. El Mariami, and J. Boukherouaa, "A Comparison Study of Reactive Power Control Strategies in Wind Farms with SVC and STATCOM," *International Journal of Electrical and Computer Engineering,* vol. 8, no. 6, p. 4836, 2018.

[74] Z. Xu, Z. Bian, and B. Cheng, "An approach to the ultimate goal of power grid development—constant voltage operation," *CSEE Journal of Power and Energy Systems,* vol. 3, no. 4, pp. 380-389, 2017.

[75] A. Sode-Yome and N. Mithulananthan, "Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement," *International Journal of Electrical Engineering Education,* vol. 41, no. 2, pp. 158-171, 2004.

[76] M. Chen, H. Wang, S. Shen, and B. He, "Research on a distance relay-based wide-area backup protection algorithm for transmission lines," *IEEE Transactions on Power Delivery,* vol. 32, no. 1, pp. 97-105, 2016.

[77] V. C. Nikolaidis, A. M. Tsimtsios, and A. S. Safigianni, "Investigating particularities of infeed and fault resistance effect on distance relays protecting radial distribution feeders with DG," *IEEE Access,* vol. 6, pp. 11301-11312, 2018.

[78] M. H. Idris, S. Hardi, and M. Z. Hasan, "Teaching distance relay using Matlab/Simulink graphical user interface," *Procedia Engineering,* vol. 53, pp. 264-270, 2013.

[79] S.-A. Ahmadi, H. Karami, and B. Gharehpetian, "Comprehensive coordination of combined directional overcurrent and distance relays considering miscoordination reduction," *International Journal of Electrical Power & Energy Systems,* vol. 92, pp. 42-52, 2017.

[80] P. P. Pattanaik and C. K. Panigrahi, "Stability and fault analysis in a power network considering IEEE 14 bus system," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, 2018: IEEE, pp. 1134-1138.

[81] N. Zhang and M. Kezunovic, "Transmission line boundary protection using wavelet transform and neural network," *IEEE Transactions on Power Delivery,* vol. 22, no. 2, pp. 859-869, 2007.

[82] J. Xia, S. Jiale, X. Deng, L. Wang, S. He, and K. Liu, "Enhanced transmission line pilot impedance and pilot protection," *IET generation, transmission & distribution,* vol. 5, no. 12, pp. 1240-1249, 2011.

[83] T. G. Bolandi, H. Seyedi, S. M. Hashemi, and P. S. Nezhad, "Impedance-differential protection: a new approach to transmission-line pilot protection," *IEEE Transactions on Power Delivery,* vol. 30, no. 6, pp. 2510-2518, 2015.

[84] L. Chen *et al.*, "Similarity comparison based high-speed pilot protection for transmission line," *IEEE Transactions on Power Delivery,* vol. 33, no. 2, pp. 938-948, 2017.

[85] J. Ma, X. Pei, W. Ma, and Z. Wang, "A new transmission line pilot differential protection principle using virtual impedance of fault component," *Canadian Journal of Electrical and Computer Engineering,* vol. 38, no. 1, pp. 37-44, 2015.

[86] C. Wang, G. Song, X. Kang, and J. Suonan, "Novel transmission-line pilot protection based on frequency-domain model recognition," *IEEE Transactions on Power Delivery,* vol. 30, no. 3, pp. 1243-1250, 2014.

[87] O. H. Gupta and M. Tripathy, "Universal pilot relaying scheme for series and shunt-compensated lines," *IET Generation, Transmission & Distribution,* vol. 12, no. 4, pp. 799-806, 2017.

[88] A. N. Milioudis, G. T. Andreou, and D. P. Labridis, "Detection and location of high impedance faults in multiconductor overhead distribution lines using power line communication devices," *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 894-902, 2014.

[89] A. Vaidya and P. A. Venikar, "Distance protection scheme for protection of long transmission line considering the effect of fault resistance by using the ANN approach," *International Journal of Electrical and Electronics Engineering,* vol. 1, no. 3, pp. 62-66, 2012.

[90] R. Dubey, S. R. Samantaray, and B. K. Panigrahi, "Adaptive distance protection scheme for shunt-FACTS compensated line connecting wind farm," *IET Generation, Transmission & Distribution,* vol. 10, no. 1, pp. 247-256, 2016.

[91] Y. Wang and V. Dinavahi, "Low-latency distance protective relay on FPGA," *IEEE Transactions on Smart Grid,* vol. 5, no. 2, pp. 896-905, 2013.

[92] A. Zamora-Mendez, M. R. A. Paternina, E. Vázquez, J. M. Ramirez, and J. A. I. O. de Serna, "Distance relays based on the Taylor–Kalman-Fourier filter," *IEEE Transactions on Power Delivery,* vol. 31, no. 3, pp. 928-935, 2015.

[93] Z. He, X. Liu, X. Li, and R. Mai, "A novel traveling-wave directional relay based on apparent surge impedance," *IEEE Transactions on Power Delivery,* vol. 30, no. 3, pp. 1153-1161, 2014.

[94] S. Vejdan, M. Sanaye-Pasand, and T. S. Sidhu, "Accelerated zone II operation of distance relay using impedance change directions," *IEEE Transactions on Power Delivery,* vol. 32, no. 6, pp. 2462-2471, 2016.

[95] D. H. Huynh and X. K. Tran, "A modeling of distance protection relay based on Kalman filter: An application for Vietnam's 500kV power transmission lines," in *2017 IEEE International Conference on Smart Grid and Smart Cities (ICSGSC)*, 2017: IEEE, pp. 157-161.

[96] A. M. Tsimtsios and V. C. Nikolaidis, "Setting zero-sequence compensation factor in distance relays protecting distribution systems," *IEEE Transactions on Power Delivery,* vol. 33, no. 3, pp. 1236-1246, 2017.

[97] A. Osman, A. Noureldin, A. El-Shafie, and D. McGaughey, "Fast orthogonal search approach for distance protection of transmission lines," *Electric power systems research,* vol. 80, no. 2, pp. 215-221, 2010.

[98] S. Robson, A. Haddad, and H. Griffiths, "Traveling wave fault location using layer peeling," *Energies,* vol. 12, no. 1, p. 126, 2019.

[99] A. Mahari and H. Seyedi, "High impedance fault protection in transmission lines using a WPT-based algorithm," *International Journal of Electrical Power & Energy Systems,* vol. 67, pp. 537-545, 2015.

[100] L. M. A. Barreira, "Neural Networks Improving the Performance of the Distance Protection," 2013.

[101] J. M. Gers and E. J. Holmes, *Protection of electricity distribution networks*. IET, 2004.

[102] J. L. Blackburn and T. J. Domin, *Protective relaying: principles and applications*. CRC press, 2015.

[103] Y. Damchi, J. Sadeh, and H. Rajabi Mashhadi, "Optimal coordination of distance and directional overcurrent relays considering different network topologies," *Iranian Journal of Electrical and Electronic Engineering,* vol. 11, no. 3, pp. 231-240, 2015.

[104] J. Verma and R. Sharma, "Distance algorithm for Transmission Line with Mid-Point Connected STATCOM," 2017.

[105] A. Manori, M. Tripathy, and H. O. Gupta, "SVM based zonal setting of Mho relay for shunt compensated transmission line," *International Journal of Electrical Power & Energy Systems,* vol. 78, pp. 422-428, 2016.

[106] A. Maori, M. Tripathy, and H. Gupta, "SVM based zonal setting of Mho relay for transmission line having TCSC," in *2014 6th IEEE Power India International Conference (PIICON)*, 2014: IEEE, pp. 1-5.

[107] R. Ilango and T. S. R. Raja, "Fault Location Method for STATCOM Connected Transmission Lines Using CCM," *Circuits and Systems,* vol. 7, no. 10, pp. 3131-3141, 2016.

[108] S. Jamali, A. Kazemi, and H. Shateri, "Distance Relay Tripping Characteristic in Presence of SSSC on Next Line," in *2007 International Conference on Power Engineering, Energy and Electrical Drives*, 2007: IEEE, pp. 487-492.

[109] A. R. Singh, N. R. Patne, and V. S. Kale, "Synchronized measurement based an adaptive distance relaying scheme for STATCOM compensated transmission line," *Measurement,* vol. 116, pp. 96-105, 2018.

[110] T. S. Sidhu, R. K. Varma, P. K. Gangadharan, F. A. Albasri, and G. R. Ortiz, "Performance of distance relays on shunt-FACTS compensated transmission lines," *IEEE Transactions on Power delivery,* vol. 20, no. 3, pp. 1837-1845, 2005.

[111] H. Abdollahzadeh, B. Mozafari, and M. Jazaeri, "Realistic insights into impedance seen by distance relays of a SSSC-compensated transmission line incorporating shunt capacitance of line," *International Journal of Electrical Power & Energy Systems,* vol. 65, pp. 394-407, 2015.

[112] I. Bhavar, S. Unde, and S. Dambhare, "Adaptive distance relaying scheme with fault resistance compensation," in *2016 IEEE Region 10 Conference (TENCON)*, 2016: IEEE, pp. 3575-3578.

[113] U. B. Parikh, B. Das, and R. Maheshwari, "Fault classification technique for series compensated transmission line using support vector machine," *International Journal of Electrical Power & Energy Systems,* vol. 32, no. 6, pp. 629-636, 2010.

[114] S. Rezaei, "An Adaptive Algorithm Based on Subharmonic and Time Domain Analysis to Prevent Mal Operation of Overcurrent Relay During Subsynchronous Resonance," *IEEE Transactions on Industry Applications,* vol. 54, no. 3, pp. 2085-2096, 2018.

[115] A. Kazemi, S. Jamali, and H. Shateri, "Effects of STATCOM on distance relay tripping characteristic," in *2005 IEEE/PES Transmission & Distribution Conference & Exposition: Asia and Pacific*, 2005: IEEE, pp. 1-6.

[116] A. R. Singh, N. R. Patne, V. S. Kale, and P. Khadke, "Digital impedance pilot relaying scheme for STATCOM compensated TL for fault phase classification with fault location," *IET Generation, Transmission & Distribution,* vol. 11, no. 10, pp. 2586-2598, 2017.

[117] S. Biswal, M. Biswal, and O. P. Malik, "Hilbert huang transform based online differential relay algorithm for a shunt-compensated transmission line," *IEEE Transactions on Power Delivery,* vol. 33, no. 6, pp. 2803-2811, 2018.

[118] N. M. Khoa and D. D. Tung, "Locating fault on transmission line with static var compensator based on phasor measurement unit," *Energies,* vol. 11, no. 9, p. 2380, 2018.

[119] A. S. Musleh, S. Muyeen, A. Al-Durra, and I. Kamwa, "Testing and validation of wide-area control of STATCOM using real-time digital simulator with hybrid HIL–SIL configuration," *IET Generation, Transmission & Distribution,* vol. 11, no. 12, pp. 3039-3049, 2017.

[120] O. H. Gupta and M. Tripathy, "Superimposed energy-based fault detection and classification scheme for series-compensated line," *Electric Power Components and Systems,* vol. 44, no. 10, pp. 1095-1110, 2016.

[121] O. H. Gupta and M. Tripathy, "ERF-based fault detection scheme for STATCOM-compensated line," *International Transactions on Electrical Energy Systems,* vol. 27, no. 6, p. e2314, 2017.

[122] B. Li and M. Lin, "Analysis of directional pilot protection on transmission line with wind farm integration," in *2011 International Conference on Advanced Power System Automation and Protection*, 2011, vol. 1: IEEE, pp. 303-308.

[123] M. K. Jena, S. R. Samantaray, and L. Tripathy, "Decision tree-induced fuzzy rule-based differential relaying for transmission line including unified power flow controller and wind-farms," *IET Generation, Transmission & Distribution,* vol. 8, no. 12, pp. 2144-2152, 2014.

[124] G. V. Raju and E. Koley, "Fuzzy logic based fault detector and classifier for three phase transmission lines with statcom," in *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, 2016: IEEE, pp. 469-474.

[125] Q. M. Alias, "STATCOM Impact on Distance Relay Performance," *Diyala Journal of Engineering Sciences,* vol. 9, no. 3, pp. 59-70, 2016.

[126] L. J. Powell, "A new standard for instrument transformer applications in industry," *IEEE Transactions on Industry Applications,* vol. 47, no. 1, pp. 301-305, 2010.

[127] E. Ali, A. Helal, H. Desouki, K. Shebl, S. Abdelkader, and O. Malik, "Power transformer differential protection using current and voltage ratios," *Electric Power Systems Research,* vol. 154, pp. 140-150, 2018.

[128] A. S. Meliopoulos *et al.*, "Transmission level instrument transformers and transient event recorders characterization for harmonic measurements," *IEEE Transactions on Power Delivery,* vol. 8, no. 3, pp. 1507-1517, 1993.

[129] K. Rudion, A. Orths, Z. A. Styczynski, and K. Strunz, "Design of benchmark of medium voltage distribution network for investigation of DG integration," in *2006 IEEE Power Engineering Society General Meeting*, 2006: IEEE, p. 6 pp.

[130] S. Devi, N. K. Swarnkar, S. R. Ola, and O. P. Mahela, "Detection of transmission line faults using discrete wavelet transform," in *2016 Conference on Advances in Signal Processing (CASP)*, 2016: IEEE, pp. 133-138.

[131] T. Kunj, M. Ansari, and C. Vishwakarrma, "Transmission Line Fault Detection and Classification by using Wavelet MultiresolutionAnalysis: A Review," in *2018 International Conference on Power Energy, Environment and Intelligent Control (PEEIC)*, 2018: IEEE, pp. 607-612.

[132] A. B. Patil, J. A. Gaikwad, and J. V. Kulkarni, "Bearing fault diagnosis using discrete wavelet transform and artificial neural network," in *2016 2nd International Conference on Applied and Theoretical Computing and Communication Technology (iCATccT)*, 2016: IEEE, pp. 399-405.

[133] O. Emmanuel, M. L. Othman, H. Hizam, and M. M. Othman, "Single line-to-ground fault special protection scheme for integrated windfarm transmission line using data mining," in *2020 2nd International Conference on Smart Power & Internet Energy Systems (SPIES)*, 2020: IEEE, pp. 76-81.

[134] J. Shi and M. Liang, "Intelligent bearing fault signature extraction via iterative oscillatory behavior based signal decomposition (IOBSD)," *Expert Systems with Applications,* vol. 45, pp. 40-55, 2016.

[135] V. Muralidharan and V. Sugumaran, "Feature extraction using wavelets and classification through decision tree algorithm for fault diagnosis of mono-block centrifugal pump," *Measurement,* vol. 46, no. 1, pp. 353-359, 2013.

[136] Y. Q. Chen, O. Fink, and G. Sansavini, "Combined fault location and classification for power transmission lines fault diagnosis with integrated feature extraction," *IEEE Transactions on Industrial Electronics,* vol. 65, no. 1, pp. 561-569, 2017.

[137] A. Kusiak and A. Verma, "A data-mining approach to monitoring wind turbines," *IEEE Transactions on Sustainable Energy,* vol. 3, no. 1, pp. 150-157, 2011.

[138] M. L. Othman, I. Aris, S. M. Abdullah, M. L. Ali, and M. R. Othman, "Knowledge discovery in distance relay event report: a comparative data-mining strategy of rough set theory with decision tree," *IEEE Transactions on Power Delivery,* vol. 25, no. 4, pp. 2264-2287, 2010.

[139] O. Emmanue, M. L. Othman, H. Hizam, M. M. Othman, E. Aker, and T. N. Samuel, "Hybrid signal processing and machine learning algorithm for adaptive fault classification of wind farm integrated transmission line protection," *International Journal of Integrated Engineering,* vol. 11, no. 4, 2019.

[140] A. S. S. Altaie and J. Asumadu, "Fault detection and classification for compensating network using combination relay and ANN," in *2015 IEEE international conference on electro/information technology (EIT)*, 2015: IEEE, pp. 351-356.

[141] P. Sharma, D. Saini, and A. Saxena, "Fault detection and classification in transmission line using wavelet transform and ANN," *Bulletin of Electrical Engineering and Informatics,* vol. 5, no. 3, pp. 284-295, 2016.

[142] K. Li, L. Lai, and A. David, "Stand alone intelligent digital distance relay," *IEEE Transactions on Power Systems,* vol. 15, no. 1, pp. 137-142, 2000.

[143] Y. Xia, K. Li, and A. David, "Adaptive relay setting for stand-alone digital distance protection," *IEEE Transactions on Power Delivery,* vol. 9, no. 1, pp. 480-491, 1994.