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Machine Learning Approach for Detection and Classification of Faults in Distribution Network with Decentralized Power Generation Facilities

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Abstract : Integrating Decentralized Power Generation Facilities (DPGFs) like Solar PV, Wind Power Generation, Microturbine etc, into Distribution Network (DN) has revolutionized Conventional Distribution Networks (CDN) into Modern Distribution Networks (MDN) but also introduces notable challenges in Fault Detection and Classification (FDC), an important part for Protection Coordination. Conventional Distribution Network protection schemes rely mainly on Overcurrent Protection (OCP), often fails to lodge bidirectional power flows, dynamic DPGF output and network topology transition that leads to delay or failure of fault isolation, increasing chances of potential system and equipment outages. This article discusses numerous Machine Learning (ML) based fault detection and identification approaches used as alternative solution for improving fault management scheme in modern distribution scheme. Key advantages along with challenges for different Machine Learning (ML) based methods are discussed. Article is concluded with suggestion for future research area and scope, highlighting role of machine learning in achieving reliable protection scheme for distribution network.

Index Terms **- Machine Learning, Fault Detection, Fault Classification, Distribution Network, Decentralized Power Generation**

I. INTRODUCTION

Modern Distribution Network in Electrical Power System is undergoing major transformation because of Integration of Decentralized Power Generation Facilities (DPGFs), mainly Solar PV and Wind Energy System connected at medium and low voltage levels for enhancing sustainability, reliability and efficiency. However, this paradigm shifting introduces significant operational complexities specifically related to protection coordination because of bidirectional power flow, dynamic power generation from renewable energy based DPGFs, voltage instability and alteration in network topologies exacerbate challenges to fault detection and classification [1]-[5], an important step to all the protection schemes. Conventional protection schemes, using overcurrent protection often fails to operate because of change or increase in fault current and directions. Inverter Interfaced sources contribute less than rotating type of DPGFs. Moreover, dynamic nature of renewable sources can introduce transient fault or may generate false alarms, demanding advances tools or methods with real time analysis.

Machine Learning (ML) [6]-[10] approaches have emerged as promising solution to address limitations imposed by renewable sources, leveraging data driven models for extracting meaningful patterns from datasets prepared from inputs through various sensors. Different techniques like Artificial Neural Network (ANN), K-Nearest Neighbors (KNN), Recurrent Neural Network (RNN), Convolutional Neural Networks (CNNs), Support Vector Machine (SVM), Wavelet Transform (WT), Random Forest (RF), Extreme Gradient Boosting (XGBoost) and Hybrid techniques enable accurate fault detection and classification, even with multi source scenario. Hybrid techniques offer superior adaptability and enhanced robustness against variabilities induced by Decentralized Power Generation Facilities. This article presents comprehensive review of Machine Learning based methods for fault detection and classification examining key challenges, performance metrics and practical implementation considerations with suggestions for future research.

II. FAULT DETECTION AND CLASSIFICATION

Various types of faults (as shown in Table 1) occur in distribution system which might cause damage to the system or equipment. It is very much important to detect fault in least time possible. Fault detection and classification is the cornerstone for any protection schemes for distribution networks. Fault is the abnormal situation which may disturb normal power flow and may lead to equipment outages and safety hazards. Fault Detection method is used to identify presence of fault minimum time possible and classification method will determine fault type, fault phase involvement and location of fault. Integration of Decentralized Power Generation Facilities in distribution network causes problems like voltage instability, bidirectional power flow, increases

fault as well as normal current which affects conventional protection of existing system. Detection and identification of faults in such condition is critical.

Table 1 Types of Faults and their chances of occurrence

Fault Type	Fault Sub-Type	Chances of Occurrence
LG	RG / YG / BG	~ 80%
LL	RY / YB / BR	~ 12%
LLG	RYG / YBG / BRG	~ 6%
LLL / LLLG	RYB / RYBG	~ 2%

Researchers have developed various fault detection and classification methods as a part of protection scheme for distribution network. Fault detection and identification method using wavelet energy spectrum entropy decomposition of disturbance waveforms [11] for extracting characteristic features was developed for distribution system with distributed generation sources. A fuzzy logic-based method for fault detection, identification and location of faults occurring within typical medium voltage grids [12] was proposed but scheme is not considering effect of distributed generation sources. An algorithm using directional overcurrent relay was developed [13] to detect fault from rising the current slope and it determine the direction of the fault current from Lissajous curves. Fault classification method using Discrete Wavelet Transform [14] for distribution system was developed but only Wind Power Generation was used as DPGF. A method utilizing features extracted from signals by the S-Transform and the concept of energy [15] was proposed for detection and classification of faults but using only one type of DG. Method of fault diagnosis in smart grid using non-conventional mother wavelet function [16] was also developed but effect of distributed generation sources was not considered. But, since past few years, Machine Learning approach has emerged as powerful tools for fault detection and classification with the help of patterns extracted from high dimensional data like voltage, current etc and are able to achieve high accuracy, robustness to noise and are adaptive to network topology changes.

III. MACHINE LEARNING BASED APPROACH

With integration of Decentralized Power Generation Facilities (DPGFs) in Distribution Network, Modern Distribution Networks are undergoing paradigm shift. This transition introduces significant challenges in fault detection and classification. Traditional protection schemes fail to work properly demanding approaches like Machine Learning which have emerged as powerful tool for fault detection and classification which addresses limitations of traditional protections by learning intricate patterns from historical and real time data, enabling adaptive, data driven fault detection and classification without exhaustive system modelling. Machine Learning paradigm includes supervised learning for labelled fault classification, unsupervised methods for fault detection and reinforcement learning for adaptive protection schemes. Different Machine Learning based approaches addressed in this section are K-Nearest Neighbors (KNN), Artificial Neural Network (ANN), Recurrent Neural Networks (RNN), Support Vector Machine (SVM), Convolutional Neural Network (CNN), Random Forest (RF), Extreme Gradient Boosting (XGBoost) and Hybrid Machine Learning (HML) methods.

3.1 Artificial Neural Network (ANN)

Artificial Neural Network (ANN) is computational method motivated by biological neural systems, applied for fault detection and classification in the field of Power System. This method excels at detection and classification of fault from data like current, voltage etc. This method is not performing well when large transient dataset is involved. Fault detection, classification and section identification method for distribution networks with distribution static synchronous compensator (D-STATCOM) using artificial neural networks (ANN) [17] was developed but without considering effect of DPGFs. Artificial Neural Networks based Fault Diagnosis Model [18] was proposed for Distribution Network but again without considering effect of DPGFs. Fault classification method based on Artificial Neural Network (ANN) [19] for power system with Wind Energy System was proposed but results will be different for System with Inverter Interfaced DGs. Artificial Neural Network (ANN) architecture for fault detection in a transmission line was proposed but fault detection scheme may not work when DPGFs are added in system.

3.2 K-Nearest Neighbors (KNN)

K-Nearest Neighbors (KNN) algorithm is non-parametric, instance-based machine learning method used for fault detection and classification for electrical power system and it remains robust baseline for fault diagnosis because of ease of implementation. KNN based fault detection and classification method [21] for distance protection of power transmission system was proposed but method is developed for transmission system and effect of DGs on FDC scheme is not considered. Comparison of KNN method with other classifier for fault data collector [22]-[23] for fault detection and classification was developed but effect of DPGFs is not considered.

3.3 Recurrent Neural Networks (RNN)

Recurrent Neural Networks (RNN) are class of neural networks prepared for processing sequential and time series data by maintaining memory of previous inputs with the help of hidden states which makes it effective for fault detection and classification for system with dynamic nature where fault is evolving over time. Method of fault location through deep learning method is proposed [24] for distribution network with DPGFs, representing advantage of using RNN based method. Comparison of deep learning methods like CNN and RNN [25] is presented for secondary distribution network for fault detection and classification showcasing pros of using RNN method for the purpose.

3.4 Support Vector Machine (SVM)

Support Vector Machine (SVM) is powerful supervised learning algorithms widely used for detection and classification of faults in distribution networks with distributed power generation facilities which originally was developed for binary classification

and finds an optimal hyperplane which maximally separate data points of different classes in high dimensional feature space, enhance robustness against noise. SVM is advantageous in small datasets with high generalization, outperform neural network in noisy environments. Multi-class support vector machine (SVMs) [26] approach for location and diagnosing of faults in distribution network was proposed but not considering the effect of DPGFs. Support Vector Machine (SVMs) [27] approach diagnosing faults in electric distribution networks with the penetration of DGs, based on the three-phase voltage and current measurements was developed but using same type of DGs. Support Vector Machine (SVM) based fault classification [28] in distribution network was proposed but considering system without DPGFs. Support Vector Machines based fault classification and location [29] on transmission lines was proposed but again applicable for transmission system and not considering the effect of DPGFs. Support Vector Machine (SVM) for fault type classification [30] in distribution network has been developed without considering the effect of Distributed Generation Sources.

3.5 Convolutional Neural Network (CNN)

CNN is class of deep neural networks designed for processing structured grid like data. Unlike fully connected network, it exploits local spatial correlations with the help of parameter sharing and sparse connectivity, achieving computational efficiency. Method of Fault Location and Detection [31] in Power Distribution Network with DPGFs using Improved CNNs was developed but used same type of DPGFs in system. Convolutional Neural Networks (CNNs) [32] based method for Power System Big Data Analysis was also developed. Method with customized Convolutional Neural Network (CNN) [33] for fault classification for distributed networks interconnected with DGs was developed but uses only PV type source as DG.

3.6 Random Forest (RF)

Random Forest is powerful ensemble machine learning algorithm used for detection and classification of faults in distribution network. It is operated by constructing multiple decision trees during training and aggregating their predictions through majority voting for classification for producing accurate outputs. Fault classification scheme based on Random Forest [34] classifier has been developed for active distribution network but considering only solar PV as DG sources.

3.7 Extreme Gradient Boosting (XGBoost)

Extreme Gradient Boosting (XGBoost) is powerful, scalable machine learning algorithm using gradient boosted decision trees is used for fault detection and classification for distribution network used to supply consumers which excels in dealing with structured data with high dimensionality, noise and class imbalance. Feature-Enhanced XGBoost based fault prediction method (FE-XGBoost) [35] was proposed for power grid but not considering effect of distributed generation sources.

3.8 Hybrid Machine Learning (HML)

Hybrid Machine Learning (HML) which integrates two different machine learning methods for enhancing fault detection and classification in complex distribution systems which addresses limitations of standalone methods and requires large dataset. Combination of Artificial Neural Network (ANN) and Support Vector Machine (SVM) algorithms [36] have been developed for classification and detection of faults on transmission lines connected with wind energy source but may get affected when PV based source is connected in system. Method based on Wavelet and ensemble of SVM classifier [37] for fault detection and classification considering non-linear load under dual mode of microgrid was proposed utilizing standard deviation of approximate coefficient obtained during feature extraction process through DWT which is used as input feature for training ensemble of SVM. Fault Detection and Classification combining Wavelet Transform and Neuro Fuzzy System [38] was proposed but using only rotating type of DGs. Method of Detection, Classification and Localization of Faults [39] with combination of Wavelet Transform and Neural Network was proposed but effect of DPGFs is not considered. Hybrid Wavelet Singular Entropy and Fuzzy System based Fault Detection and Classification method [40] for Distribution Line with Distributed Energy Sources was proposed but using only wind power generation as DERs.

IV. DISCUSSION

Detection and classification of faults in electrical distribution network have become challenging since years because integration of distributed power generation facilities causes bidirectional power flow, increase in fault & normal current level and dynamic nature of DPGFs. Machine Learning methods have become promising because of result accuracy. Performance of different machine learning methods [41]-[43] varies by different points like accuracy, robustness to noise, computational speed and adaptability to DPGF induced issues. Comparison of different Machine Learning methods is presented in Table 2. Based on reviews and studies, hybrid methods are considered to better in performance than other methods. They achieve higher adaptability and accuracy by addressing DPGF related challenges to fault detection and classification outperforming individual methods.

Table 2. Comparison of Machine Learning Methods

Method	Relative Speed	Robustness to Noise / DPGF penetration	Strength / Weakness
KNN	Fast	Low	Simple, No Training; Struggle with high dimensional data
ANN	Moderate	Moderate (Overfitting Risk)	Versatile for nonlinear patterns; less robust than ensembles against noise
RNN	Slow	Moderate (Good for Sequences)	Handles temporal dynamics; computationally heavy for real time
SVM	Fast	High (Margin based)	Effective for multi class; limited on very large DPGF datasets

CNN	Moderate (Optimizable)	High (Feature Extraction)	Excels in signal like data; GPU dependent
RF	Fast	Very High (Ensemble Averaging)	Robust to noise / DPGF variability; interpretable
XGBoost	Fast	Very High (Boosting)	Handles imbalanced data; scalable for large simulations
Hybrid	Moderate	Very High	Best overall

V. CONCLUSION

The interconnection of distributed power generation facilities like wind and solar into distribution network has revolutionized energy delivery but introduced complexities in fault detection and classification. Conventional schemes which are reliant on overcurrent protection often falter in variable environments which further leads to delayed responses and undetected faults. This review article has appropriately explored machine learning approaches as transformative solution, demonstrating their accuracy, speed and real time capabilities. From review comparison, it can be concluded that using hybrid machine learning method (e.g., WPT+CNN, WPT+SVM, WPT+XGBoost) for fault detection and classification is better option than all other individual machine learning methods. Machine Learning approaches are better option for fault detection and classification.

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