IMPLEMENTATION OF DIGITAL PROTECTION IN DISTRIBUTION SYSTEM WITH PENETRATION OF DISTRIBUTED GENERATION

A Synopsis submitted to Gujarat Technological University for the Award of

Doctor of Philosophy

In

ELECTRICAL ENGINEERING

by

DESAI ISHAN MUKESHCHANDRA
(Enrollment No.: 179999914003)

under supervision of

DR. NILESH CHOTHANI

GUJARAT TECHNOLOGICAL UNIVERSITY
AHMEDABAD

March - 2026

Implementation of Digital Protection in Distribution System with Penetration of Distributed Generation

1. Abstract

With increase in Integration / Penetration of Distributed Generation (DG) sources like Solar PV and Wind Energy Conversation System, Traditional Radial Distribution Network (TRDN) gets transformed into Modern Active Distribution Network (MADN) with bidirectional power flow, increased fault current level and dynamic operating conditions. These alterations render conventional protection schemes ineffective that leads to problems like relay miscoordination, false tripping and relay blinding. Comprehensive analysis is done to understand parameters affecting relay coordination of Distribution Network. This thesis proposes a reliable digital protection scheme based on Wavelet Packet Transform (WPT) for multi resolution feature extraction from three phase current combined with Extreme Gradient Boosting (XGBoost) for fault detection and classification. Proposed hybrid WPT+XGBoost method is validated through extensive simulations on modified IEEE 4-Bus and IEEE 9-Bus distribution test systems with variable DG penetration level and system load, variation in terms of number of DGs, location and types of DGs. Simulations are also done considering different fault types, fault locations and fault resistances. Proposed method achieves more than 99% fault detection and classification accuracy outperforming conventional protection and other Artificial Intelligence / Machine Learning (AIML) based methods. Proposed method ensures reliable protection maintaining selectivity and sensitivity in presence of various Distributed Generation sources. Work demonstrates suitability of proposed scheme based Digital Protection Scheme for Modern Active Distribution Network, also helps in developing adaptive, self-healing scheme for Smart Grid.

2. Brief Description on the state of the art of the Research Topic

Integration of Distributed Generation has advantages like environment friendliness, improvement in system reliability, reduction in loss and maintenance cost [1]-[3] but causes many issues like bidirectional power flow, chances of unintentional islanding, frequency / voltage instability and increased & dynamic fault current level [3]-[6]. Mainly it creates issues related to protection like protection blinding, chances of feeder false tripping and relay miscoordination. There is an evolution in Digital Protection for Distribution System with Distributed Generation from traditional protection to adaptive protection schemes. Researchers have developed different protection strategy for distribution system with distributed generation. High Impedance Fault (HIF) detection using energy raising of linear predictor error signals as indicator [7] was developed for distribution system but it is not considering effect of distributed generation sources, inrush currents or nonlinear loads. Current signals approach-based fault detection and classification for distribution system [8] with multiple distributed generation facility was developed utilizing communication system but fails to operate when communication channels fail. Sensor independent deep learning method [9] for fault detection, classification and location in Low Voltage distribution system but deep learning requires large amount of data for processing.

Fault detection and classification based on Teager–Kaiser energy operator [10] for AC Microgrid was developed where determination of faulty phase is performed using indices derived from squared currents. Detection and classification of disturbances that evolves in succession using Energy Preserving Ensemble Empirical Mode Decomposition (EPEEMD) and Least Square Support Vector Machine (LSSVM) [11] techniques was developed for grid connected system but developed for system with Inverter Interfaced DGs like Solar PV. Deep learning approaches was developed for fault detection and classifications [12] for secondary distribution network where various methods were compared and Recurrent Neural Network (RNN) is found to be more suitable. Algorithm based on positive sequence measurement [13] for detection of fault, islanding and power swings was developed for DG integrated radial distribution networks. Researchers have also proposed different Artificial Intelligence / Machine Learning (AI/ML) based Fault Detection and Classification (FDC) methodologies. Various AI/ML based methods and their limitations are represented in Table 1.

Table 1. Artificial Intelligence / Machine Learning based Fault Detection and Classification (FDC) methodologies

Sr. No.	Technique	Description	Limitations*
1	Artificial Neural Network (ANN) [14]-[19]	Multi-Layer Perceptron (MLP) Artificial Neural Network (ANN) based approach for Fault Localization & Identification, ANN based FDC approach, FDC using Feed Forward Neural Network with back propagation, ANN based communication assisted scheme.	Model training and updates are time consuming, requires large data and computational resources for training.

2	Wavelet Packet Transform (WPT) / Wavelet Transform (WT) [20]-[24]	Analysis of wavelet transform (WT) and wavelet packet transform (WPT) based islanding detection in grid connected PV system, Fault Identification and Location (FIL) technique using wavelet multi resolution approach, WT based frequency multi-resolution technique for detecting different faults, WT based intelligent technique to detect and classify power system faults, Discrete Wavelet Transform (DWT) to detect and classify High Impedance Fault.	Large errors produced by wavelet transform but WPT will provide uniform frequency sub band with better time frequency resolution, Methods fail to extract geometric features for disturbance detection whenever the noise level in the voltage function crosses 40 db.
3	Support Vector Machines (SVM) [25]-[30]	Support vector machine (SVM) for Fault Classification and Detection (FDC), multiple features-based support vector machine (SVM) for Islanding detection, Multi-class Support Vector Machine (SVMs) based approach for location and diagnosing faults, Support Vector Data Description method - a commonly used one-class classifier, Multiple Features based scheme for Islanding Detection.	Computationally intensive and time consuming, fault inception angles are not considered in training process, only rotating type of DGs are used, scenario will be different when two different types of DGs are used.
4	K-Nearest Neighbor (KNN) [31]-[32]	KNN based algorithm for Fault Detection and Classification (FDC) for distance protection, KNN based Fault Detection, Classification and Location (FDCL) method for Power System.	Less classification accuracy and high computational complexity.
5	Convolutional Neural Network (CNN) [33]-[35]	Transient Stability Assessment (TSA) and instability mode prediction, 20-layer deep neural network (CNN) for fault detection and location, Fault classification for Distribution Network with DGs using Convolutional Neural Network (CNN) based algorithm.	Effect of Renewable Energy Sources (RES) not considered.
6	XGBoost [36]	Fault Detection in Low Voltage Neutral Point Ungrounded (LVNPU) system using Extreme Gradient Boosting (XGBoost).	Careful and time-consuming tuning because of many hyperparameters.

7	Hybrid [37]-[44]	Single Feedforward Artificial Neural Network (SFANN) + K-Nearest Neighbors (KNN) for estimating fault location, Artificial Neural Network (ANN) + Discrete Wavelet Transform (DWT) for fault detection and classification, Wavelet Transform + Deep Neural Network for fault detection, Dual Tree Complex Wavelet Transform (DT-CWT) + Data Mining, DWT + Evolving Neural Network, WT + ANN, Multi-Channel Convolutional Neural Network (CNN) + Long Short-Term Memory (LSTM) network for fault detection, Gravitational Search Algorithm + ANN.	Single ANN for all fault types can be source of error, not useful when identifying lost phase, performance drops when there is abrupt change in fault pattern, computationally complex system to implement for Distribution Network with Distributed Generation Sources.

* General limitations are mentioned below.

From reviewing above articles, it can be said that each method has its own technical limitations for fault detection and classification in terms of speed and accuracy but also has one or more limitations like (i) considering only one type of DG (either rotating or inverter interfaced DG), (ii) considering DGs with fixed or same capacity, (iii) DG effect is not considered, (iv) focus on detection of only one type of fault, not considering fault location and (v) communication system is used for exchanging required system data which if fails, system will not work properly. Reliable and adaptive protection must be developed to address at least two or more of these issues.

Table 2. Theoretical comparison of Machine Learning methods

Method	Robustness	Computational Speed	Data Requirement	Strength
ANN	Medium (sensitive to DG variability)	Medium (Training scales poorly with data)	High (needs large labelled datasets)	Simple Architecture
WPT	High (decomposes signals for transient capture)	High (fast decomposition)	Low (works on raw signals)	Excellent for extracting energy features from fault transients

SVM	High (effective with kernel)	High (fast for small-medium datasets)	Medium (performs well on balanced data)	Handles high-dimensional features
KNN	Low Moderate (sensitive to feature scaling)	Low (no training)	High (large dataset required)	Simple implementation
CNN	High (end-to-end learning; noise-resistant)	Medium (GPU-accelerated inference)	High (benefits from large simulated fault data)	Feature extraction from raw signals
XGBoost	High (gradient boosting handles DG noise)	High (parallelizable; fast on tabular features)	Medium (ensemble reduces overfitting)	Efficient dimensionality reduction before classification
Hybrid	**Very High (combines strengths,**	**Medium (varies by combo**	**Medium-High**	**Best overall**

Machine learning approaches (like ANN, CNN, KNN, WPT, SVM) are gaining traction as an individual technique for Fault Detection and Classification for Distribution System with Distributed Generators. Extreme Gradient Boosting (XGBoost), a robust classifier is also gaining importance with advantages like high accuracy and efficiency in handling difficult classification tasks. Theoretical comparison of these methods [7]-[47] considering parameters like robustness, computational speed, data requirement and strength is given in Table 2. From Table 1 and Table 2, it is observed that hybrid method is better in Fault Detection, Classification and Location. Combining advantages of Wavelet Packet Transform (WPT) being powerful tool which enables extraction of both Time-Frequency features from fault current signals to effectively captures abnormal events like Faults and Extreme Gradient Boosting (XGBoost) being robust classifier with high accuracy and efficiency for event classification, hybrid WPT+ XGBoost scheme for Fault Detection and Classification is proposed. Proposed WPT+ XGBoost based scheme is superior in achieving better results with accuracy with variable Operating Conditions and Fault parameters like Fault Type, Fault Resistance and Fault Location that showcased its ability to enhance grid reliability and support integration of DG sources in Distribution System.

3. Definition of the Problem

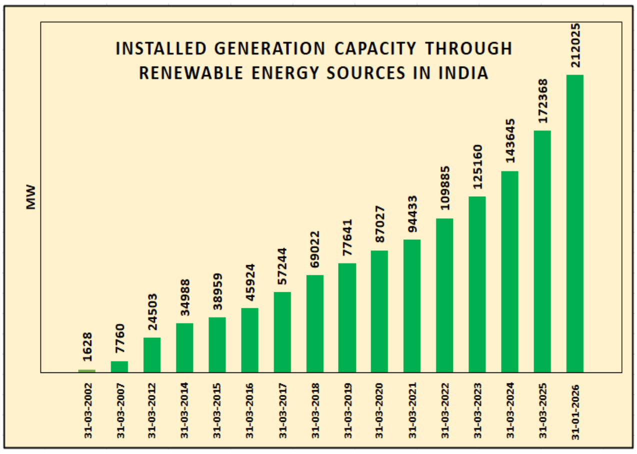

Figure 1. Installed Generation Capacity from Renewable Energy sources in India (in MW)

Modern Active Distribution Network (MADN) faces notable protection issues because of high penetration of Distributed Generation sources (DGs). In India, it is important as there is hugh rise in integration of Renewable Energy Sources in last 20 years as shown in Fig. 1. Traditional overcurrent relays or protection schemes assume unidirectional power or current flow and constant fault current level.

But integration of Distributed Generators will introduce (i) bidirectional current flow which causes miscoordination of traditional protection scheme, (ii) reduction in fault current contribution from grid (or from DG, if new DG source is added) which leads to protection blinding, (iii) variable and dynamic fault current contribution from different sources ($I_{f\text{-}SG} > I_{f\text{-}IG} > I_{f\text{-}PV}$) may lead to under reach / over reach of relay, (iv) miscoordination during transition of system topology (ring main to radial) or operating condition (grid connected to isolated islanded), (v) inability to detect low current faults which cannot be detected by traditional methods and (v) difficulties in protection coordination because of dynamic fault current level. All these issues compromise system stability and reliability, increasing chances of outage and equipment damage. Existing protection schemes are costly, complex and insufficiently robust to dynamic nature of DGs which necessitates fast, sensitive, reliable protection approach.

4. Objective of Work

Main objective of this work is to do investigation and analysis of factors affecting system parameters and protection coordination and propose an enhanced Digital Protection Scheme with the aim of maintaining selectivity, speed and reliability of Fault Detection & Classification (FDC) and Isolation while overcoming limitations of conventional protection schemes for Modern Distribution Network (MDN) with significant integration of Distributed Generation sources like Solar PV, Wind and Small Hydro. Following objectives should be considered for this work.

- To critically review and analyse impact of penetration of Distributed Generation (DG) sources on Distribution System parameters and conventional protection schemes (mainly overcurrent protection) and identify key factors which are affecting system protection and causes problems like protection blinding, false tripping, loss of coordination and islanding.
- To analyse effect of different fault parameters like Fault Location, Fault Types and Fault Resistance in presence of DG sources on protection coordination.
- To critically review existing protection schemes and identify issues faced by them when DGs are present.
- To propose an improved Fault Detection and Classification Scheme for System Protection (or Hybrid Scheme) which ensures secure and coordinated operation in presence of DG sources.
- To examine the performance of proposed scheme through extensive simulations with various operating condition as mentioned above and do comparison with other existing schemes considering security, reliability, selectivity and speed of operation.
- To provide recommendations for further solutions with Digital Protection for Distribution System with DG penetration and future research directions.

5. Scope of Work

Integration of Distributed Generators like Solar PV, Wind, Small Hydro etc will introduce significant challenges in Distribution System and affect conventional protection scheme provided for Distribution System Protection. This work aims to explore and develop digital protection scheme for distribution network considering penetration of Distributed Generation sources. It also focuses on enhancing system reliability and ensuring safe operation under dynamic generation from DGs. This thesis will cover following scope of work:

- **Distribution System Considered:** Modified IEEE 4-Bus Distribution System is considered with 12.47 kV system voltage. System is considered without DG source/s and with DG source/s (Synchronous Generator, Induction Generator, Solar PV) with 1 MW and 0.7 MW capacity. System is also considered with load increment 1 MW.
- **Simulation and Analysis:** Distribution System simulation conducted, incorporating different types of DG units, analyse their fault current contribution in case of fault and required data is generated using PSCAD/EMTDC software. Generated data are simulated in MATLAB through coding for generating different details like accuracy, F1 score etc. for different methods and finding suitable method for fault detection and classification required for reliable protection scheme.

- **Address of Protection Challenges:** Protection challenges are addressed by simulating distribution network considering different fault parameters (Fault Locations, Fault Types, Fault Resistances, Fault Inception Angle), penetration of Distributed Generation sources (DGs of different types and capacity) and increment in system demand.
- **Digital Protection Technique:** After simulation and analysis of different methods, protection algorithm is finalised considering Hybrid method for Fault Detection and Classification (FDC) and adaptive protection scheme.

6. Original Contribution by the Thesis

Study presented in thesis represents comprehensive review of various existing schemes and their limitations. Simulation for studying effects of integrating Distributed Generation sources in Distribution Network on system parameters and specifically on protection coordination (or protection settings) is carried out using PSCAD/EMTDC software. Effects on protection coordination is studied considering various Distributed Generation (DG) parameters like DG types, DG location, DG capacity, Fault parameters like Fault types, Fault location, Fault resistance as well as load variation. Overcurrent protection algorithm is developed for Industrial Distribution Network with DG sources and also study of effects of DGs with various Setting Groups (SG) is carried out. Data generation for various cases is done with PSCAD/EMTDC software which then is utilized in MATLAB to calculate performance parameters for various methods used for Fault Detection and Classification (FDC). Based on analysis, hybrid WPT+XGBoost technique is found to be more accurate and reliable offering superior feature extraction from high frequency transients and efficient ensemble learning for fault classification with accuracy more than 99%. Algorithm for FDC using WPT+XGBoost is also developed for protection of distribution system with DGs.

7. Methodology of Research, Results and Comparison

7.1 Analysis of Parameters affecting Protection Coordination

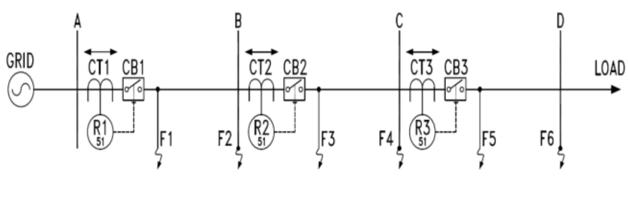

Figure 2(a). Radial Distribution Network fed with one source (without transformer)

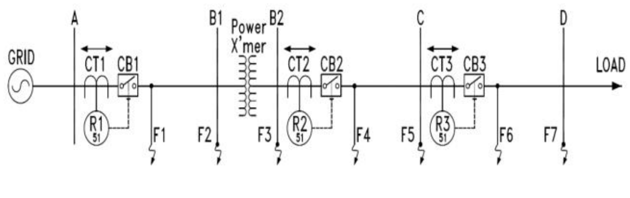

Figure 2(b). Radial Distribution Network fed with one source (with transformer)

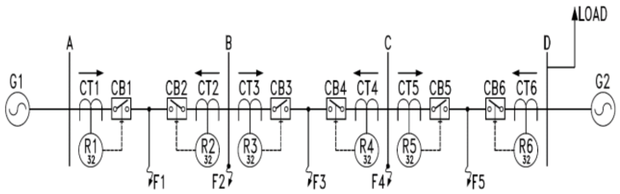

Figure 3(a). Radial Distribution Network fed with more than two sources (grid only)

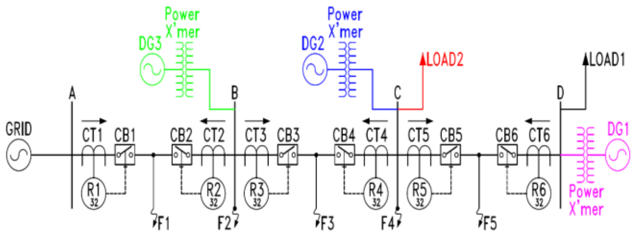

Figure 3(b). Radial Distribution Network fed with more than two sources (grid + DGs)

Effect of various parameters on Protection Coordination of Distribution Network (Modified IEEE 4-Bus system with system voltage 12.47 kV and load demand of 6 MW with each line section of 20 km) fed through one source (as shown in Fig. 2(a) and 2(b)) and more than one sources (as shown in Fig. 3(a) and 3(b)) is analysed using PSCAD/EMTDC software as below:

- **For system fed with one source:** For protection of distribution system with one source, three overcurrent relays (51) with IDMT characteristics following IEC-60255 standard are used. To understand the effect on protection coordination, various cases as shown in Table 3 are considered. Analysis is done considering fault parameters like (i) Fault Locations (on each bus except generator bus and midpoint of each line sections), (ii) Fault types (LG and LL) and (iii) Fault resistances (0 Ω, 4 Ω, 8 Ω and 12 Ω). System with transformer (rated 6.3 MVA, 12.47/4.16 kV) is also taken into account as there will be two different voltages as well as currents in normal as well as faulty conditions.

Table 3. Cases for analysis of effect on protection coordination (distribution system with one source)

Case No.	Discription
1	Radial feeder without transformer (system fed at one end (grid only))
2	Radial feeder with transformer (system fed at one end (grid only))
3	Radial feeder without transformer (system fed at one end (SG only))
4	Radial Feeder without transformer (system fed at one end (IG only))

Current contribution from various types of sources in faulty condition (considering fault location F1 in Fig. 2(a) and 2(b)) is shown in Fig. 4 which depicts fault current contribution from synchronous generator is higher than induction generator. Effect on protection coordination (in terms of relay current setting and considering LL fault) for different cases is represented in Table 4.

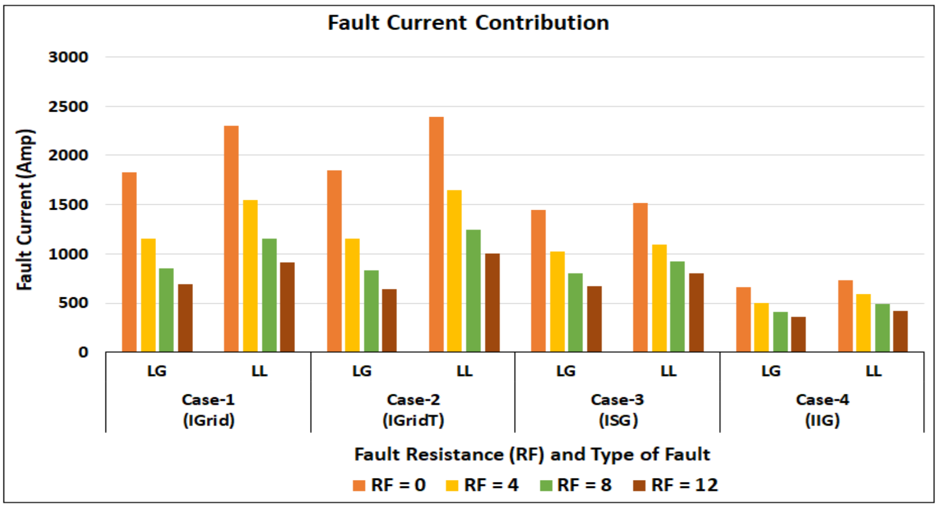

Figure 4. Current contribution from various types of sources in faulty condition (for system with one source)

Table 4. Relay current settings (Ip) for different cases (for system with one source)

Fault Resistance	Relay	Relay Current Settings (Ip) (A)			
		Case - 1	Case - 2	Case - 3	Case - 4
RF = 0	R1	0.25	0.06	0.22	0.17
	R2	0.2	0.11	0.2	0.11
	R3	0.15	0.07	0.17	0.09
RF = 4	R1	0.24	0.05	0.21	0.14
	R2	0.19	0.08	0.19	0.09
	R3	0.15	0.06	0.16	0.08
RF = 8	R1	0.185	0.04	0.17	0.13
	R2	0.18	0.07	0.17	0.09
	R3	0.15	0.06	0.15	0.08
RF = 12	R1	0.16	0.03	0.15	0.12
	R2	0.16	0.07	0.15	0.085
	R3	0.14	0.06	0.14	0.08

- **For system fed with more than one source:** For protection of distribution system with more than one sources (either only Grid or Grid+DG), six directional power relays (32) are used. For analysis of effect on protection coordination, various cases as shown in Table 5 are considered. Effect is analysed considering fault parameters like (i) Fault Locations (on Bus B, Bus C and midpoint of each line sections), (ii) Fault type (LG) and (iii) Fault resistances (4 Ω and 12 Ω). Analysis of effect of integrating various DG sources is performed with combination of either same or different DG types (Synchronous Generator, Induction Generator and Solar PV) and Capacity.

Table 5. Cases for analysis of effect on protection coordination (distribution system with more than one sources)

Case No.	Discription (SG: Synchronous Generator, IG: Induction Generator)
C1	Radial Feeder (System Fed at two ends (Grid only))
C2	Radial Feeder (System Fed at two ends (Grid only)) with load increment by 1 MW
C3	Radial Feeder fed at two ends (Grid and SG (1 MW))
C4	Radial Feeder fed at three ends (Grid and two SG (1 MW)) with load increment by 1 MW
C5	Radial Feeder fed at three ends (Grid and two SG (1 MW and 0.7 MW)) with load increment by 1 MW
C6	Radial Feeder fed at three ends (Grid, one SG (1 MW) and one IG (1 MW)) with load increment by 1 MW
C7	Radial Feeder fed at three ends (Grid, one SG (1 MW) and one Solar PV (1 MW)) with load increment by 1 MW
C8	Radial Feeder fed at Four ends (Grid, one SG (1 MW), one IG (1 MW) and one Solar PV (1 MW)) with load increment by 1 MW
C9	Radial Feeder fed at Four ends (Grid, three SG (1 MW)) with load increment by 1 MW
C10	Radial Feeder fed at Four ends (Grid, two SG (1 MW), one IG (1 MW)) with load increment by 1 MW

Table 6. Current contribution from various types of sources in faulty condition (system with more than one sources)

Current Contribution from Different Sources (A)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
IGrid1	616	643	625	468	501	657	627	646	478	462
IGrid2	1517	1563	-	-	-	-	-	-	-	-
ISG1	-	-	993	976	981	963	980	943	888	939
ISG2	-	-	-	918	667	-	-	-	908	878
ISG3	-	-	-	-	-	207	-	-	979	-
IIG	-	-	-	-	-	-	-	207	-	178
IPV	-	-	-	-	-	-	151	149	-	-

Current contribution from various types of sources in faulty condition (considering fault location F3 in Fig. 3(a) and 3(b)) is shown in Table 6. From Table 6 and also as mentioned previous sections, fault current contribution from Synchronous Generator is higher than Induction Generator and it is least in case of Solar PV which is the main reasons for alteration in protection coordination. This effect will be more prone when only either wind or solar pv is integrated as DG source in distribution system. Effect on protection coordination (in terms of relay current setting and considering LG fault) for different cases with different fault resistances is represented in Table 7.

Table 7. Relay current settings (Ip) for different cases (for system with more than one sources)

Fault Resistance	Relay	Relay Current Settings (Ip) (A)									
		C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**
RF = 0	**R1**	0.45	0.40	0.42	0.38	0.40	0.28	0.28	0.28	0.32	0.30
	R2	0.07	0.12	0.12	0.08	0.40	0.12	0.17	0.16	0.14	0.17
	R3	0.20	0.225	0.19	0.26	0.24	0.18	0.18	0.13	0.28	0.20
	R4	0.22	0.225	0.16	0.20	0.16	0.14	0.16	0.16	0.22	0.22
	R5	0.09	0.21	0.18	0.135	0.20	0.16	0.18	0.195	0.16	0.15
	R6	0.45	0.45	0.26	0.26	0.26	0.22	0.24	0.20	0.32	0.20
RF = 4	**R1**	0.42	0.38	0.36	0.34	0.38	0.24	0.26	0.24	0.30	0.28
	R2	0.05	0.11	0.12	0.07	0.30	0.11	0.15	0.16	0.12	0.16
	R3	0.19	0.19	0.18	0.22	0.20	0.14	0.14	0.12	0.24	0.16
	R4	0.20	0.22	0.16	0.16	0.14	0.14	0.15	0.145	0.20	0.22
	R5	0.085	0.19	0.16	0.13	0.18	0.16	0.15	0.16	0.16	0.15
	R6	0.41	0.35	0.23	0.20	0.22	0.18	0.20	0.17	0.26	0.17
RF = 8	**R1**	0.35	0.30	0.30	0.28	0.32	0.15	0.22	0.18	0.26	0.20
	R2	0.018	0.10	0.08	0.06	0.26	0.10	0.12	0.16	0.10	0.15
	R3	0.165	0.16	0.17	0.20	0.16	0.12	0.13	0.10	0.16	0.12
	R4	0.14	0.15	0.15	0.12	0.12	0.12	0.14	0.135	0.16	0.16
	R5	0.082	0.18	0.14	0.12	0.16	0.14	0.14	0.15	0.14	0.15
	R6	0.32	0.28	0.18	0.16	0.18	0.13	0.14	0.14	0.17	0.14
RF = 12	**R1**	0.30	0.25	0.24	0.18	0.20	0.13	0.20	0.16	0.22	0.14
	R2	0.012	0.10	0.04	0.05	0.24	0.10	0.08	0.14	0.08	0.15
	R3	0.16	0.14	0.165	0.15	0.135	0.105	0.12	0.09	0.12	0.10
	R4	0.12	0.13	0.13	0.09	0.105	0.11	0.13	0.13	0.12	0.132
	R5	0.08	0.15	0.12	0.10	0.14	0.125	0.13	0.12	0.10	0.15
	R6	0.22	0.22	0.16	0.15	0.16	0.10	0.12	0.12	0.12	0.12

7.2 Overcurrent protection for Industrial Distribution Network

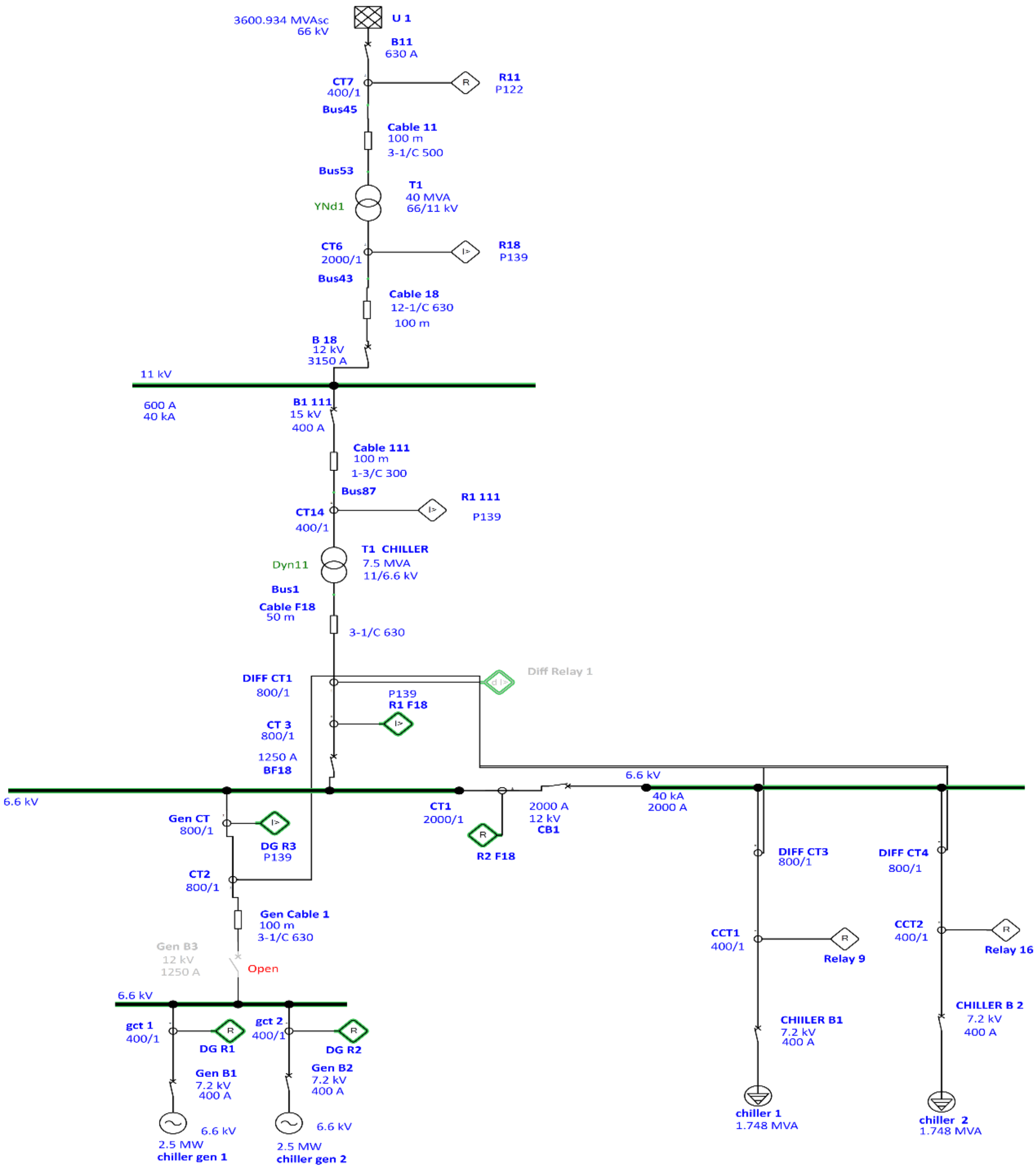

Figure 5. 9-Bus Industrial Distribution System

Adaptive overcurrent protection algorithm for 9-Bus Industrial Distribution System (as shown in Fig. 5) is developed as shown in Fig. 6. Load Flow Analysis (using NR method) and Short Circuit Analysis using ETAP software following IEC 60255 standard is performed in which is helpful in calculating relay setting parameters. Simulation of various faults is done with different system locations and operating mode for calculation of fault currents, operating time and identification of relay pairs for reliable protection of distribution network. Re-calibration is performed by relay automatically and it resets relay parameters like Pickup Current and Time Multiplier Setting. If change in system topology or configuration is detected, data will be sent to relay which modifies its parameters.

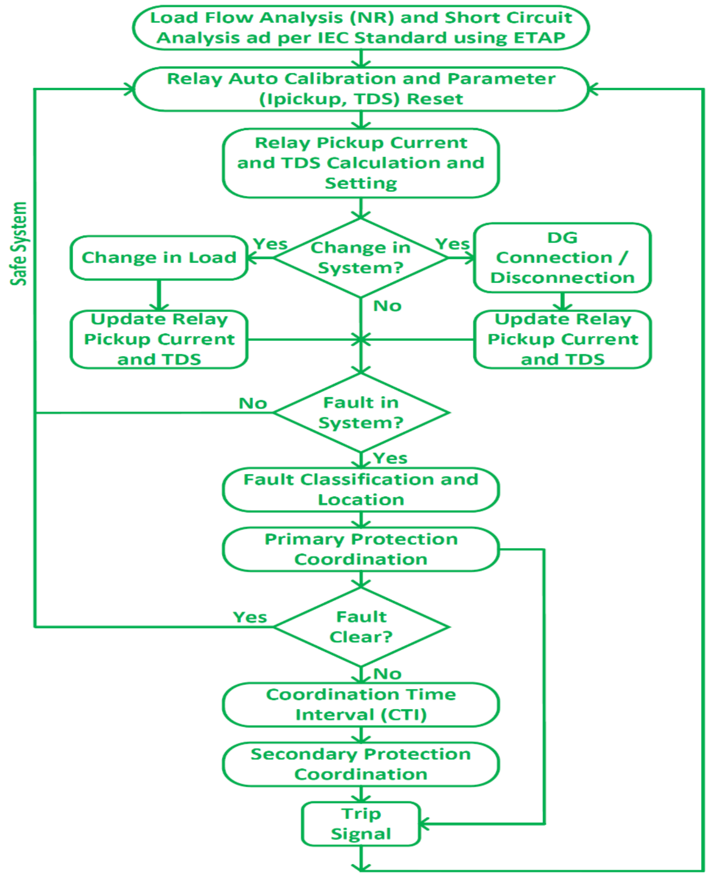

Figure 6. Protection Algorithm for 9-Bus Industrial Distribution System with DG sources

Table 8. Setting Groups (SG)

SG No.	Setting Group (SG) Configurations
1	PG* only
2	PG + 1 DPGR**
3	PG + 2 DPGR
4	Island + 1 DPGR
5	Island + 2 DPGR
* PG = Power Grid ** DPGR = Distributed Power Generation Resources	

After configuring relay parameters, presence of fault is detected in system. If fault is present, primary protection coordination will be actuated, sending trip signal to respective breakers to isolate faulty part of the system. If primary protection fails to operate or in case fault is still unclear, considering Coordinated Time Interval (CTI) secondary protection coordination is actuated. Once the fault is cleared, relay resets itself back to initial condition.

Table 9. Relay Pickup Current and Operating Time summary for differentSetting Groups (SG)

SG No.	Setting Group (SG) Arrangement	Relay	System Fault Current seen by Relays (kA)	Ipickup (Amp)	Time Dial Setting (TDS)	T1 (Top) (ms)
1	PG Only	R16	7.828	0.98	0.1	0.227
		R2F16	7.828	0.40	0.12	0.360
		R1F16	7.828	0.98	0.15	0.446
2	PG + 1 DPGR	R16	9.309	1.17	0.1	0.227
		R2F16	9.309	0.55	0.12	0.385
		R1F16	7.828	0.98	0.15	0.446
3	PG + 2 DPGR	R16	10.885	1.37	0.1	0.227
		R2F16	10.885	0.77	0.11	0.386
		R1F16	7.828	0.86	0.15	0.421
4	Island + 1 DPGR	R16	1.48	0.46	0.1	0.329
		R2F16	1.48	0.16	0.12	0.540
		DGR3	1.48	0.39	0.14	0.620
5	Island + 2 DPGR	R16	3.057	0.46	0.1	0.242
		R2F16	3.057	0.31	0.12	0.518
		DGR3	3.057	0.77	0.14	0.604

Simulation of Protection Coordination is performed for various Setting Groups (SG (Table 8)) and summary of relay operating sequence, relay pickup current and relay operating time is prepared as shown in Table 9 considering fault to be on Feeder of Chiller 2 (as shown in Fig. 5). IEC standard inverse curve is used for coordination of respective relays for various Setting Groups (SG) for distribution system. From analysis with various Setting Groups, relay R2F18 (as shown in Fig. 5) is found to be common and important. With comprehensive simulation (considering different Setting Groups), it is concluded that risk of miscoordination is mitigated with provided protection scheme.

7.3 Fault Detection and Classification using WPT+XGBoost

IEEE 4-Bus system is simulated in PSCAD/EMTDC software to generate post fault data considering fault locations (mid-point and on bus), fault resistances (0 Ω, 3 Ω, 6 Ω, 9 Ω, 12 Ω, 15 Ω, 18 Ω), fault types (LG, LL, LLG, LLL) and fault inception angle (0°, 5°, 10°, 15°, 20°). Generated data is utilized in calculating performance parameters like % accuracy and F1 score for Fault Detection and Classification for various methods using MATLAB. Based on theoretical comparison and literature review, for Fault Detection and Classification, methods like Convolutional Neural Network (CNN), Artificial Neural Network (ANN), Wavelet Packet Transform (WPT), Support Vector Machine (SVM), Extreme Gradient Boosting (XGBoost) and hybrid (WPT+CNN, PCA+CNN) are considered for comparison with proposed method.

Table 10. Fault Detection and Classification Performance

Method	Accuracy	F1 Score
ANN	94.25	94.70
WPT	98.41	98.49
SVM	97.34	96.97
CNN	98.82	94.5
XGBoost	92.4	92.4
WPT+CNN	98.43	97.4
PCA+CNN	99.2	98.9
WPT+XGBoost	**99.8**	**99.6**

After simulating more than 2000 cases, considering benefits from hybrid method from Table 2 and combining benefits from WPT and XGBoost, it is found that proposed WPT+XGBoost method is better in Fault Detection and Classification with accuracy more than 99% as shown in Table 10. This scheme has achieved even higher F1 score which support its selection for Fault Detection and Classification for Distribution System with Distributed Generation sources.

8. Achievement with respect to Objectives

Objective Defined	Objective Achieved
To critically review existing protection schemes and identify issues faced by them when DGs are present.	Comprehensive literature review is done to analyse existing protection scheme and issues faced by them. Each method has its own limitations but general limitations are

	considering only one type of DGs and DGs with fixed or same capacity, focus on detection of only one type of fault and using communication system for exchanging required system data.
To critically review and analyse impact of penetration of Distributed Generation (DG) sources on Distribution System parameters and conventional protection schemes (mainly overcurrent protection) and identify key factors which are affecting system protection.	Extensive review of various literature along with simulation using PSCAD/EMTDC software is done to analyse impact of DG penetration on system parameters like voltage and conventional protection scheme because of increasing fault current, dynamic current contribution from different DGs and DG locations.
To analyse effect of different fault parameters like Fault Location, Fault Types and Fault Resistance in presence of DG sources on protection coordination.	Detail simulation is done to analyse impact of fault parameters like fault location, fault types and fault resistance on protection parameters (relay pickup current, time dial setting).
To propose an improved Fault Detection and Classification Scheme for System Protection (or Hybrid Scheme) which ensures secure and coordinated operation in presence of DG sources.	Based of literature review, theoretical comparison is prepared and found that hybrid fault detection and classification scheme is more suitable when DGs are present in Distribution System.
To examine the performance of proposed scheme through extensive simulations with various operating condition as mentioned above and do comparison with other existing schemes considering security, reliability, selectivity and speed of operation.	Considering various cases, data are generated through PSCAD/EMTDC software and FDC performance parameters are calculated using MATLAB. Methods like ANN, CNN, SVM, WPT, XGBoost and hybrid (WPT+CNN, PCA+CNN) are compared with proposed WPT+XGBoost. Results support selection of WPT+XGBoost technique for fault detection and classification with accuracy more than 99%.
To provide recommendations for further solutions with Digital Protection for Distribution System with DG penetration and future research directions.	Proposed scheme can be extended for hardware implementation. CATBoost is also one of the techniques for fault detection and classification whose performance needs to be assessed.

9. Conclusion

Increasing usage and integration of Distributed Generation sources like Small Hydro, Solar PV and Wind Power Generation and other Inverter Interfaced Distributed Generation sources (DGs) in Distribution System brings opportunities as well as various challenges. It mainly affects conventional protection schemes because of bidirectional power flow, increasing normal as well as fault currents and reduction in current contribution from grid (or DG in case new DG source is added) that leads to protection blinding. Conventional protection schemes are facing issues in maintaining sensitivity and selectivity under these dynamic conditions which demands accurate and reliable Fault Detection and Classification (FDC) scheme.

For the study, comprehensive literature review and extensive simulational analysis performed through PSCAD/EMTDC software highlights various factors that has significant impact on protection coordination like fault current contribution from DGs ($I_{f\text{-}SG} > I_{f\text{-}IG} > I_{f\text{-}PV}$), DG penetration and network topology. Through simulational analysis, it is also found that protection coordination is also affected by DG location, combination of DG types integrated in system, fault types, fault location and fault resistance. An adaptive overcurrent protection is also developed for Industrial Distribution System where with different source combinations and system condition (grid connected or islanded) and analysis for calculating protection parameters is performed using ETAP software. Through extensive simulations with various setting groups, it is concluded that risk of protection miscoordination is mitigated with proposed overcurrent protection.

This study also proposes hybrid method for Fault Detection and Classification (FDC) for reliable protection distribution system with distributed generation sources combining Wavelet Packet Transform (WPT) for feature extraction with Extreme Gradient Boosting (XGBoost) as powerful ensemble classifier with higher accuracy. Simulation of various cases for distribution system with distributed generation sources for data generation is performed and generated data is used in MATLAB to calculate performance parameters for various methods like ANN, CNN, SVM, WPT, XGBoost and Hybrid schemes for comparison with proposed method. Hybrid technique combining WPT with XGBoost for fault detection and classification gives accuracy more than 99% along with better F1 score as well. Proposed method exhibits faster computation, making it more feasible for real time implementation. WPT+XGBoost approach contributes towards enhanced protection scheme with higher reliability.

List of Publications

Published Papers

[1] Desai, I., Chothani, N., & Jacob, P. (2026). Parameters affecting Protection Coordination of High Voltage Distribution Network with Distributed Energy Resources. *Bulletin of Electrical Engineering and Informatics*, 15(2), 986-998. doi: https://doi.org/10.11591/eei.v15i2.10045.

[2] Chothani, N., Desai, I., Kit chan, C., Singh, S., Varshney, D., & Naik, N. (2026). PCA and CNN-based detection and classification of faults in distribution network with distributed energy resources. *Applications in Engineering Scien*ce, 25, 1-12. doi: https://doi.org/10.1016/j.apples. 2026.100300.

[3] Desai, I., Jacob, P., Chothani, N., & Mangroliya, D. (2026). Overcurrent Protection Scheme for Industrial Distribution System with Decentralized Power Generation Resources. *SSRG International Journal of Electrical and Electronics Engineering*, 13(1), 19-30. doi: https://doi.org/10.14445/23488379/IJEEE-V13I1P103.

[4] Desai, I., & Chothani, N. (2025). Machine Learning Approach for Detection and Classification of Faults in Distribution Network with Decentralized Power Generation Facilities. *Journal of Emerging Technologies and Innovative Research*, 12(11), 226-230. doi: https://doi.org/ 10.56975 /jetir.v12i11.571528.

[5] Desai, I., Chothani, N., & Jacob, P. (2025). Comprehensive review on implementation of digital protection in distribution system with distributed generation sources. *Proceedings of Parul University International Conference on Engineering and Technology 2025 (PiCET 2025)*, 1-8. doi: https://doi.org/10.1049/icp.2025.1563 (published in IET Conference Proceeding 2025).

[6] Desai, I., & Chothani, N. (2023). Analysis of factors affecting protection of distribution system with distributed generation sources. *Proceedings of Parul University International Conference on Engineering and Technology 2022 (PiCET 2022)*, 2855 (1), 1-12. doi: https://doi.org/ 10.1063/5.0168525 (published in AIP Conference Proceedings 2023).

[7] Chothani, N., & Desai, I. (2021). Fourier Transform and Probabilistic Neural Network based Fault Detection in Distribution System Containing DGs. *Proceedings of 2021 Innovations in Power and Advanced Computing Technologies (i-PACT)*, 1-6. doi: https://doi.org/10.1109/i-PACT52855.2021.9696718.

Accepted Papers

[1] Desai, I., Chothani, N., & Jacob, P. (2026). Fault Detection and Classification for Distribution Network with Decentralized Power Generation Sources using combined WPT and XGBoost. *Proceedings of International Conference on Electrical, Electronics, and Sustainable Innovations (ICEESI 2026)*, 1-5.

Reference

[1] Mohamed, A. T., Helal, A. A., & El Safty, S. M. (2019). Distribution System Reliability Evaluation in Presence of DG. *Proceedings of 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, 1-6. doi: https://doi.org/10.1109/EEEIC.2019.8783657.

[2] Razavi, S. E., Rahimi, E., Javadi, M. S., Nezhad, A. E., Lotfi, M., Shafie-khah, M., & Catalao, J. P. S. (2019). Impact of distributed generation on protection and voltage regulation of distribution systems: A review. *Renewable and Sustainable Energy Reviews*, 105, 157-167. doi: https://doi.org/10.1016/j.rser.2019.01.050.

[3] Bhise, D. R., Kankale, R. S., & Jadhao, S. (2017). Impact of Distributed Generation on Protection of Power System. *Proceedings of International Conference on Innovative Mechanisms for Industry Applications*, 399-405. doi: https://doi.org/10.1109/ICIMIA.2017.7975644.

[4] Brearley, B. J., & Prabu, R. R. (2017). A review on issues and approaches for microgrid protection. *Renewable and Sustainable Energy Reviews*, 67, 988-997. doi: https://doi.org/10.1016/j.rser.2016.09.047.

[5] Manditereza, P. T., & Bansal, R. (2016). Renewable distributed generation: The hidden challenges - A review from the protection perspective. *Renewable and Sustainable Energy Reviews*, 58, 1457-1465. doi: https://doi.org/10.1016/j.rser.2015.12.276.

[6] Cisneros-Saldana, J. I. D., Samal, S., Begovic, M. M., Samantaray, S. R. (2024). On Protection Schemes for AC Microgrids: Challenges and Opportunities. *IEEE Transactions on Industry Applications*, 60(3), 4843-4854. doi: https://doi.org/10.1109/TIA.2024.3353721.

[7] Grimaldi, R. B. G., Chagas, T. S. A., Montalvao, J., Brito, N. S. D., dos Santos, W. C., & Ferreira, T. V. (2021). High impedance fault detection based on linear prediction. *Electric Power Systems Research*, 190, 1-9. doi: https://doi.org/10.1016/j.epsr.2020.106846.

[8] Mahfouz, M. M. A., & El-Sayed, M. A. H. (2016). Smart Grid Fault Detection and Classification with Multi-Distributed Generation Based on Current Signals Approach. *IET Generation, Transmission & Distribution*, 10(16), 4040-4047. doi: https://doi.org/10.1049/iet-gtd.2016.0364.

[9] Sapountzoglou, N., Lago, J., Schutter, B. D., & Raison, B. (2020). A generalizable and sensor-independent deep learning method for fault detection and location in low-voltage distribution grids. *Applied Energy*, 276, 1-22. doi: https://doi.org/10.1016/j.apenergy.2020.115299.

[10] Jarrahi, M. A., Samet, H., & Ghanbari, T. (2020). Novel Change Detection and Fault Classification Scheme for AC Microgrids. *IEEE Systems Journal*, 14(3), 3987-3998. doi: https://doi.org/10.1109/JSYST.2020.2966686.

[11] Kishor, N., Singh, R., Mohanty, S. R., & Yadav, O. (2020). Evolving Disturbances Detection and Classification in Real-time for Grid-Connected System. *IEEE Transactions on Industrial Electronics*, 68(9), 8265-8273. doi: https://doi.org/10.1109/TIE.2020.3013739.

[12] Mnyanghwalo, D., Kundaeli, H., Kalinga, E., & Hamisi, N. (2020). Deep learning approaches for fault detection and classifications in the electrical secondary distribution network: Methods comparison and recurrent neural network accuracy comparison. *Cogent Engineering*, 7(1), 1-25. doi: https://doi.org/10.1080/23311916.2020.1857500.

[13] Ebrahim, M. A., Wadie, F., & Abd-Allah, M. A. (2020). An Algorithm for Detection of Fault, Islanding, and Power Swings in DG-Equipped Radial Distribution Networks. *IEEE Systems Journal*, 14(3), 3893-3903. doi: https://doi.org/10.1109/JSYST.2019.2944870.

[14] Bhuyan, A., Panigrahi, B. K., & Pati, S. (2022). Fault Classification in a DG Connected Power System using Artificial Neural Network. *Indonesian Journal of Electrical Engineering and Informatics*, 10(2), 498-507. doi: https://doi.org/10.52549/ijeei.v10i2.3777.

[15] Mousavi, A., Mousavi, R., Mousavi, Y., Tavasoli, M., Arab, A., & Fekih, A. Artificial Neural Networks-Based Fault Localization in Distributed Generation Integrated Networks Considering Fault Impedance. *IEEE Access*, 12, 82880-82896. doi: https://doi.org/10.1109/ACCESS. 2024.3412991.

[16] Lout, K., & Aggarwal, R. K. (2014). Performance analysis of a novel AI based approach to fault classification and location in an active distribution network with Type 3 and Type 4 wind turbine connections. *Proceeding of 12th IET International Conference on Developments in Power System Protection (DPSP 2014)*, 1-6. doi: https://doi.org/10.1049/cp.2014.0021.

[17] Nanda, R. P., Bisoi, D., Behera, A., Panigrahi, B. K., & Satapathy, A. K. (2019). Classification of Faults in a Wind Connected Power System Using Artificial Neural Network. *Proceeding of 3rd International Conference on Computing Methodologies and Communication (ICCMC)*, 504-507. doi: https://doi.org/10.1109/ICCMC.2019.8819675.

[18] Qusayer, A. F., & Suhail Hussain, S. M. (2024). Communication Assisted Protection Scheme Based on Artificial Neural Networks for Multi-Microgrid. *IEEE Access*, 12, 24442-24452. doi: https://doi.org/10.1109/ACCESS.2024.3352027.

[19] Jamil, M., Sharma, S. K., & Singh, R. (2015). Fault detection and classification in electrical power transmission system using artificial neural network. *Springer Plus*, 4(334), 1-13. doi: https://doi.org/10.1186/s40064-015-1080-x.

[20] Pinto, S. J., & Panda, G. (2016). Performance evaluation of WPT based islanding detection for grid-connected PV systems. *International Journal of Electrical Power & Energy Systems*, 78, 537-546. doi: https://doi.org/10.1016/j.ijepes.2015.11.104.

[21] Thakre, M., Gawre, S. K., & Mishra, M. K. (2013). Distribution System Faults Classification and Location Based on Wavelet Transform. *International Journal of Computer Theory and Engineering*, 2(4), 86-91. URL: https://www.researchgate.net/publication/360945595_ Distribution_system_faults_classification_and_location_based_on_wavelet_transform.

[22] Bramareswara Rao, S. N. V., Narayana, N. R., Prasanna, T. D., Narasimha Rao, M. S. N. L., & Gowri Chand, P. (2022). Fault Detection in Cluster Microgrids of Urban Community using Multi-Resolution Technique Based Wavelet Transforms. *International Journal of Renewable Energy Research*, 12(3), 1204-1215. doi: https://doi.org/10.20508/ijrer.v12i3.13129.g8505.

[23] Sundararaman, B., & Jain, P. (2023). Fault Detection and Classification in Electrical Power Transmission System Using Wavelet Transform. *Engineering Proceeding*, 59(1), 1-8, doi: https://doi.org/10.3390/engproc2023059071.

[24] Roy, S., & Debnath, S. (2021). PSD based high impedance fault detection and classification in distribution system. *Measurement*, 169, 1-17. doi: https://doi.org/10.1016/j.measurement. 2020.108366.

[25] Chuan, O. W., Ab Aziz, N. F., Yasin, Z. M., Salim, N. A., & Wahab, N. A. (2020). Fault classification in smart distribution network using support vector machine. *Indonesian Journal of Electrical Engineering and Computer Science*, 18(3), 1148-1155. doi: http://doi.org/ 10.11591/ijeecs.v18.i3.pp1148-1155.

[26] Alam, M. R., Muttaqi, K. M., & Bouzerdoum, A. (2014). An Approach for Assessing the Effectiveness of Multiple-Feature-Based SVM Method for Islanding Detection of Distributed

Generation. *IEEE Transactions on Industry Applications*, 50(4), 2844-2852. doi: https://doi. org/10.1109/TIA.2014.2300135.

[27] Agrawal, R., & Dhadbanjan, T. (2012). Identification of Fault Location in Distribution Networks Using Multi Class Support Vector Machines. *International Journal of Emerging Electric Power Systems*, 13(3), 1-17. doi: https://doi. org/10.1515/1553-779X.3019.

[28] Lin, Z., Duan, D., Yang, Q., Hong, X., Cheng, X., & Yang, L. (2020). One-Class Classifier Based Fault Detection in Distribution Systems with Varying Penetration Levels of Distributed Energy Resources. *IEEE Access*, 8, 130023-130035. doi: https://doi.org/10.1109/ACCESS. 2020.3009385.

[29] Moloi, K., Hamam, Y., & Jordaan, J. A. (2020). A Support Vector Machine Based Technique for Fault Detection in A Power Distribution Integrated System with Renewable Energy Distributed Generation. *Advances in Science, Technology and Engineering Systems Journal*, 5(4), 577-588. doi: https://doi.org/10.25046/aj050468.

[30] Alam, M. R., Muttaqi, K. M., & Bouzerdoum, A. (2013). An Approach for Assessing the Effectiveness of Multiple Features Based SVM Method for Islanding Detection of Distributed Generation. *Proceeding of 2013 IEEE Industry Applications Society Annual Meeting*, 1-9. doi: https://doi.org/10.1109/IAS.2013.6682475.

[31] Recioui, A., Benseghier, B., & Khalfallah, H. (2015). Power System Fault Detection, Classification and Location Using the K- Nearest Neighbors. *Proceeding of 4th International Conference on Electrical Engineering (ICEE)*, 1-6. doi: https://doi.org/10.1109/ INTEE.2015.7416832.

[32] Majd, A. A., Samet, H., & Ghanbari, T. (2017). k-NN based fault detection and classification methods for power transmission systems. *Protection and Control of Modern Power Systems*, 2(32), 1-11. doi: https://doi.org/10.1186/s41601-017-0063-z.

[33] Shi, Z., Yao, W., Zeng, L., Wen, J., Fang, J., Ai, X., & Wen, J. (2020). Convolutional neural network-based power system transient stability assessment and instability mode prediction. *Applied Energy*, 263, 1-13. doi: https://doi.org/10.1016/j.apenergy.2020.114586.

[34] Khalaf, M. H., & Tousi, B. (2024). Fault Location and Detection in Power Distribution Systems with Presence of Distributed Generations using Improved CNNs. *Journal of Electrical Systems*, 20(10s):7840-7865. doi: https://doi.org/10.52783/jes.6999.

[35] Rai, P., Londhe, N. D., & Raj, R. (2021). Fault classification in power system distribution network integrated with distributed generators using CNN. *Electric Power Systems Research*, 192, 1-9. doi: https://doi.org/10.1016/j.epsr.2020.106914.

[36] Zhang, J., Li, Y., Zhang, Z., Zeng, Z., Duan, Y., & Cao, Y. (2019). XGBoost Classifier for Fault Identification in Low Voltage Neutral Point Ungrounded System. *Proceeding of 2019 IEEE Sustainable Power and Energy Conference (iSPEC)*, 1-5. doi: https://doi.org/10.1109/iSPEC48194.2019.8974996.

[37] Jamali, S., Bahmanyar, A., & Ranjbar, S. (2020). Hybrid Classifier for Fault Location in Active Distribution Networks. *Protection and Control of Modern Power Systems*, 5(2), 1-9. doi: https://doi.org/10.1186/s41601-020-00162-y.

[38] ElNozahy, M. S., EL-Shatshata, R. A., & Salama, M. M. A. (2016). Single-phasing detection and classification in distribution systems with a high penetration of distributed generation. *Electric Power Systems Research*, 131, 41-48. doi: https://doi.org/10.1016/j.epsr.2015.10.008.

[39] Yu, J. J. Q., Hou, Y., Lam, A. Y. S., & Li, V. O. K. (2019). Intelligent Fault Detection Scheme for Microgrids with Wavelet-Based Deep Neural Networks. *IEEE Transactions on Smart Grid*, 10(2), 1694-1703. doi: https://doi.org/10.1109/TSG.2017.2776310.

[40] Biswal, T., Parida, S. K., & Mishra, S. (2023). A DT-CWT and Data mining-based approach for High Impedance Fault Diagnosis in Micro-grid System. *Procedia Computer Science*, 217, 1570-1578. doi: https://doi.org/10.1016/j.procs.2022.12.357.

[41] Silva, S., Costa, P., Gouvea, M., Lacerda, A., Alves, F., & Leite, D. (2018). High impedance fault detection in power distribution systems using wavelet transform and evolving neural network. *Electric Power Systems Research*, 154, 474-483. doi: https://doi.org/10.1016/j.epsr.2017.08.039.

[42] Guan, G., & Liao, Y. (2019). A New Islanding Detection Method Based on Wavelet-transform and ANN for Micro-grid Including Inverter Assisted Distributed Generator. *International Journal of Emerging Electric Power Systems*, 20(5), 1-10. doi: https://doi.org/10.1515/ijeeps-2019-0074.

[43] Xi, Y., Tang, X., Li, Z., Shen, Y., & Zeng, X. (2022). Fault detection and classification on insulated overhead conductors based on MCNN-LSTM. *IET Renewable Power Generation*, 16(7), 1425-1433. doi: https://doi.org/10.1049/rpg2.12380.

[44] Narasimhulu, N., Ashok Kumar, D. V., & Vijaya Kumar, M. (2020). Detection and Classification of High Impedance Fault in Power Distribution System using Hybrid Technique. *Journal of Circuits, Systems and Computers*, 29(08), 2050118-1- 2050118-25. doi: https:// doi.org /10.1142/S0218126620501182.

[45] Alhanaf, A. S., Farsadi, M., & Balik, H. H. (2024). Fault Detection and Classification in Ring Power System with DG Penetration Using Hybrid CNN-LSTM. *IEEE Access*, 12, 59953-

59975. doi: https://doi.org/10.1109/ACCESS.2024.3394166.

[46] Alhanaf, A. S., Balik, H. H., & Farsadi, M. (2024). Intelligent Fault Detection and Classification Schemes for Smart Grids Based on Deep Neural Networks. *Energies*, 16(22), 1-19. doi: https://doi.org/10.3390/en16227680.

[47] Gururajapathy, S. S., Mokhlis, H., & Illias, H. A. (2017). Fault location and detection techniques in power distribution systems with distributed generation: A review. *Renewable and Sustainable Energy Reviews*, 74, 949-958. doi: https://doi.org/10.1016/j.rser.2017.03.021.