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Research Paper

An Efficient Protection Scheme for Wind Integrated Microgrid Considering Dissimilar AC Faults and Varying Fault Resistance

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Abstract: In spite of the numerous benefits over the traditional power distribution system, protection of the microgrid is a challenging and complex task. The varying fault resistances due to dissimilar grounding conditions can affect the performance of the protection scheme. Under such conditions, the magnitude of the fault current can vary from lower to higher level. In addition to the above, the dissimilar magnitude of fault current during grid connected and islanded mode demands a protection scheme that can easily discriminate the mode of operation. The magnitude of fault current in grid-connected and islanded modes needs a robust protection scheme. In this regard, an ensemble of subspace kNN based robust protection scheme has been proposed to detect the faulty conditions of the microgrid. The tasks of the mode detection, fault detection/classification as well as faulty line identification has been carried out in the proposed work. In the proposed protection scheme, discrete wavelet transform (DWT) has been used for processing of the data. After recording the voltage and current signals at bus-1, the protection scheme has been validated. The validation of the protection scheme in Section 6 reveals that the protection scheme is efficiently working.

Keywords: Fault Detection/classification, Grid-connected and Islanded Mode, Ensemble of kNN, Microgrid, Faulty Line Identification.

1 Introduction

The need of the electrical energy is rapidly increasing among the world due to proliferation in the modern infrastructure and continuous utilization of electrical appliances. A number of traditional power generation sites have been installed in the world to full the required demand of power such as Thermal, Nuclear and other petro product based plants.

Acronyms

DWT	Discrete wavelet transform
WFDG	Wind firm distributed generator
DERs	Distributed energy resources
DBN	Deep belief network
T-T	Time-Time
MVA	Megavolt ampere
PCC	Point of common coupling
DT	Decision tree
ANN	Artificial neural network
NC	Not considered
MW	Megawatt
ABC	Phase
ENSkNN	Ensemble of kNN

Symbols

ms	Millisecond
km	Kilometer
Ω-ohm	%-Percentage
L1-L11	Load

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However, they are incapable to poise the difference between actual demand of the power and total availability. In addition to the above difficulty, reduced reserve capacity of such fuels restricts the use of such types of fuel. The other major drawbacks of such plants are the contamination of the air quality due to hazardous air particles. Therefore, the energy scenario is shifting from the nonrenewable to renewable sources of energy as a future power technology. The microgrid is the best option to integrate such types of the sources (such as PV, wind, biomass, and geothermal based sources) from each other through power converters. The microgrid is the cluster of DERs, loads, energy storage devices and converters with clearly defined electrical boundaries [1-4]. On the basis of the availability of the power at the buses, microgrid can be categorized as AC, DC and hybrid-microgrid [5]. As compared with DC microgrid, AC microgrid offers various benefits such as facility of the voltage conversion, zero crossings, stability in the voltage as well as reliable in case of grid failure. In spite of the dealt benefits, protection of the AC microgrid is the difficult and challenging task due to occurrence of the number of fault issues such as level of the fault current after faulty conditions in the grid connected and islanded mode of operation, varying operational dynamics of DERs (especially when PV and wind in the system), fault in converters, and various types of line and ground AC faults (AG, AB BG, BC, CG, AC, ABG, ACG, AB, BC, and ABC) [6-8].Further, varying nature of fault resistance due to dissimilar ground conditions such as dry or wet soil, sand and contact from branches of tree can makes the protection task more challenging. Under theses circumstance level of the fault can vary between low levels to high level as per value of the fault resistance. The main reason behind varying fault resistance is distinct contact surface with conductor. The protection scheme must be effective and invulnerable to maintain the stability in the system. To demonstrate the problem statement related with the above difficulties Fig. 1 (a), (b) and as Fig. 2 (a), (b) are considered where Fig. 1 is indicating to variation in the fault current during AG fault with fault resistance of 70 Ω while BG fault with fault resistance of 30Ω respectively (In Fig. 1(a) and (b) grid connected mode has been considered during simulation of test microgrid system under study and the same can be analyzed for islanded mode also). In Fig. 2 (a) and (b) variation in magnitude of the fault current under ABG fault has been considered under grid connected and islanded mode of operation where the magnitude of the current is changing. Therefore, the protection scheme must be robust and capable to identify the mode of operation.

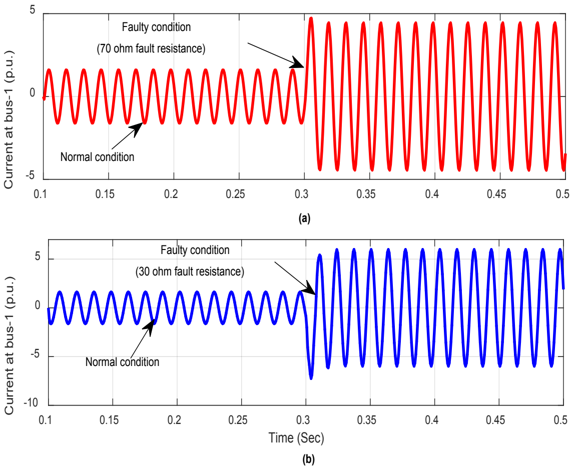

Fig. 1 (a) Variation in magnitude of the fault current during AG fault with 70 ohm fault resistance (grid-connected mode). (b) Variation in magnitude of the fault current during BG fault with 30 ohm fault resistance (grid-connected mode)

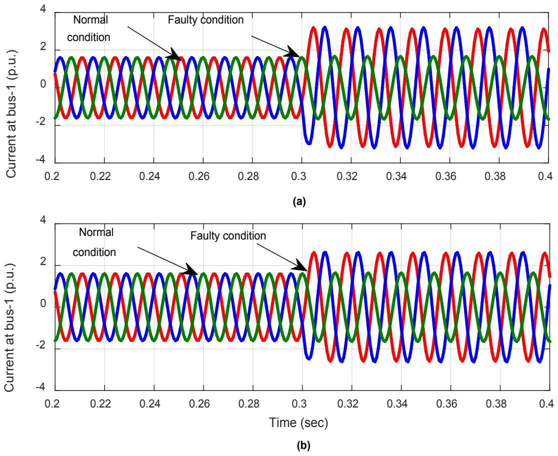

Fig. 2 Current waveforms after ABG fault in bus-1 (a) Grid-connected mode (b) islanded mode.

A number of protection scheme schemes have been proposed in existing literatures for protection of the AC microgrid where some of the protection schemes are mentioned here such as: A protection scheme for inverter dominated microgrid in [9], where direction of power flow, magnitude of current as well as voltage sags have been taken for development of protection scheme. Hilbert and Huang transform based protection scheme in [10] S-transform based protection scheme [11], a differential protection scheme [12-13], a combined protection scheme based on DBN and T-T transform in [14], TWE-based protection scheme in [15], a novel protection scheme based on change of positive sequence of current in [16], and bi-level and multi-agent based protection scheme [17]. However, reported protection schemes are not considering the impact of fault current during grid connected and islanded mode as well as varying fault resistances in analysis of the protection scheme. Motivated by the above challenges in the protection scheme, in proposed work an ensemble of subspace kNN has been proposed to perform the tasks of mode detection, fault detection/classification and faulty line(section) identification under grid connected and islanded mode of operation. The ensemble based approach has been widely used in various types of classification problems due to its higher accuracy instead of the standalone classifiers. The major contributions of this work are as follows:

i) Simulation of the AC microgrid system under study for analysis of the various types of fault scenarios.
ii) Processing of acquired signals of post fault voltage and current for analysis of the protection scheme using discriminatory attributes of dissimilar faulty conditions.
iii) Performance evaluation of all modules in protection scheme under dissimilar fault conditions
iv) Validation of the protection scheme under dissimilar fault resistances and loading conditions.

The rest of the paper is organized as follows: To explore the analysis of the proposed AC microgrid, single line diagram is demonstrated in Section 2. In Section 3 overview of the DWT is given while Section 4 is dedicated for overview of the proposed technique. In Section 5, development of the protection scheme is given. In Section 6 and Section 7, performance analysis and conclusion is given.

2 Single Line Diagram of Proposed Microgrid System

The schematic diagram of the AC microgrid is illustrated in Fig. 3. The MATLAB/ SIMULINK software has been used for the implementation of the proposed microgrid system. The proposed system consists of two DERs namely SDG (1.2 MVA) and WFDG (10MW) at bus-3 and bus-6 respectively while a utility grid is integrated at bus-1 through PCC and transformer T-1. The PCC helps in the operation of the microgrid under the islanded mode of operation [18-20] if any fault occurs in the grid side network of the microgrid. A total of thirteen lines and thirteen buses are used in the system at a particular distance, where the length of the each line is 0.5 km. -6. L-1 to L-11 are the non-linear loads that are amalgamated at each bus.

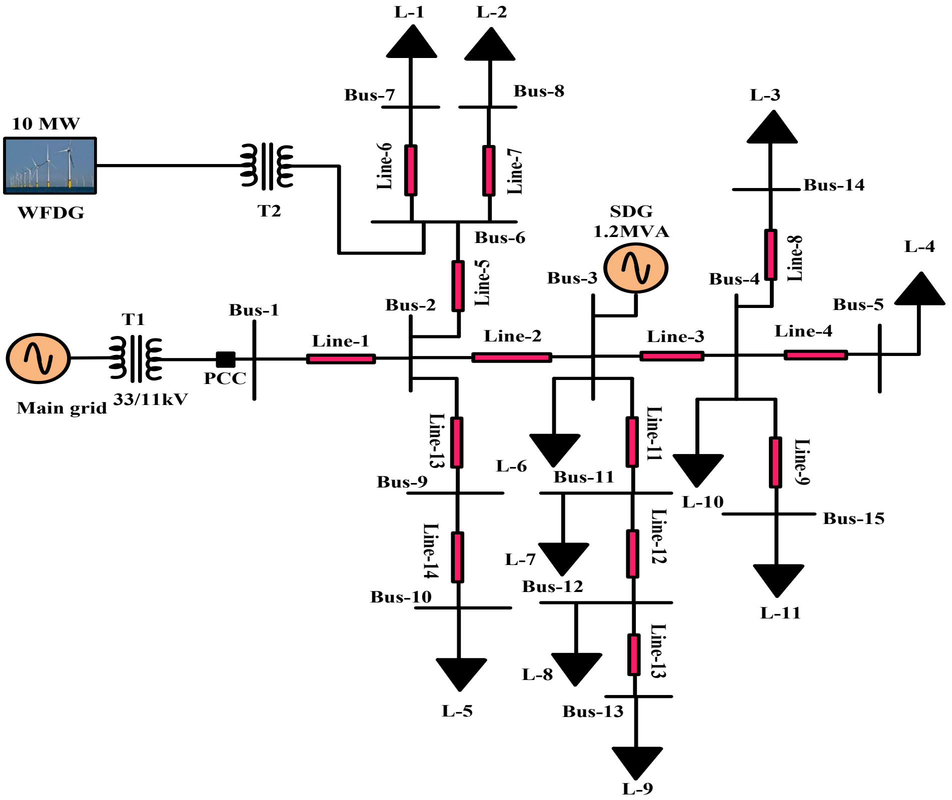

Fig. 3 Single line diagram of AC microgrid.

3 Feature Extraction Using DWT (Discrete Wavelet Transform)

To remove extraneous information from the raw time-domain signal of voltage and current, DWT has been used for processing of the signals. It offers benefits over Fourier transform because of information processing in both the time and frequency domains instead of only frequency domain. The other drawback of the FT is its incapability for direct information from an oscillatory signal. The main aim of DWT in this work is to get pertinent data information from the signals. To analyze the transient conditions as well as discrimination in the faulty and no-fault conditions, DWT is a special tool of the signal processing. The DWT has been extensively used in a number of applications due to its capability of speed and reliability in the analysis of transient conditions in power system [21-23]. The db3 wavelet is used as a mother wavelet for the analysis of signals which is represented by the bellow equation (Eq. (1)).

$$\emptyset_{ju}(t) = 2^{-j/2}\, \emptyset\, (2^{-j}\, t - u) \tag{1}$$

Here j, and u are the integers.

For standard deviation of the signals have been calculated through the below equation:

$$\sqrt{(1/N)\sum_{i=1}^{N}(x_i - \mu)^2} \tag{2}$$

In proposed work standard deviation is used in classifier as an input feature. The extraction of the features and its importance is clearly described in [24], where the authors have considered various parameters as features for the work. On the basis of the same concept, a set of features are dealt with in the work. Suppose if the features are F_{et1}, F_{et2} F_{et3}, F_{et4}, …, F_{etn} , then that has been obtained from the above equitation, Further, they can be represented as follows:

$$F_{et} = [F_{et1}\, , F_{et2}\; F_{et3}\; F_{et4}\; \dots\dots\dots F_{etn}] \tag{3}$$

Where these features can be used in the training and testing of the datasets for distinct modules of the protection scheme.

4 Overview Of Proposed Algorithm (Ensemble Based kNN)

The ensemble of subspace kNN is widely adopted by the researchers in recent years due to its higher classification accuracy and learning capability on dissimilar datasets [25-27]. The ensemble based algorithm has been widely used in various fields such as detection of broken bar in induction machine and forecasting [28-29], high impedance fault detection [30] and intrusion detection [31]. A number of standalone modules have been used in development of the ensemble module. Therefore, accuracy of the ensemble based algorithm is greater when compared with single module based algorithm. After training of the various subsets of the ensemble module, the final prediction is done on the basis of the voting strategy (Eq. (4)). To carry out the tasks of mode detection, fault detection/classification as well as faulty line identification the kNN has been used as base classifiers where attributes are randomly selected for all base classifiers.

$$\sum_{i=1}^{T} W_i\, d_{K,J} = max_{n=1}^{c} \sum_{i=1}^{T} W_i\, d_{K,m} \tag{4}$$

Where, T is the number of classifiers, C is the class and $d_{k,m}$ is the binary output for which assigned value is 1 if it predicts corresponding class otherwise it is 0.

5 Development of the Protection Scheme for Fault Detection/Classification and Faulty line/Section Identification under Grid Connected and Islanded Mode

The protection scheme based on ensemble of classifier is dealt in this section. To clearly depict operation and development of protection scheme Fig. 4 is used. The sequence of the protection scheme can be understood as follows: firstly voltage and current signals obtained from the bus-1 of the proposed AC microgrid have been retrieved then processed through the DWT for further used. A total of five ensemble modules have been used in protection scheme from ENSkNN-1 to ENSkNN-5. Firstly, mode of operation is identified by ENSkNN-1, then based on output of the module (grid-connected or islanded) remaining modules will be automatically triggered in the next stage.

For fault detection/classification two ensemble modules namely ENSkNN-3 and ENSkNN-5 are used where former is used in grid connected while later is used in islanded mode. For faulty line identification under both of the modes ENSkNN-2 and ENSkNN-4 are used respectively. Once the fault is detected and faulty lines are identified by the protection scheme, relaying action will isolate the faulty section from rest of the microgrid system.

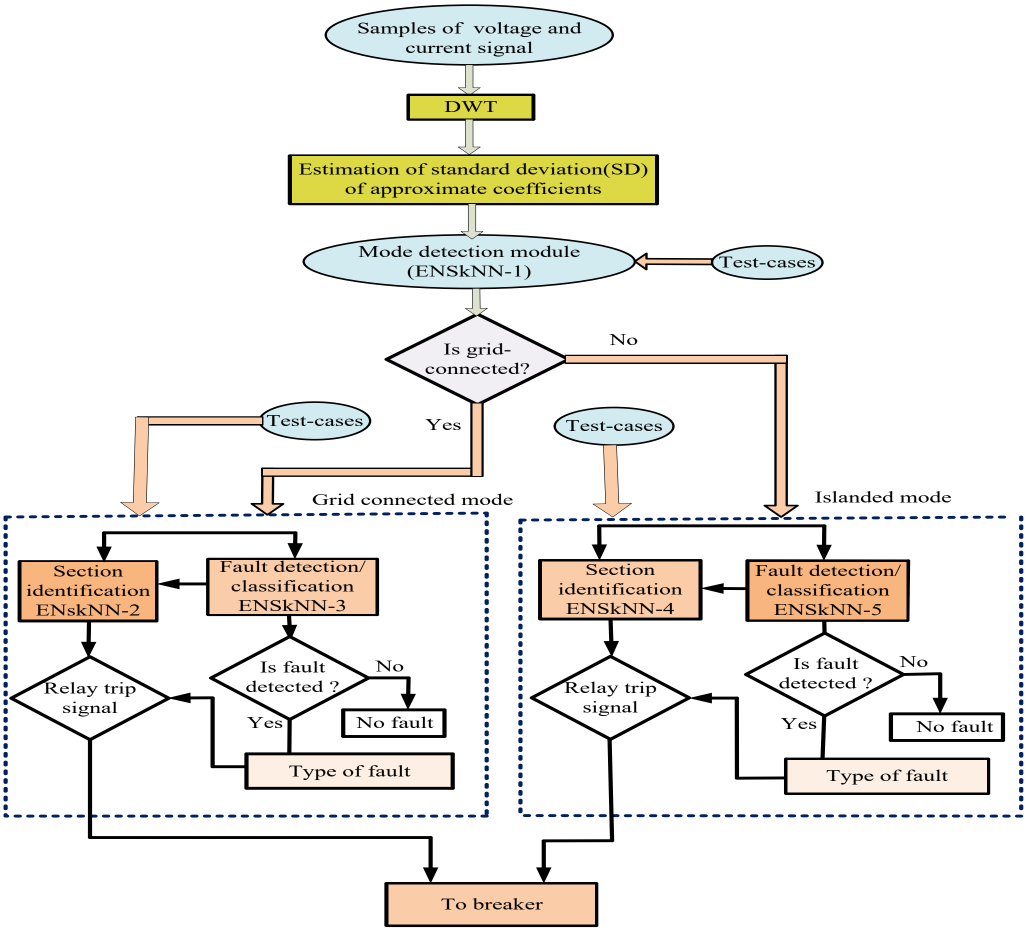

Fig. 4 Flow chart of AC microgrid under grid connected and islanded mode.

The prompt fault detection and isolation of the faulty line can reduce the risk of the complete shutdown of the system. As a result power interruption difficulties can removed to ensure proper power supply in rural village and hilly areas. If fault is not detected, protection scheme will indicate no fault condition.

6 Result Analysis

The efficiency of the proposed ensemble of classifier (ENSkNN) based protection scheme has been evaluated in this subsection. Table 1 shows the list of the fault parameters for all probable types of AC fault scenarios have been taken into consideration when generating the datasets. The range of the fault resistance and location in each bus (bus-1 to bus-13) is considered between 10 to 100 ohm and 0.1 to 0.5 km, respectively. Apart from above parameters, three fault inception angles have also been considered while generating the fault scenarios. A total of 150 no fault cases have also been generated by variation in non-linear load (±20 to ±60) under both of the modes. The effectiveness of all the ensemble modules has been validated during tasks of mode detection, fault detection/classification and faulty line (section) identification under both of the modes. The DWT has been used after retrieving the voltage and current signals from the near bus of PCC (bus-1). For training and testing of the modules, dissimilar fault scenarios have been used, which have not been used during training of the modules. Further, the performance of the protection scheme has been evaluated in the various subsections:

Table 1 Training and testing pattern for modules of the protection scheme.

Parameters for AC fault	Specification of fault parameters	Total cases
Type of fault	11	Total=21450+130 no fault cases=21580 15106 =Traing 6474=Testing
Fault resistance	5 cases in each line (10 to 100), total cases- 26	
Length of fault	Total 65 cases (5 cases in each line)	
Inception angle	(0^0 , $45^0$and 90^0)	
No. of line(section)	13 (Line-1 to Line-13)	
Types of mode	2 (grid connected and islanded)	

6.1 Mode Detection (ENSkNN-1)

A total of 5450 fault cases have been used for testing of the mode detection module under both modes of operation. After evaluation of the testing of module it has been investigated that the module is efficient and effectively operating in both of the modes**.** The efficiency after validation of the module is found to be 100% and 98.83% for grid connected and islanded mode, respectively. Further, the outcome of the mode detection module has been compared with DT and ANN-based modules on the same dataset. The results in Table 2 indicate that the module is robust and reliable.

Table 2 Performance comparison of proposed scheme in terms of percentage accuracy (ENSkNN-1).

Types of algorithms	Mode of operation		Accuracy (%)
	Grid connected (%)	Islanded mode (%)	
ENSkNN	100	98.83	99.41
DT	98.88	96.69	97.78
ANN	96.19	95.76	95.97

6.2 Fault Detection/Classification (ENSkNN-3 and ENSkNN-5)

The robustness of the modules ENSkNN-3 and ENSkNN-5 has been evaluated in this subsection for the task of the fault detection/classification. A total of 2360 test cases including 45 no fault cases have been used under grid connected and islanded mode. The overall accuracy achieved during fault detection/classification is 99.63 % for grid connected mode and 98.85 % for islanded mode.

Table 3 summarizes the performance of the proposed fault detection/classification modules. To investigate the efficiency during fault detection reliability indices such as dependability, security and accuracy has considered. The dependability indicates the probability of the possible detection of the fault from actual given fault cases. While calculating the security of the module no fault cases have been used. In other words, dependability is the ratio of the actual given fault cases to actual detected fault cases while security can be investigated through the ratio of the actual given no fault cases to actual predicted no fault cases. The same has been carried out during testing of the DT and ANN based fault detector/classifiers. The comparative analysis demonstrates in Table 3 that the ensemble based fault detector/classifier works better as compared two reaming two classifiers on the same testing datasets. Further, to depict the differences in the percentage accuracies during fault detection/classification, Fig. 5 and Fig. 6 has been plotted under grid- connected and islanded mode of operation. The plots clearly revels that the proposed protection scheme is better for the fault detection and improving the resiliency of the proposed microgrid system.

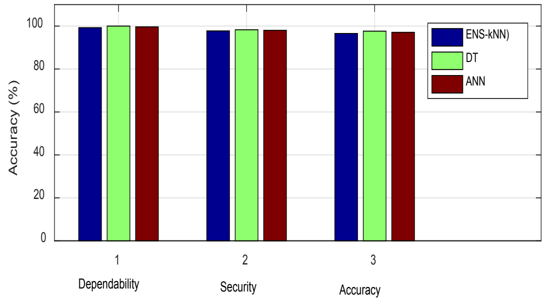

Fig. 5 Comparison of percentage accuracy in terms of reliability indices (grid-connected mode).

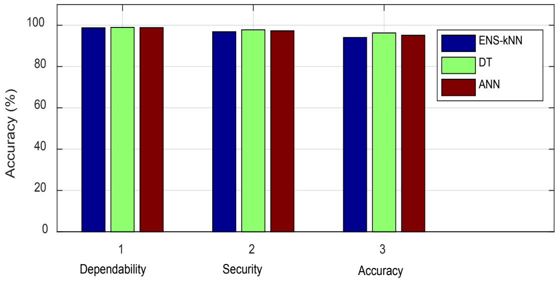

Fig. 6 Comparison of percentage accuracy in terms of reliability indices (islanded mode).

Table 3 Reliability analysis and comparison of the proposed scheme**.**

Name of algorithms	Mode of operation					
	Grid connected			Islanded		
	Dependability (%)	Security (%)	Overall accuracy (%)	Dependability (%)	Security (%)	Overall accuracy (%)
ENSkNN	99.26	100	99.63	98.77	98.94	98.85
DT	97.76	98.29	98.02	96.86	97.79	97.32
ANN	96.55	97.63	97.09	94.06	96.27	95.16

6.3 Faulty Line (Section) Identification (ENSkNN-2 and ENSkNN-4)

The faulty line identifier for protection scheme should be capable to point out the faulty line for appropriate restoration of the supply. The prompt identification of undesirable events in power Therefore in this subsection, the efficiency of the line identification modules have been proposed under grid connected and islanded modes of operation. A total of 5980 fault cases have been considered in both of the modes for testing of the ENSkNN-2 and ENSkNN-4 modules. All lines from Line-1 to line-13 have been considered for analysis of the faulty line in both of the modes. Table 4 demonstrates response of the both of the faulty line identifier modules (for grid connected and islanded mode) separately. Further, the performances of the proposed ensemble modules for faulty line identification have been compared with other two reported modules (DT and ANN) for the same datasets. The accuracy achieved during faulty line identification is 99.28% and 98.41% respectively for grid connected and islanded mode while less accuracy for the remaining algorithm based faulty line identifiers. Further to depict the accuracy of the line identifier during grid-connected and islanded mode, Fig. 7 and Fig. 8 are considered.

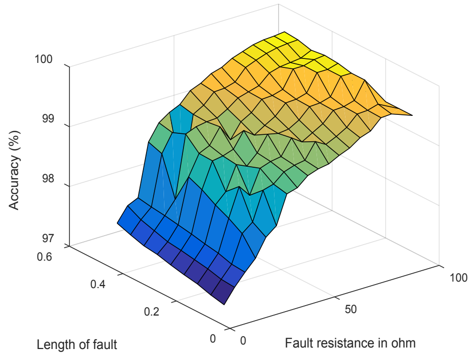

Fig. 7 Accuracy of the protection scheme during section identification (grid-connected mode).

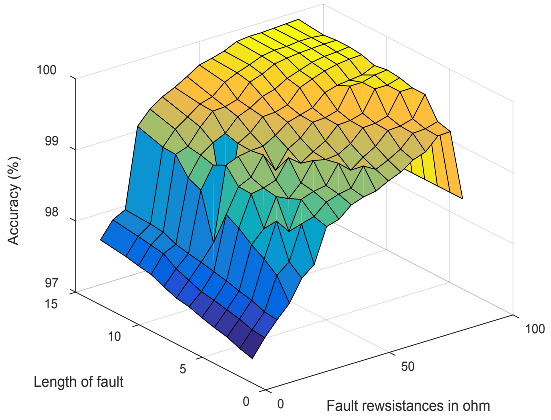

Fig. 8 Accuracy of the protection scheme during section identification (Islanded mode).

Variation in the fault resistance, length of fault as well as detected accuracy has been considered in the both of the plots (some random cases have also been considered during analysis of the faulty line identification). The overall performance reveals that the protection scheme for faulty line identification is accurate and dependable for all cases as dealt in Table 4.

6.4 Performance of Protection Scheme under Distinct Types of AC Faults under Varying Fault Resistance

The effectiveness of the protection scheme must be examined for efficient and reliable operation of the microgrid. Therefore, in this subsection immunity of the protection scheme has been analyzed under dissimilar fault scenarios and varying fault resistances. The dissimilar values of fault resistances have been considered during investigation of the protection scheme, where range is considered between 10 ohm to 100 ohm. In addition to above, six dissimilar categories of AC faults have been considered (AG, BG, CG, AC, ABG and BC).

Table 4 Reponses of the scheme during faulty line identification (grid connected and islanded mode)

Mode of operation	Faulty line (section) identification	No of test cases	ENSkNN (%)	DT (%)	ANN (%)
Grid-connected mode	Line-1	230	100	97.33	95.11
	Line-2	220	100	96.54	94.32
	Line-3	250	99.43	96.27	94.05
	Line-4	210	98.86	97.16	94.94
	Line-5	250	98.92	97.38	95.16
	Line-6	200	99.37	97.57	95.35
	Line-7	260	99.13	96.76	94.54
	Line-8	230	98.84	98.16	95.94
	Line-9	250	99.11	96.77	94.55
	Line-10	230	98.67	98.26	96.04
	Line-11	230	99.16	98.35	96.13
	Line-12	200	100	97.88	95.66
	Line-13	260	99.26	97.64	95.42
	Overall accuracy (%)		99.28	97.39	95.17
Islanded mode	Line-1	230	99.11	95.26	93.46
	Line-2	220	98.56	94.44	94.12
	Line-3	250	98.75	95.36	92.94
	Line-4	210	97.88	95.29	93.88
	Line-5	250	97.94	96.46	94.29
	Line-6	200	98.76	95.75	94.56
	Line-7	260	98.22	95.29	93.59
	Line-8	230	97.95	96.37	94.36
	Line-9	250	98.36	95.84	93.88
	Line-10	230	97.88	97.38	94.76
	Line-11	230	98.73	97.54	95.28
	Line-12	200	98.58	96.16	96.88
	Line-13	260	98.66	95.86	94.76
	Overall accuracy (%)		98.41	95.92	94.36

Table 5 Performance against dissimilar AC faults and varying fault resistances

Mode of operation	Type of fault	Fault resistance (Ω)	Faulty (section)	Response of ENS-kNN	Relay response time (ms)
Grid connected mode	AG	10	Bus-1	AG	4.7
	BG	25	Bus-3	BG	4.9
	CG	50	Bus-4	CG	7.2
	AC	65	Bus-6	AC	6.4
	ABG	75	Bus-10	ABG	5.6
	BC	100	Bus-13	BC	4.2
Islanded	AG	10	Bus-1	AG	6.6
	BG	25	Bus-3	BG	8.7
	CG	50	Bus-4	CG	8.4
	AC	65	Bus-6	AC	9.2
	ABG	75	Bus-10	ABG	7.3
	BC	100	Bus-13	BC	6.6

The results in the Table 5 reveal that the protection scheme is capable to detect the all types of reported faults when fault resistances have been varied. The relay response time during varying fault resistances and dissimilar faults can be analyzed in bellow table.

6.5 Response of the Protection Scheme during Dissimilar Loading Conditions

The unwanted and rapid loading conditions can lead the maloperation of the system that can create instability in the microgrid. Therefore, investigation has been carried out under dissimilar loading conditions as dealt in Table 6 in this subsection. The variations in the loading condition have been evaluated under dissimilar types of AC faults as well as a number of buses. The range of the loading condition is considered in the range of the ±20 %to ±60% under grid connected and islanded mode. The result in the Table 6 indicates the robustness and accuracy of the protection scheme under dissimilar fault scenarios.

Table 6 Performance of the protection scheme under dissimilar loading conditions and faults

Mode of operation	Load variation (%)	Bus	Fault type	Response of the protection scheme
Grid-connected	±20	Bus-1	AG	AG
	±30	Bus-6	BG	BG
	±40	Bus-10	CG	CG
	±60	Bus-8	ACG	ACG
	±60	Bus-12	AB	AB
	±20	Bus-4	BC	BC
	±30	Bus-13	ACG	ACG
	±40	Bus-3	AB	AB
	±50	Bus-5	CG	CG
	±60	Bus-7	ABC	ABC
	±20	Bus-1	AG	AG
Islanded	±30	Bus-6	BG	BG
	±40	Bus-10	CG	CG
	±60	Bus-8	ACG	ACG
	±60	Bus-12	AB	AB
	±20	Bus-4	BC	BC
	±30	Bus-13	ACG	ACG
	±40	Bus-3	AB	AB
	±50	Bus-5	CG	CG
	±60	Bus-7	ABC	ABC

Table 7 Comparison of protection scheme on basis of dissimilar parameters

Parameters of comparison	Existing microgrid protection schemes			
	[14]	[15]	[16]	Proposed scheme
Input features	Current-signals only	Current-signals only	Current-signals only	Voltage and current
Fault parameters	Resistance (up to 20 ohm only)	Resistance(only two values are mentioned and not analyzed for lower values)	Varying fault resistances has not considered,	Varying fault Resistances have been analyzed from low value to high(10 ohm to 100 ohm), length of fault, Location of fault
Tasks- performed	Fault detection only	Fault detection only	Fault detection only	Mode detection, Fault detection/classification Faulty line identification (section) identification
Testing cases under dissimilar fault scenarios	NC	NC	NC	6474

6.6 Comparison of the Proposed Scheme with Existing Protection Schemes

In this subsection the performance of protection scheme under dissimilar parameters have been compared with existing protection schemes. The comparison in Table 7 clearly indicating that protection scheme is more efficient and outperforms when comparing with other schemes.

7 Conclusion

The microgrids have become as an incredibly greater power distribution system in recent years. However protection of the microgrid is challenging task due to variation in the current during grid connected and islanded mode of operation. In addition, to the above condition varying nature of fault resistance can creates some serious hindrance in the system. In this work, a protection scheme based on ensemble of kNN has been proposed and exploited its capability during dissimilar fault resistances and distinct loading conditions in the microgrid. The proposed ensemble based protection framework has been developed to perform the tasks of mode detection for identification of mode of operation as well as fault detection/classification and faulty line identification. The samples of the voltage and current were retrieved from bus-1 and processed through the DWT for further used in the protection scheme. To investigate the robustness of protection scheme, DT and ANN based algorithm were also used. Dissimilar types of faults have been considered during analysis of the protection scheme. The results in the section 6 indicate its appropriateness under both modes of operation.

Intellectual Property

The author confirms that they have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing to publication, with respect to intellectual property.

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Credit Authorship Contribution Statement

S. Prasad Tiwari: Data curation, Conceptualization, Methodology, Software, Formal analysis, Original draft writing, Review and editing.

Declaration of Competing Interest

The author hereby confirms that the submitted manuscript is an original work and has not been published so far, is not under consideration for publication by any other journal and will not be submitted to any other journal until the decision will be made by this journal. All authors have approved the manuscript and agree with its submission to “Iranian Journal of Electrical and Electronic Engineering”.

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