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Research Paper

A Local Measurement-Based Protection Scheme for DER Integrated DC Microgrid Using Bagging Tree

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Abstract: In recent years, DC microgrid has attracted considerable attention of the research community because of the wide usage of DC power-based appliances. However, the acceptance of DC microgrid by power utilities is still limited due to the issues associated with the development of a reliable protection scheme. The high magnitude of DC fault current, its rapid rate of rising and absence of zero crossing hinders achieving reliable protection in DC microgrid. Further, the intermittency associated with the non-conventional distributed generators demands adaptiveness under varying weather conditions. In this paper, the above-mentioned issues are addressed by developing a bagging tree-based protection approach for a multi-terminal DC microgrid. The proposed scheme addresses the intermittency associated with renewable sources. It performs the functions of mode detection, fault detection/classification, and faulty section identification using local information of current and voltage signals only. The same avoids the communication network related drawbacks like data loss and latency.

Keywords: DC Microgrid Protection, Distributed Generators Grid Connected Mode, Islanded Mode, Pole to Ground Fault, Pole to Pole Fault, Bagging Tree.

Acronyms

CO	Carbon Monoxide
CO_2	Carbon Dioxide
SO_2	Sulpher Dioxide
AC	Alternating current
DC	Direct current
PG	Pole to ground
PP	Pole to pole
FD/C	Fault detection/classification
FS/I	Faulty section/identification
WTG	Wind turbine generator
SDG	Synchronous diesel generator
PV	Photovoltaic
UG	Utility grid
BT	Bagging tree
SVM	Support vector machine
DT	Decision tree
V	Voltage
kW	Kilowatt
LEDs	Lighting emitting diodes
DERs	Distributed energy resources

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1 Introduction

WITH the rapid development in modern infrastructure and incessant depletion of fossil fuels, the crisis of the energy availability is increasing day by day. The same has compelled the power system engineers towards the adoption of green and alternate sources of energy like solar power-based photovoltaic array, wind, tidal, geothermal and biomass energy. In the modern era, these sources are playing a crucial role in the reduction of hazardous particles such as CO, CO_2, SO_2 in the atmosphere. The adoptions of these alternative non-conventional sources of energy have led to the concept of microgrid [1-2]. The integration of microgrids within the existing power distribution network has increased the reliability and resilience of the system [3]. Further, the microgrid is continuously imparting smartness to the existing power network because of it's capability to respond to the dynamic variations in the power demand. Based on the power at the buses of the microgrid, it can be categorized as AC, DC and hybrid microgrid [4]. The wide usage of DC power in various applications such as data centers, LEDs (used for lighting applications in commercial and domestic purpose), electrical vehicles, energy storage, electric ships, digital computers, grinders, savers, satellites and aircrafts have led to the popularity of DC microgrid [5-8]. DC microgrid has various advantages over AC microgrid such as lesser conversion stages and leads, reduces grid losses, no need of synchronization and absence of skin effect [5-8]. However, the acceptance of DC microgrid to the extent of AC microgrid is still a challenge because of the lack of published standard, solution, or experience with this regard to its protection [8-9]. Moreover, the large magnitude and fast transient of DC fault current can cause damage to the converter and other apparatus close to it [10-11]. Hence fast detection of fault and isolation of faulty section is essential to protect the semiconductor switches against large currents. Also, the difference in the magnitude of the level of fault current during grid-connected and islanded mode (in grid-connected mode the magnitude of fault current is approximately 20-50 times as compared to islanded mode), bidirectional behavior of converter and lack of zero-crossing signal further adds to the complexity of the protection task more complicated.

A number of protection schemes have been reported in recent years on the development of the protection for DC microgrids. The significant among them include scheme based on wavelet transform for low voltage DC microgrid system [12], resistance estimation based fault detection [13], voltage prediction [14], communication assisted overcurrent protection [15], non-unit protection using local measurement [16], differential protection scheme based on current measurement [17], voltage and current measurement using least square-based estimation technique [18], unit protection using superimposed current signals [19], inductance estimation [20], communication-assisted centralized protection [21] and localized protection using transient behavior of the current and voltage [22]. A brief review of the schemes reported for DC microgrid protection reveals that the existing schemes have not addressed the challenges associated with the intermittent behavior of the renewable sources integrated with DC microgrid. The varying voltage and current profile arising due to uncertain comportment of the non-conventional distributed generators may result in false tripping of the DC microgrid. In this regard, a scheme based on ensemble classifier approach for DC microgrid has been reported in [23]. Also, the classical protection schemes such as current differential protection use multi-point measurement information during DC line faults, which may lead to relay malfunction during failure or delay in the communication channel. The problem is more pronounced for complex DC microgrids with multi terminal ring-type structure.

Motivated by the advantages of DC microgrid and the challenges associated with its protection, a bagging tree-based protection scheme has been proposed for DC microgrid in this paper. Bagging tree (BT) is an emerging and effective machine learning technique which has been extensively used for solving classification tasks for different applications like non-intrusive appliance recognition [24], text classification of railway fault hazards [25], household appliance classification [26] and online voltage security assessment [27]. Bagging tree possess the advantages of improved stability and fewer chances of over fitting of training data which makes it an eminent data mining tool for complex problems in multidimensional space. The accurate and fast fault detection ability of the proposed bagging-tree based scheme brings merits like rapid repair and restoration of the supply whereas identification of faulty sections avoids the disconnection of larger parts of a DC microgrid in the event of a fault or contingency. The proposed scheme has been validated for different pole to pole and pole to ground fault cases at different sections and locations with varying fault parameters in the microgrid. The efficacy of the scheme has also been confirmed for the intermittent behavior of non-conventional distributed generators. The major contributions/highlights of the proposed work can be summarized as:

i. Development of fast and accurate bagging tree-based protection scheme for DC microgrid.
ii. Performing the task of fault detection, classification, and section identification for DC microgrid under varying operating scenarios and fault conditions.
iii. Validation of the proposed scheme for immunity against varying nature of the fault and microgrid operation including intermittency in non-conventional distributed generators.

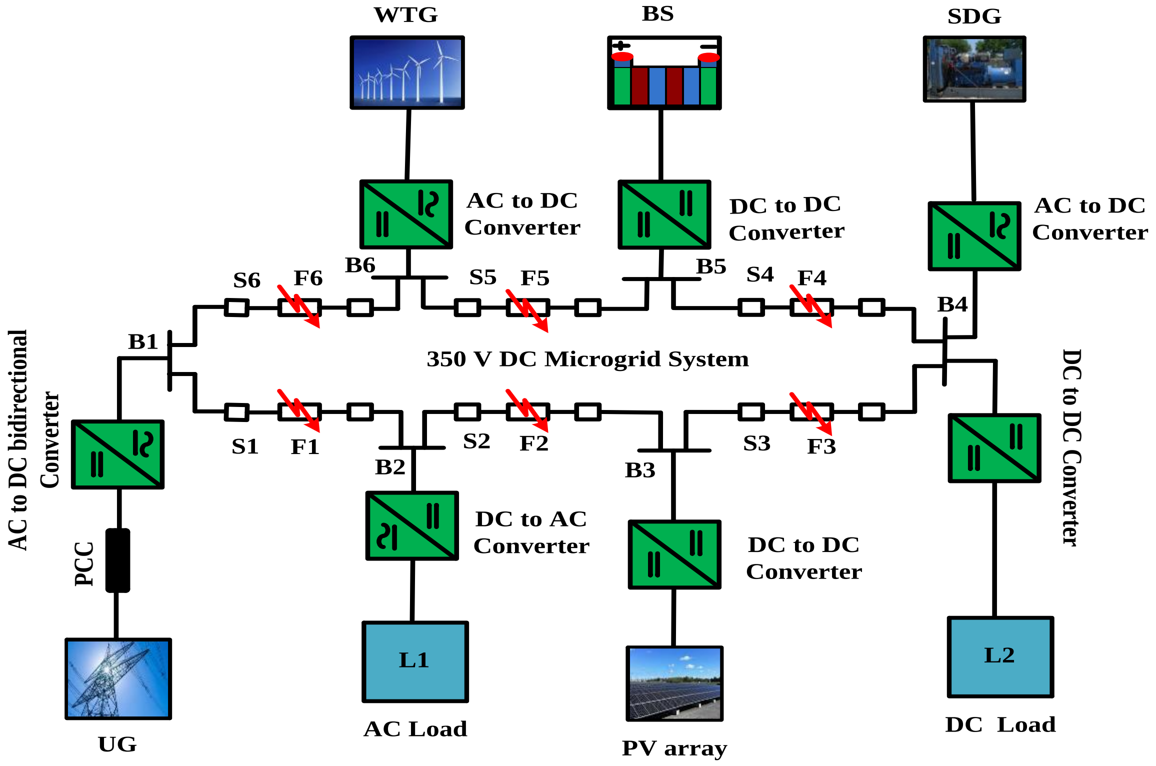

Fig. 1 DC microgrid system with ring configuration

The rest part of the article is arranged as follows: the DC test microgrid model is illustrated and dealt in section 2. The development of the proposed algorithm is dealt in section 3. The performance of the proposed scheme has been analyzed and validated in section 4. Finally, section 5 illustrates the conclusion of the proposed work.

2 DC Test Microgrid Model

A 350 V, 500 kW DC microgrid with ring configuration is illustrated in Fig. 1 [18, 23]. Three distributed energy resources i.e. photovoltaic (PV) array, synchronous generator (SDG) and wind turbine generator (WTG) are amalgamated with a common ring bus of DC microgrid system. The DC microgrid consists of six sections represented by B1, B2, B3, B4, B5 and B6. Two loads (linear and nonlinear) L1 and L2 are connected at bus B3 and B4. The DERs are connected to the microgrid at the different buses through the power electronics converters.

The integration of DC microgrid with utility grid facilitates the operation of the microgrid under both grid-connected and islanded mode with help of the bidirectional converter. To enhance the stability of the power distribution network battery is used at bus B4 as an energy management unit to provide the backup in the system stability. The DC microgrid under study has been simulated under adverse fault and power system operating scenarios.

3 Development of Bagging Tree-Based Protection Scheme

3.1 Bagging Tree Based Classifier

In recent years, the bagging tree or bootstrap algorithm has emerged as a promising emerging tool among the data mining algorithms. The mapping of the bagging trees is more effective for analysis of the input datasets in multi-dimensional space. The bagging tree involves an aggregation of decision trees and is considered if the target is to reduce the variance among the classified output of a single decision tree [28]. Fig. 2 demonstrates the architecture of the bagging tree where the samples for both training and testing phases are fed to N decision trees. The algorithm divides the datasets into various subsets of sampled data for training with random replacement using a bootstrapping approach for an input dataset comprising of *N* samples, during bootstrapping the entire set of samples is divided into *m* (number of DTs) sub-sets. Each DT perform the mapping between the corresponding data subset and related class (fault type). Using the individual output of the m DTs, a final output is derived using a voting strategy. For datasets *N1*, *N2*…& *Nm* being fed to the DTs, the aggregated classes is derived as:

$$[C_1, C_2, C_3 \ldots C_m] = [f^1(N_1), f^2(N_{12}) f^3(N_3) \ldots f^m(N_m)] \tag{1}$$

Using the voting strategy, the final classes is obtained as:

$$C_{1final} = mode\ (C_1, C_2, C_3 \ldots C_{mn}) \tag{2}$$

3.2 Bagging Tree Based DC Microgrid Protection

The overall architecture of proposed protection scheme is illustrated in Fig. 3. As mentioned earlier, the fault current is approximately 20-50 times higher in grid connected mode compared to islanded mode of operation of microgrid. Hence incorporating adaptiveness in the operation of the protection scheme demands separate bagging tree modules are essential for both the modes of operation. The execution of the proposed protection scheme initiates with identifying the mode. In order to identify the mode of operation of the DC microgrid system under study, a bagging-tree based classifier (BT-1) has been developed. After enactment of binary classifier BT-1, either of the two binary outputs (i.e. "0" and "1" representing grid connected mode and islanded mode respectively) are provided. The detection of operating mode is followed by the fault identification and isolation of faulty section. A total of four BT based classifiers have been developed for the same. The "0" output of BT-1 triggers BT-2 and BT-3 simultaneously to identify the fault and corresponding faulty section. While if the output of BT-1 is "1", which corresponds to BT-4 and BT-5 will be executed to provide the output.

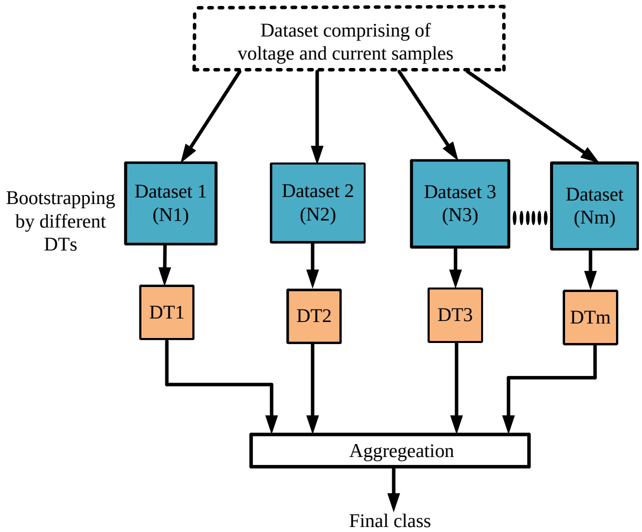

Fig. 2 Structure of the bagging tree for data prediction

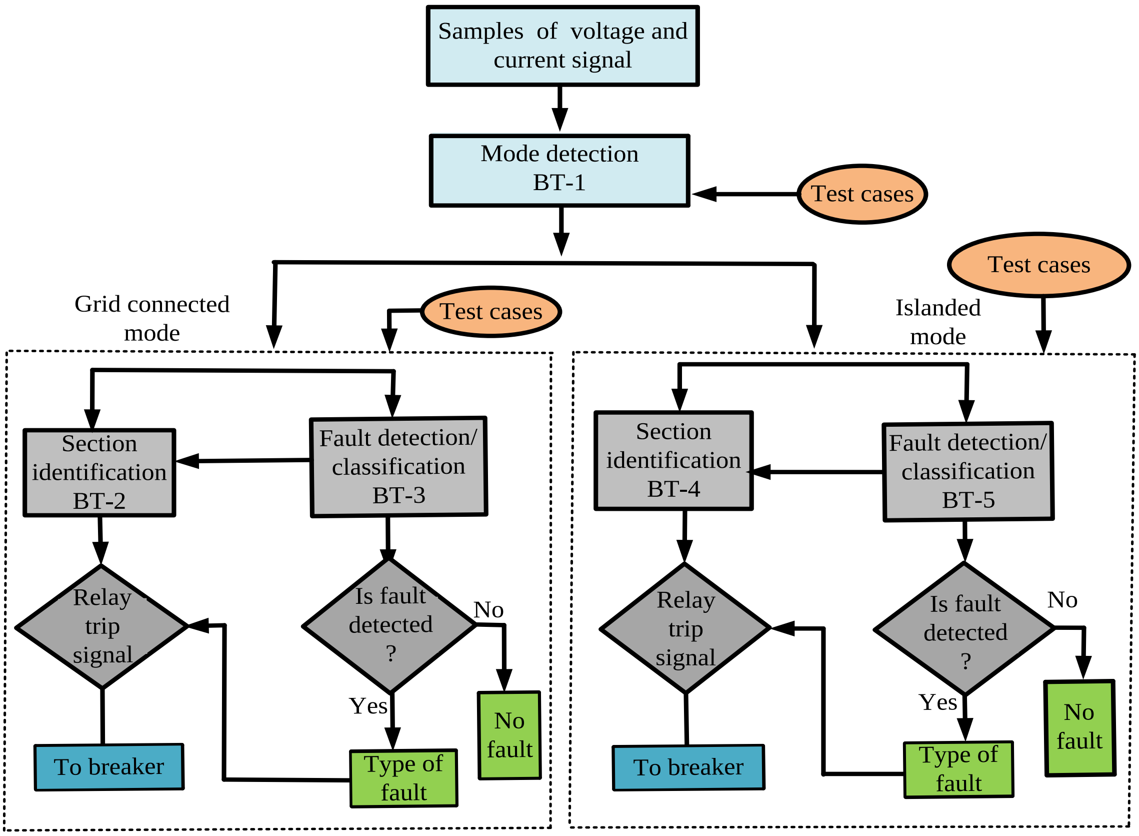

Fig. 3 Architecture of the proposed bagging tree-based protection scheme

Table 1 Training parameters

Parameters	Names of Bagging trees				
	BT-1	BT-2	BT-3	BT-4	BT-5
Maximum number of splits	25	24	24	20	25
Dimension of subspace	1	1	1	1	1
Number of learners	30	28	26	29	23

To consider the robustness of the protection scheme against the undesirable fault situations, various dissimilar faults under different microgrid operating cases have been simulated and utilized to form training and testing matrix for all the BTs. For designing the classifier modules, the magnitude of voltage and current at bus-1 of the DC microgrid have been considered. Once the faulty sections and the type of faults are identified, a trip signal is issued by the proposed scheme to operate the circuit breaker and isolate the faulty section from the rest of the healthy section. The parameters considered during training of BTs such as maximum number of splits, subspace dimension and learners are depicted in Table 1. The same has been arrived at by tuning the parameters over a series of pilot runs, to maximize the classification accuracy.

For training, the overall dataset has been segregated into two classes i.e. grid connected mode and islanded mode. After successful training of the BTs, the efficacy of the modules on the trained data has been examined using confusion matrix in Fig. 4. From the figure, it is clear that true positive rate (correctly detected mode) and false positive rate (incorrectly detected mode) are 100% and 0% respectively which reveals the high accuracy and selectivity of classification (mode detection) of given dataset. Similarly, for fault detection/classification and faulty section identification, classes are assigned to each BT. For designing the BTs for fault detection/classification, a total of three classes are assigned to the training data set representing "no-fault", "pole to ground fault", and "pole to pole fault". The confusion matrix for the BT corresponding to grid-connected mode (BT-3) is depicted in Fig. 4 which reflects the effectiveness of the proposed scheme in achieving high extent of mapping between the input feature and corresponding output during training.

4 Performance Analysis

In this section the performance of the proposed algorithm is analyzed on the testing dataset. A protection scheme is considered as robust and invulnerable only if it provides trip signal accurately and quickly under any unacceptable fault conditions, while avoiding undesired tripping under healthy microgrid operation. Hence, to authenticate the effectiveness of proposed scheme under varying fault and microgrid operating scenarios, numerous fault cases with variation in fault condition, fault resistance, fault location and fault type and microgrid operating case with variation in loads have been taken into consideration. Scenarios pertaining to both the operating modes (grid connected and islanded) as well as both fault types (PG and PP) have been- considered. The sample set for a particular case comprises of the voltage and current samples at the relaying bus unlike machine learning based schemes which considers a window for feature extraction, the relaying action for the proposed scheme is derived using the instantaneous values. To evaluate the effect of weather intermittency, the solar irradiance (200-600 W/m2) and wind speed (6-12 m/s) associated with the PV array and WTG has been considered. A dataset consisting of 31944 fault and 350 no-fault cases during grid connected and islanded modes have been generated by simulating the microgrid model using MATLAB/Simulink. The entire dataset comprising of 32294 is divided into 70% & 30% for training and testing respectively.

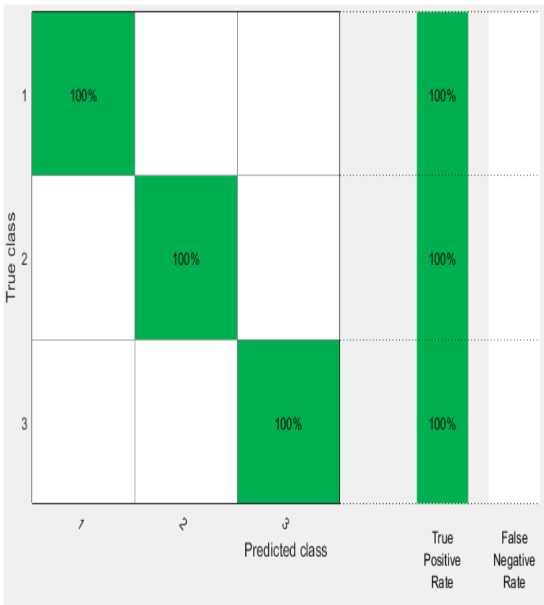

Fig. 4 Confusion matrix during training of dataset

Table 2 Training testing pattern under grid connected and islanded mode of operation

Parameters during training of classifier	Specification of fault parameters during training	Total cases	Total training cases	Total testing cases
Types of mode	2	31944+350 no fault cases=32294	22623	8671
Section	6			
Types of fault	2			
Fault resistance	11			
Fault distance	11			
Inception of fault	1			

Table 3 The performance comparison of proposed scheme in terms of reliability indices.

Name of algorithms	Mode of operation					
	Grid connected			Islanded		
	Dependability (%)	Security (%)	Overall accuracy (%)	Dependability (%)	Security (%)	Overall accuracy (%)
Proposed scheme	99.69	100	99.84	99.09	100	99.54
SVM	98.55	98.29	98.42	98.11	98.91	98.51
DT	97.55	97.11	97.33	97.23	98.55	97.89

Table 2 illustrates the details of the parameters which have been considered to generate the training and testing data to perform the desirable protection task. The performance of proposed scheme is discussed in subsequent subsections.

4.1 Mode Detection

As stated in section 1 that there is a significant difference between the magnitudes of the current profile measured at relaying bus under grid connected and islanded mode. Thus, the protection scheme must be adaptive to the operating mode of DC microgrid. To examine the effectiveness of bagging tree-based protection scheme in detecting the operating mode of DC microgrid, a total number of 4283 test cases has been simulated in both the operating modes, for which the accuracy of the proposed scheme is found to be 100%. The scheme is also compared with some other well-known machine learning techniques such as DT and SVM in Fig.5 and it is found that the proposed scheme outperforms both the DT and SVM based classifiers.

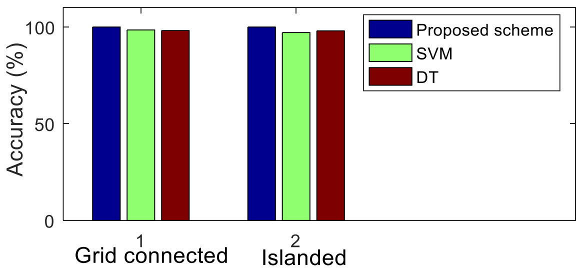

Fig. 5 Comparison of the proposed mode detector as to SVM and DT based techniques

4.2 Fault Detection/Classification

The sensitivity of any protection scheme to different faults must be high to enhance the invulnerability of the microgrid against fault. In this regard, to analyze the appropriateness of proposed scheme under faults and abnormal conditions arising because of load variation, a total number of 4283 cases and 30 no fault cases under both modes have been considered. The reliability of the proposed scheme has been evaluated in terms of in terms of standard indices i.e. dependability and security. Dependability and security can be defined as:

Dependability: Dependability is defined as the ratio of the actual predicted fault cases to the total number of fault cases (Eq. (3)). It gives the information about the number of misdetection of faults. The percentage of dependability is calculated as:

$$\text{Dependability} = \frac{\text{Total predicted fault cases}}{\text{actual number of fault cases}} \times 100 \quad (3)$$

Security: Security of the protection system indicates the possibility of the generation of the false alarm signal. It is defined as the ratio of the actual number of predicted no fault cases to the total number of actual no-fault cases (Eq. (4)).

$$\text{Security} = \frac{\text{Total predicted no fault cases} \times 100}{\text{actual number of no fault cases} \times 100} \quad (4)$$

The proposed scheme has been further compared with SVM and DT based machine learning techniques in terms of the above-mentioned reliability indices in Table 3. The results clearly indicates that the reliability of the proposed scheme is much higher compared to SVM and DT based schemes. Along with the statistical indices, the proposed scheme has also been validated in terms of receiver operating characteristic (ROC) and area under the curve (AUC) of the classifier modules.

Table 4 Performance of proposed bagging tree under grid connected and islanded mode

Mode of operation	Type of fault	Fault resistance (Ω)	Faulty section	Response of bagging tree	Relay operation time in (ms)
Grid connected mode	PG	50	S1	PG	1.4
	PG	75	S3	PG	1.6
	PG	100	S5	PG	1.3
	PP	0.4	S4	PP	1.6
	PP	0.4	S3	PP	1.6
	PP	0.4	S6	PP	1.7
Islanded mode	PG	25	S4	PG	1.6
	PG	40	S3	PG	1.7
	PG	20	S5	PG	1.6
	PP	0.4	S4	PP	1.5
	PP	0.4	S6	PP	1.7
	PP	0.4	S2	PP	1.6

The area under the ROC curve gives information about a measure of the separability among the classes. High AUC and hence reliability relates to distinct classification of dissimilar operating scenarios with similar voltage-current dynamics. The ROC curve of the proposed BT-based classifier for a specific fault type (‘PG’ fault) is depicted in Fig. 6. Similarly, ROC curves for PG and PP faults have also been obtained for other BTs.

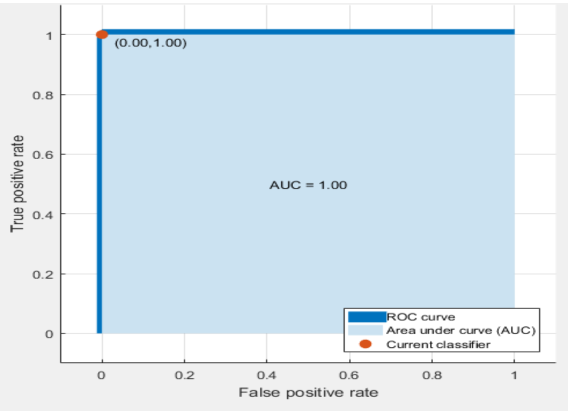

Fig. 6 Receiver operator characteristic after training of data

The steepness of the slope of ROC and the value of AUC (i.e. equal to one) replicates the efficacy of the proposed BT-based classifier. The high magnitude of DC fault current and its rapid rate of rising demands early isolation for safe guarding the voltage source converters (VSC) in DC microgrid. The same demands faster execution of the proposed scheme in addition to high reliability. Hence relay operation has also been evaluated for execution time during pole to pole and pole to ground faults at different section in line in Table 4. From the results, it can be seen that the maximum relay execution time is 1.7ms and 1.8ms during grid-connected mode and islanded mode of operation respectively. The same confirms the rapidity of the scheme in detecting the faults. Further, the relay operation time of the proposed scheme for the microgrid operating modes has also been depicted in Fig. 7 for a PG faults of Table 4.

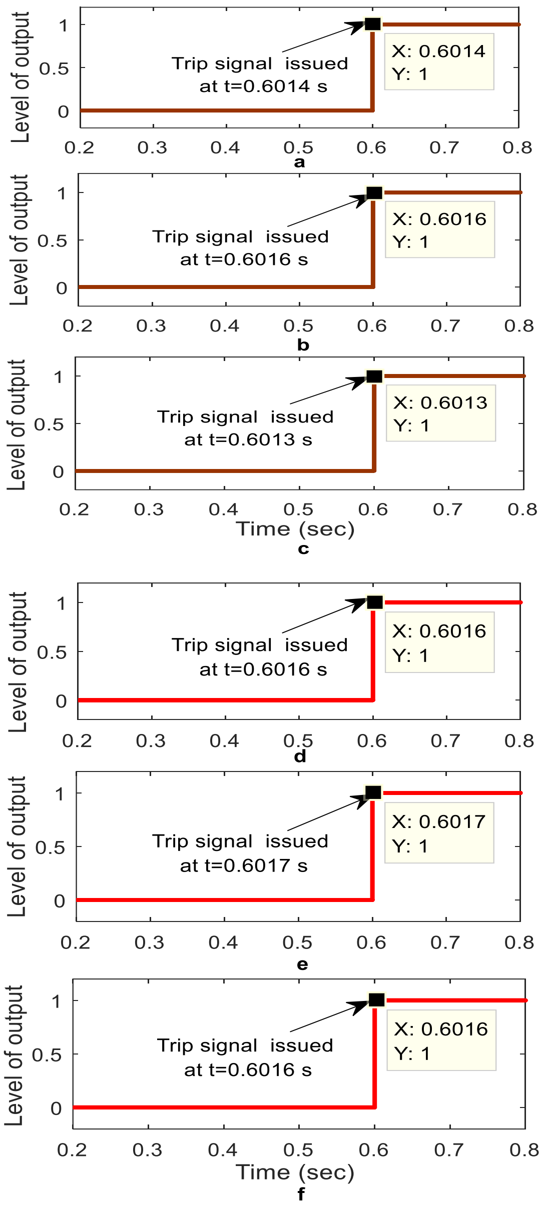

Fig. 7 Generation of Trip signal during pole to ground fault for microgrid operation under grid connected (a), (b), (c) and islanded mode (d), (e), (f)

Table 5 Performance comparison of proposed fault section identifier in terms of reliability indices

Mode of operation	Section	No of test cases	Bagging Tree (accuracy %)	SVM (accuracy %)	DT (accuracy %)
Grid connected mode	S1	204	98.86	97.85	97.22
	S2	208	99.71	97.66	98.36
	S3	200	99.54	97.21	98.55
	S4	204	98.26	98.52	97.65
	S5	206	99.33	97.36	97.55
	S6	202	99.76	98.63.	98.33
	Overall accuracy %		98.24	97.87	97.94
Islanded mode	S1	207	99.09	97.55	98.32
	S2	204	98.91	97.63	97.69
	S3	204	98.68	97.69	97.63
	S4	202	99.55	97.56	96.51
	S5	204	99.69	97.55	97.63
	S6	207	98.97	96.91	98.33
	Overall accuracy %		99.14	97.48	97.68

Table 6 Performance comparison of proposed bagging tree-based protection scheme under weather intermittency in distributed generators for grid-connected mode

DERs	Variations in the level of solar irradiance (W/m^2) and wind speed (m/s)	Types of fault	Faulty sections	Response of the Bagging Trees	Relay operation time (ms)
PV array	300	PG	S2	PG	1.4
	500	PG	S3	PG	1.5
	600	PG	S5	PG	1.3
	200	PP	S4	PP	1.6
	400	PP	S2	PP	1.5
	500	PP	S3	PP	1.3
Wind turbine generator	8	PG	S2	PG	1.7
	10	PG	S3	PG	1.3
	12	PG	S5	PG	1.3
	6	PP	S4	PP	1.7
	8	PP	S2	PP	1.6
	10	PP	S3	PP	1.7

4.3 Section Identification

The results depicted in the table confirm that the scheme is consistent in performing the section identification task. Further, a comparison has been carried out between the proposed scheme and SVM and DT-based schemes. Comparison results depicted in Table 5 show the superiority of the proposed scheme over other schemes in accurately identifying the faulty section.

4.4 Response of the Proposed Scheme for Intermittency Associated with Non-Conventional Distributed Generators

The high extent of integration of non-conventional distributed generators in DC microgrid makes the protection task complicated. The complexity arises due to deviation in voltage and current profile during random fluctuations in the weather scenarios, which significantly impacts the performance of the conventional threshold-based relays. Hence, it is essential to evaluate the robustness of the proposed protection scheme against weather intermittency arising in non-conventional distributed generators (wind generator and PV array). In this regard, different pole to pole and pole to ground faults with variation in solar irradiance level and wind speed over a definite time-span has been simulated and the performance of the proposed scheme has been analyzed. Some of the test results among the testing dataset with relay operation time are depicted in Table 6 and Table 7 for grid-connected and islanded mode respectively. The results illustrate that the scheme is able to detect all the faults and identifies the faulty section within 1.7ms even under the intermittent behavior of the distributed generators. For all the fault cases of Table 5, the execution time was found to be less than 2ms.

5 Conclusion

The performance of the proposed DC microgrid protection scheme is significantly affected by the weather dependent intermittent behavior of non-renewable distributed generators such as photovoltaic system and wind energy system.

Table 7 Performance comparison of proposed bagging tree-based protection scheme under weather intermittency in distributed generators for islanded mode

DERs	Variations in the level of solar irradiance (W/m^2) and wind speed (m/s)	Types of fault	Faulty sections	Response of the Bagging Trees	Relay operation time (ms)
PV array	300	PG	S2	PG	1.4
	500	PG	S3	PG	1.5
	600	PG	S5	PG	1.3
	200	PP	S4	PP	1.6
	400	PP	S2	PP	1.5
	500	PP	S3	PP	1.3
Wind turbine generator	8	PG	S2	PG	1.7
	10	PG	S3	PG	1.3
	12	PG	S5	PG	1.3
	6	PP	S4	PP	1.7
	8	PP	S2	PP	1.6
	10	PP	S3	PP	1.7

The selectivity of the conventional threshold-based relays is severely compromised during wide weather fluctuations. Further, the high fault current level and the fast rate of rising of the fault current are major challenges towards developing a reliable protection scheme. To address the issues of DC microgrid protection, a fast and accurate bagging tree-based protection scheme for DC microgrid has been developed and validated. The contributions made in this context are threefold. Firstly, a mode detector has been developed which detects the mode of operation of the DC microgrid. Further, a fault detector/classifier has been designed which is immune to the variation in voltage and current profile arising because of the intermittency associated with non-conventional distributed generators. The third contribution relates to the development of section identification scheme which enables the isolation of only the faulty section during fault, while maintaining the rest of the healthy section in service. The proposed scheme is validated for different pole to pole and pole to ground fault with varying fault parameters at different sections of the microgrid. The scheme has been compared with other state of art machine learning techniques i.e., SVM and DT. The results demonstrate the efficacy of the scheme even under varying operating scenarios, fault cases and weather conditions.

Intellectual Property

The authors confirm 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. P. Tiwari: Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing-original draft. **E. Koley:** Conceptualization, Investigation, Methodology, Supervision, Validation, Visualization, Writing-original draft, Writing- review & editing.

Declaration of Competing Interest

The authors hereby confirm 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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