Microgrid confrontations and smart resolution

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ABSTRACT

Hybrid microgrids are emerging as an alternate solution for connecting distributed AC/DC energy resources. Effective fault detection and response are highly essential for the microgrid controller (MGC) for protection of the microgrid. The conventional schemes of protection cannot be applied in microgrid because of dynamic conduct and unconventional topology of the microgrids. It is highly essential to develop an appropriate scheme for detection and classification of faults for the effective protection of microgrids. In this paper, a novel and smart solution based on the application of an intelligent machine learning (ML) fine tree algorithm is applied to the hybrid microgrid controller. This algorithm resulted in effective detection & classification of faults which in turn was used for separation of faulty segment. The intelligent model obtained with the proposed algorithm performed well and fault detection accuracy has been showcased for various fault scenarios. The overall fault detection accuracy obtained is 98%. Severity of faults and associated confrontations are also discussed in this work. Performance efficacy of the proposed ML based protection algorithm for MGC is substantiated in MATLAB environment.

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1. INTRODUCTION

The installation of distributed generators such as photovoltaic (PV) modules, wind, micro gas turbines, and batteries in microgrids has changed the traditional layout of the electricity grid over the past years. Most of the micro sources are not suitable for direct injection into the electrical grid and must be connected through power electronics (PE) interfaces. The application of these interfaces poses many challenges in protecting microgrids. Conventional protection schemes are not suitable for unconventional topology of microgrids. The dynamic behavior of microgrid system and the overlapping characteristics of several faults make it difficult to detect any abnormal condition accurately. Devising a proper protection scheme suitable for modern grid is the need of the hour. There is a requirement to develop standards for protection and safety aspects of microgrid systems.

Alam *et al.* [1] discussed the current challenges and issues in the microgrid implementation. The protection of DC side of the microgrid is equally necessary because of various reasons such as presence of intermittent sources and power electronic interfaces as these sources cannot be connected directly to the grid [2], [3]. Sliding mode observer method is proposed by Criollo *et al.* [4] for detecting the abnormal condition in microgrid. Research gaps in microgrid protection coordination are discussed with possible solution and associated challenges [5]. One of the most challenging and considerable tasks is to develop and implement a non-conflicting protection scheme for distributed generation based microgrids as discussed in [6], [7]. Importance of bus sectionalized hybrid microgrid to achieve seamless switching is discussed [8]. An inclusive review of challenges involved in microgrid implementation, and associated protection schemes are discussed in [9]. Performance analysis and comparison of various parameters of a microgrid with respect to the conventional system has been discussed in [10]. Prasad and Parimi [11] proposed a data driven approach to address issues in the hybrid microgrid. Summary of various research works related to control issues of hybrid microgrid with other topologies, the technical and economic challenges are surveyed and presented [12], [13].

Impedance matrix and area concept methods are studied using precalculated information that is required for setting the time of operation of relay [14], [15]. Oudalov and Fidigatti [16] suggested adaptive protection scheme which requires precalculated information for detection of faults. Wang *et al.* [17] shows that due to varying output of renewable sources, the relays connected in the microgrid system experience different operating currents and due to limited fault current contribution by these sources the precalculated information for threshold-based overcurrent protection is not sufficient for designing protection system for the microgrid. Panda *et al.* [18] proposed and implemented proportional-integral-derivative (PID) control technique for the inverter used in hybrid microgrid to regulate the output voltage. The power quality problems in a microgrid affect the operation of protective devices which can lead to severe problems in the entire microgrid network [19]. To get faster and more accurate solutions for complex multi objective non-linear systems machine learning (ML) methods are proposed [20], [21]. Li *et al*. [22] modeled the ambiguity of reserves by considering probabilistic constraints and applied ML based algorithm for the controller. Operation optimization modelling technique based on multi objectives has been presented by Shadmand and Balog [23]. Sitharthan *et al.* [24] discussed a protection scheme for the PE interfaced distributed generators. The scheme proposed is found to be adequate for grid and islanded operation of the microgrid. Microgrid protection strategy is the main issue which needs to be addressed by the researchers for ensuring the reliable operation of the microgrid [25]. Yang *et al.* [26] presented the fault behavior through mathematical model and associated characteristics which helped in understanding the issues in devising a protection scheme for a microgrid system. A comprehensive review on applications of machine learning on power system resilience enhancement is presented. Application of artificial intelligence in the field of power system is suggested by Xie *et al.* [27].

It is observed that not much attention is given to protection area of microgrid which lays down the foundation for microgrid implementation. In this paper microgrid protection challenges such as change in fault level, blinding of protection and bidirectional power flow in various sections or zones of the considered hybrid microgrid has been discussed. It is realized that with all such issues, conventional protection schemes cannot be deployed for the protection of the microgrid system under consideration. The key theme of this work is to develop a suitable algorithm for fault detection and classification in hybrid-microgrid. The conventional fault detection methods are not suitable for hybrid microgrid owing to unconventional topology reported in literature. A novel solution based on supervised machine-learning fine tree approach is applied for the fault detection and classification in the hybrid microgrid. An overall fault detection accuracy of 98 % is obtained by the proposed solution.

2. SYSTEM CONSIDERED AND ASSOCIATED CHALLENGES

Figure 1 represents the schematic illustration of the system under consideration. The maximum power supplied capacity is 50 kWp with PV array which includes 5 PV modules with standard test conditions, wind power source 50kW nominal output and with a speed of 12 m/s has been considered. A battery of 500V, 40Ah rating and AC load rated 150kW, 50KVAR. A DC load of 200 kW and a 3-phase grid is connected via three phase transformers of star-delta configuration rated with 100 KVA, 25 kV/260 V, and 50Hz. The microgrid controller interacts with micro source controllers and the loads to balance generation and load. In grid connected mode, the core purpose of microgrid controller is to provide power management while in separated mode the objective is to regulate voltage and frequency with demand. Blinding of protection and bidirectional power flow are the main challenges observed in hybrid microgrid implementation. These protection issues are discussed in this section. A simplified network interconnecting microgrid to the grid is revealed in Figure 2. At fault point F, fault current would be contributed by grid, synchronous machine based distributed energy resource (SBDER) and inverter based distributed generator (IBDER) and can be given as (1)-(4).

$$I_F = I_{FGrid} + I_{FSBD} + I_{FIBD} \quad (1)$$

$$I_F = I_{FGrid} \pm \sum_{D=0}^{n} I_{FD} \quad (2)$$

$$I_F = 0 \pm \sum_{D=0}^{n} I_{FD} \quad (3)$$

$$I_{FSBD} > I_{FIBD} \quad (4)$$

I_F is the fault current at point 'F'. I_{FSBD} is the fault current supplied by synchronous generator based distributed generator. I_{FIBD} is fault current contribution by inverter based distributed generator. If a fault is set between R1 and R2, fault current indicated in Figure 3 shows that direction of the fault current contributed by SBDER would get changed and relay R3 and R5 will no longer be able to decide whether it is a fault current or normal current. Relay R2 also will not be able to decide whether it is a fault current, or a new load demand appeared in the network in the same section. It creates blinding of protection and bidirectional flow of power for relay R2 which results in false tripping of R2 relay. As a result, each relay will experience dynamics in fault level which can lead to false tripping and blinding in the associated section. The same applies for another fault location also. So, it is very challenging to decide on setting the tripping time of the associated switchgear. Hence, protection practices developed for conventional system are not advisable for the microgrid system. An appropriate smart algorithm for the controller is required for detection and classification of faults for the protection of microgrids un-conventional structure.

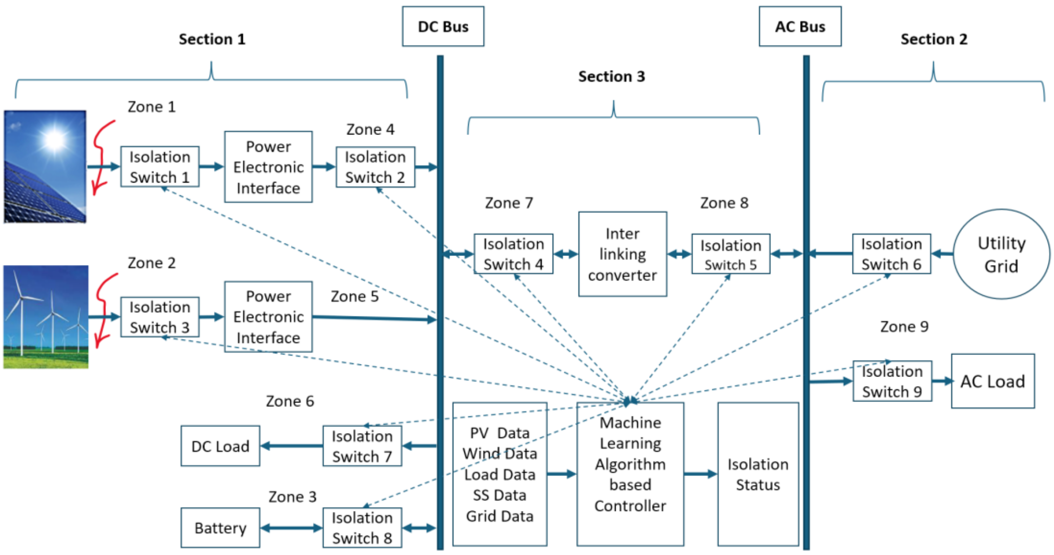

Figure 1. Schematic diagram of the hybrid microgrid under consideration

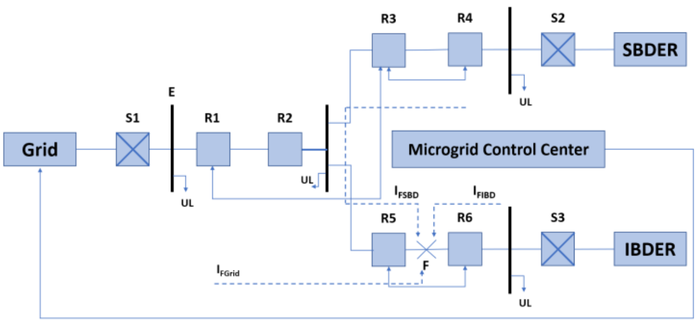

Figure 2. Fault current contribution (fault is at point F between R5 and R6)

The current contributed by various generators during fault condition (under grid connected operation) show in (1) and (2). The fault current contributed by various generators during islanded mode of operation show in (3). The current during fault supplied by synchronous generator is more than the current contribution by inverter based distributed generator during fault show in (4). Additionally, response characteristics show the transients present in the hybrid system after fault also poses challenge in devising a protection scheme [26]. The DC capacitor current is obtained by (5) and (6).

$$\frac{d^2 I_c}{dt^2} + \frac{R}{L}\frac{d}{dt} I_c + \frac{1}{LC} I_c = 0 \quad (5)$$

$$I_c(t) = A\sin(\omega_s t + y) + Be^{-\frac{R}{L}(t)} + \frac{C}{w_d}\omega_0 e^{-\frac{R}{L}(t)}\sin(\omega_s t + \beta) + \frac{D}{w_d}\omega_0 e^{-\frac{R}{L}(t)}\sin(\omega_s t) \quad (6)$$

$I_c(t)$ is the DC link capacitor current at time 't' ω_s is the frequency of the system, R denotes DC link resistance, L denotes DC link inductance & C denotes capacitance of the link. y and β are the grid voltage angle of phase A and B respectively. The phase constants A, B, and C are the functions of R, L, and C. Devising a protection scheme is a major challenge due to the above-mentioned reasons. DC link capacitor current is obtained from (5) and (6). The response characteristics of a microgrid are divided into transient and steady state characteristics. Steady state component is injected from the power system side whereas transient component is injected from capacitance and inductance present in the system.

From Figures 2, 3, and 4, it is clear that very challenging it is to decide on setting the operation time of the associated switchgear in a microgrid as it cannot be fixed owing to changes in fault level and direction of power flow in both grid and islanded mode. Due to these challenges, conventional fault detection algorithms used for the protection of the conventional grid cannot be applied to the hybrid microgrid system under consideration. Hence, there is a need to develop a suitable algorithm for detection and classification of the faults in a hybrid microgrid.

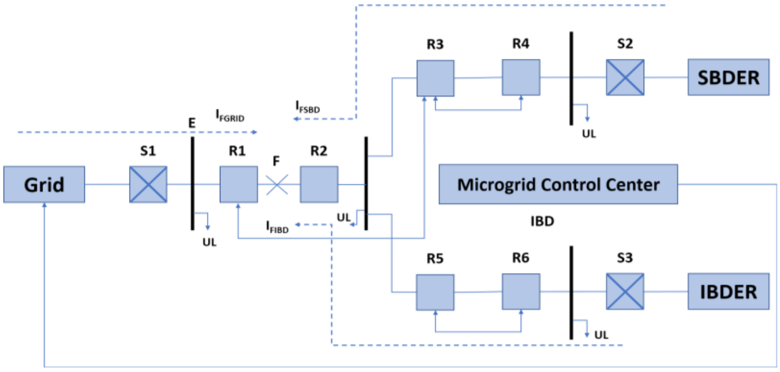

Figure 3. Fault current contribution (fault is at point F between R1 and R2)

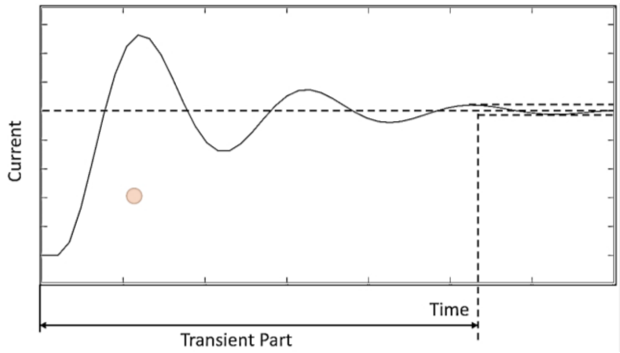

Figure 4. Response characteristics [26]

3. PROPOSED SOLUTION

It is essential to detect the fault at early stages to increase the system accessibility, reduce the repair and maintenance cost. Conventional fault detection schemes cannot be applied in microgrids owing to their unconventional topology. As mentioned in report published by National Renewable Energy Laboratory that due to change in topology and varying output of the renewable sources the relays connected in the microgrid system experience different operating currents and also due to limited fault current contribution by these sources the threshold-based overcurrent protection is not sufficient for protection design of the microgrid [17]. The unconventional topology of the microgrid leads to varying fault level, blinding zones, and bidirectional power flow as discussed in section 2. Due to these protection confrontations in hybrid microgrid, it is very challenging to set a protective gear such as a relay at a specific threshold value as it is done in conventional grid. Not much attention has been paid to this aspect of hybrid microgrid in literature as of now.

To address the above issue, a novel intelligent solution based on machine learning (ML) fine tree algorithm has been proposed and implemented in this paper. This solution helps to detect and classify the faults in hybrid microgrid. Results obtained are used for disengaging the breakers to isolate the faulty section. There are two basic approaches or algorithms in ML, supervised algorithm and unsupervised algorithm. Supervised algorithm is defined by the use of labeled datasets. On the other hand, unsupervised learning algorithm uses unlabeled data sets. In this proposed approach a data set for the system shown in Figure 1 is obtained for various fault scenarios. These datasets are used to train the model for predicting the output accurately. In this work a supervised ML algorithm (fine tree algorithm) has been implemented and implementation approach is shown in Figure 5. Results obtained from the implemented microgrid controller (MGC) algorithm are used for disengaging the breakers to isolate the faulty section. Overall fault detection accuracy obtained through this algorithm is 98%. The proposed algorithm follows a data driven approach and is found to be appropriate for fault detection in microgrids.

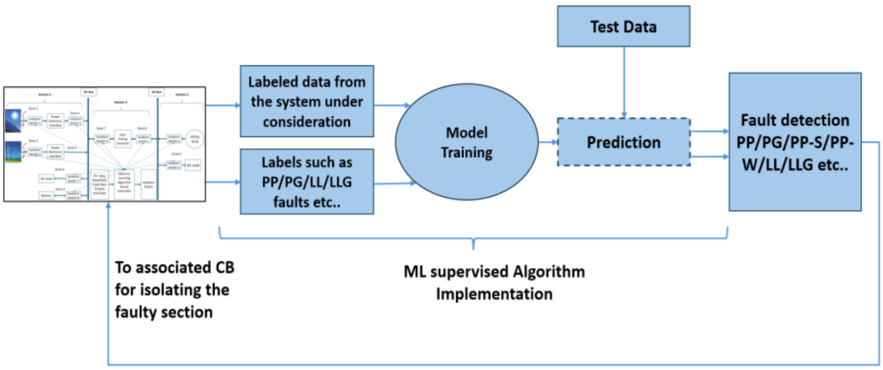

Figure 5. Proposed algorithm implementation approach

4. METHODOLOGY ADOPTED

In this work, machine learning (ML) fine tree algorithm has been proposed and implemented to detect and classify the faults in hybrid microgrid for its protection. ML fine tree algorithm is a data driven, supervised algorithm which is defined by the use of labeled data set [27]. Hybrid microgrid system under consideration is divided into various zones (solar, wind, battery, load, and grid zone). Voltage and current signature are observed for various fault conditions. This data is required to build the tree structure. The collected data set has been classified into various classes through the structure of fine tree formation. The data set has been divided into two parts, learning data set and testing data set. The tree progressively grows in order to classify all scenarios based on the data. Various types of faults are studied in this work to show their effect on voltage and current signature.

Performance evaluation of above model is achieved through confusion matrix. Confusion matrix in machine learning is a performance evaluation tool. This is a matrix of numbers that shows where a developed model with the proposed algorithm got confused. It displays the number of true positives and negatives, false positives and negatives. True positive is the number of fault cases that was predicted by the algorithm, and the Test Data do have the cases that's why it is 'True Positive'. True Negative is the number of fault cases that was predicted by the algorithm, and the Test Data do not have these cases that's why it is 'True Negative'. Similarly, False positive are the fault cases that were predicted by the algorithm, but the Test Data do not have the cases hence it is 'False positive'. 'False Negative' are the cases that were not predicted by the algorithm, but the Test data do have the cases. Based on the confusion matrix terms presented in Figure 6, fault detection accuracy is computed and is presented in (7).

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (7)$$

The result reveals the prediction performance of the developed fault detection model in terms of accuracy. This is a supervised fault detection and classification algorithm. Figure 7 shows the methodology adopted for the system under consideration. different fault cases are considered for training the network, example pole to pole fault (PP) and pole to ground fault (PG) at DC side, faults at various locations under various modes of operation. The collected current and voltage signals from the implemented hybrid microgrid provide the appropriate information based on prevailing condition in the network. During the fault, current, and voltage level changes very sharply depending on the type of fault which may further cause damage to the system. Different response classes are considered for training the network such as fault at various locations (solar source side, wind power source side, grid side, load side, and inverter side) with changing irradiation, with varying wind speed, and with and without fault impedance. Fine tree (supervised algorithm) algorithm is deployed for training the model.

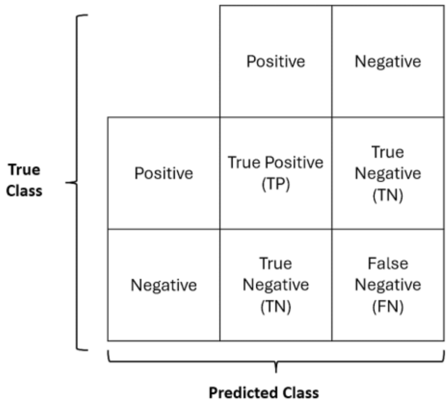

Figure 6. Confusion matrix structure

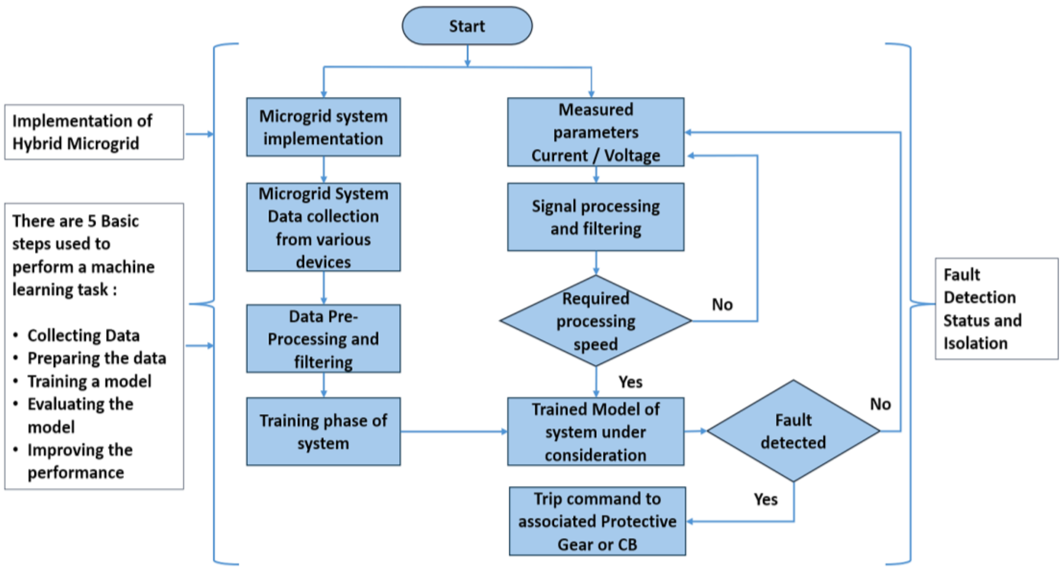

Figure 7. Methodology flow chart

5. RESULTS AND DISCUSSION

For the application of the proposed algorithm, the entire system is divided into various zones (solar, wind, battery, inverter, DC load, and AC load). Data is collected for various fault cases and the effect of two such cases (PP fault at solar and PG fault at solar) is presented in this work in Figures 8 and 9. In this section results are discussed when the system was subjected to various types of faults and after applying proposed algorithm for fault detection. A pole to pole (PP) and a pole to ground (PG) fault is set in solar zone, the currents in various zones of the hybrid microgrid are presented in Figures 8 and 9 with respect to time. Issues discussed in section 2 through simplified networks are observed and discussed. In zone 1 (solar section), After setting the PP fault, current is changed from steady value of 95A and reaches 2000A in reverse direction due to presence of power electronic devices which exhibit negative incremental impedance and hence causes serious issues in power systems. Also, PP fault in zone 1 is causing blinding and bi-directional effect in 1, 3, 4, and 7 zones which may lead to malfunctioning of the relays connected in the associated areas. PG fault at solar zone is set at t = 0.069 seconds resulting in current change from steady value of 94.9A to around 74.9A. Later at 0.019 seconds, the change in current is resumed to earlier value acquired under steady-state condition.

Results presented in Figures 8 and 9 reveals that PP fault is more severe than a PG fault. So, it is highly required to detect these faults at a faster rate to ensure the system's safety and protection. Subsequently the proposed fault detection scheme has been implemented and discussed to overcome these challenges. Figures 8 and 9 show the challenges (discussed in section 2) observed in hybrid microgrid during fault condition. In order to overcome these challenges, the proposed ML fine tree algorithm has been implemented.

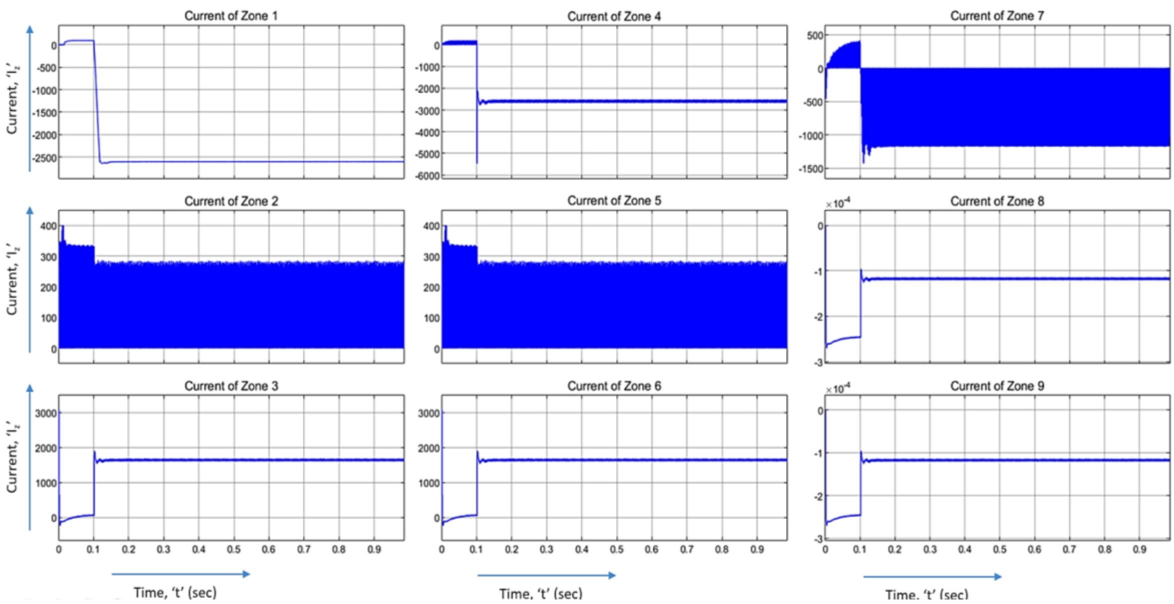

Figure 8. Pole to pole fault in zone 1- blinding effect and bidirectional effect can be seen in zone 1, 3, 4, and zone 7

Figure 8. pole to pole fault in zone 1- blinding effect and bidirectional effect can be seen in zone 1,3, 4, and zone 7. To implement the proposed algorithm, various features such as voltage and currents in each zone of the system are considered for data collection. After collecting the data, ML model with fine tree algorithm was developed and performance of the developed model is evaluated by confusion matrix. Figure 10 shows the confusion matrix for 7 response classes labelled as 0, 1, 2, 3, 4, 5, and 11 to find fault detection accuracy of the proposed algorithm. Table 1 shows the simplified confusion matrix for 7 response classes. Label '0' is assigned to no fault. '1, 2, 3, 4, 5' for pole-to-pole fault at solar zone, at wind zone, at battery, at load, and inverter zone respectively and label '11' for pole to ground fault at solar zone. Fault detection accuracy obtained is 99.04 % for no fault or normal condition (0-NF), 100% for pole-to-pole fault at solar zone (1-PP-S), 100% for pole to pole fault at wind section or zone (2-PP-W), 100% for pole to pole fault at battery zone (3-PP-B), 99% for pole to pole fault at inverter zone (4-PP-In) and 100% for pole to pole fault at DC load zone (5-PP-L) 87% for pole to ground fault at solar zone (11-PG-S). The overall accuracy of prediction obtained is 98% with the selected algorithm. Fault detection results obtained with the proposed algorithm are deployed for the associated protective gears to isolate the fault section (wind section shown in this case) from healthy section.

Figure 11 shows the circuit breaker status after detecting the fault successfully at wind turbine side. At time t = 0.054 sec, fault in wind zone is detected by algorithm and breaker is opened. Table 1 shows fault detection accuracy obtained from the applied fine tree algorithm. Figure 12 shows the fault detection accuracy provided by the implemented algorithm in terms of confusion matrix. It is observed that overall, 98% of fault cases were correctly predicted and detected by the proposed ML fine tree algorithm for MGC.

Table 1. Fault detection accuracy

Sr. No	Fault	Assigned labels	Accuracy (%)	Sr. No	Fault	Assigned labels	Accuracy (%)
1.	No fault	0	99.04%	5.	PP-In	4	99%
2.	PP-S	1	100%	6.	PP-L	5	100%
3.	PP-W	2	100%	7.	PG-S	11	87%
4.	PP-B	3	100%				

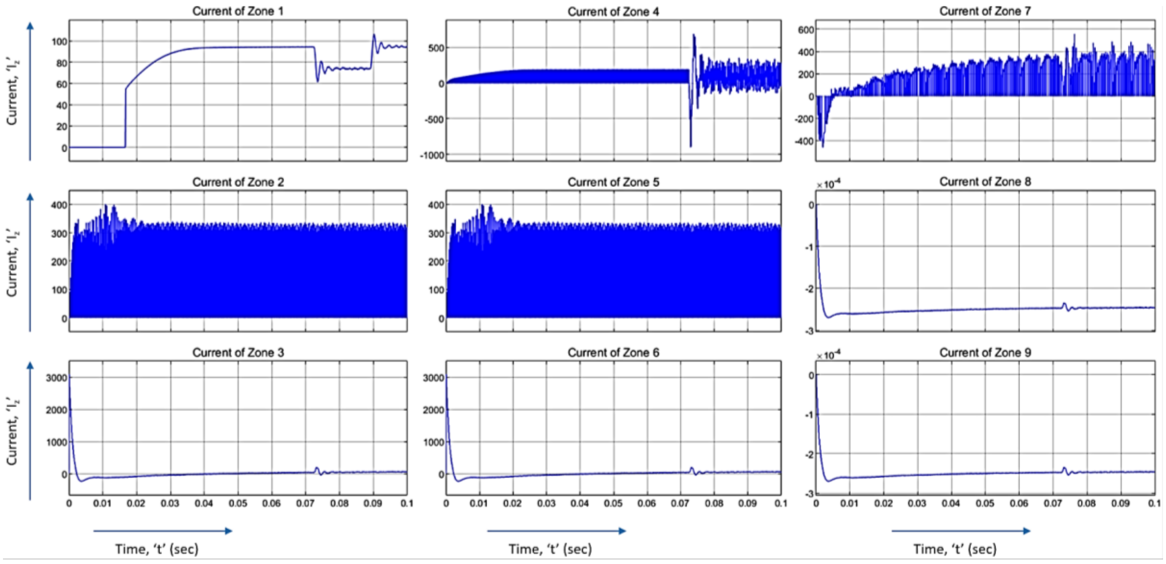

Figure 9. Pole to ground fault on solar side zone 1 - blinding effect and bidirectional effect can be seen in zone 3, 4, 8, and zone 9

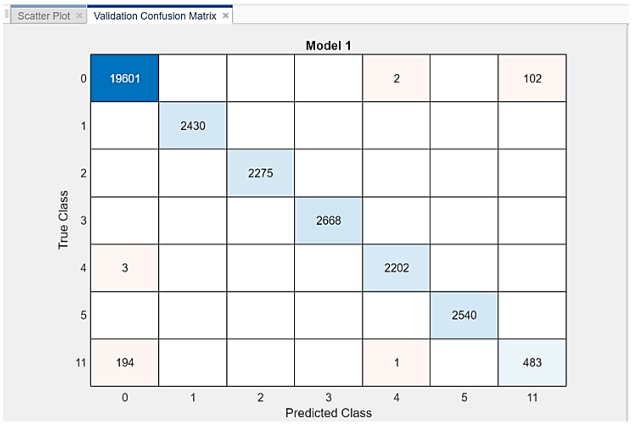

Figure 10. Confusion matrix – for performance evaluation of the proposed ML-fine tree algorithm

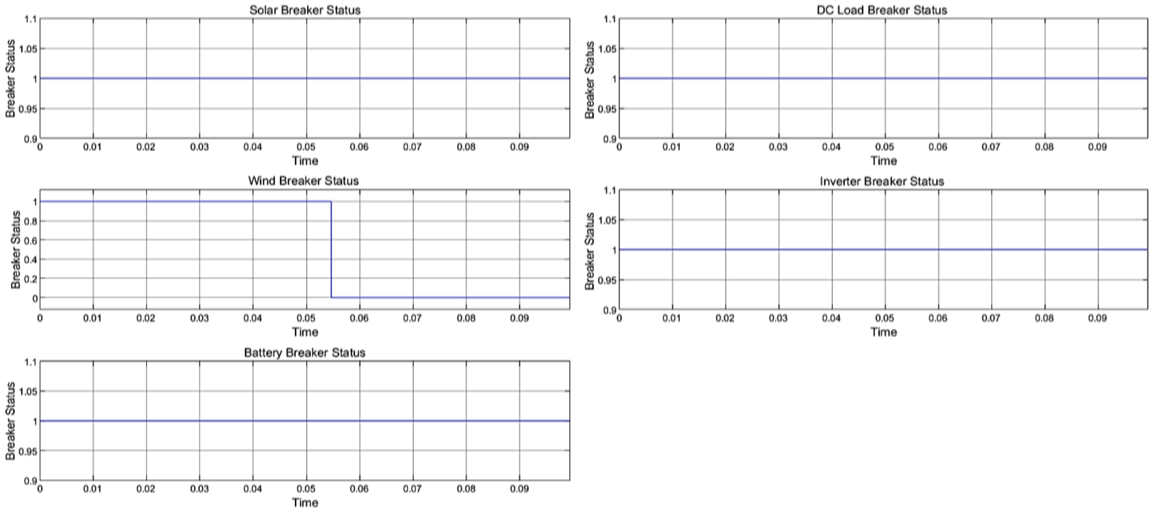

Figure 11. Breaker or isolation switch status after fault detection by proposed ML fine tree algorithm at wind side: (breaker status 1- closed and 0 – opened)

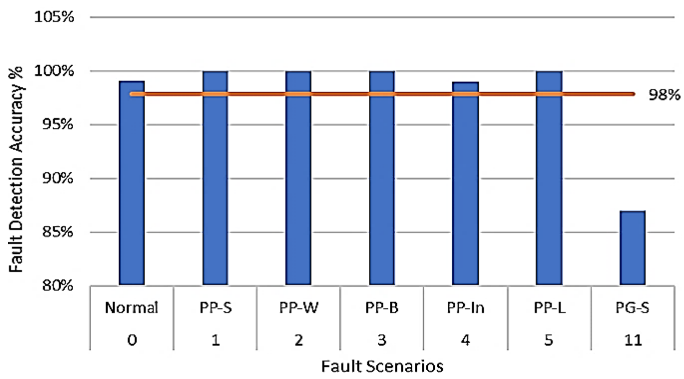

Figure 12. Fault detection accuracy for various faults – with respective labels

6. CONCLUSION

Developing a robust controller with a suitable protection algorithm for detection of fault and protection of hybrid microgrids is very challenging. This paper outlined the reasons for these challenges, discussed through simplified network and simulation results of PP and PG faults. Conventional protection algorithm cannot be applied for microgrid protection owing to its unconventional topology. A novel ML based fine tree algorithm has been proposed and implemented for detection & classification of faults in hybrid AC/DC microgrid structure. The proposed method resulted in fault detection accuracy of 99.04 % for no fault condition, 100% for pole-to-pole fault at solar zone, 100% for pole-to-pole fault at wind zone, 100% for pole-to-pole fault at battery zone (3-PP-B), 99 % for pole-to-pole fault at inverter zone, 100 % for pole-to-pole fault at DC load zone (5-PP-L) and 87 % for pole to ground fault at solar zone (11-PG-S). An overall fault detection accuracy of 98 % is obtained. In future, the work can be extended by realizing internet of things (IOT) based smart controller with proposed algorithm for detection and classification of faults in hardware in loop environment.

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