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ORIGINAL PAPER

A comprehensive protection scheme for micro-grid using fuzzy rule base approach

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Abstract The paper presents a comprehensive primary and backup protection scheme for micro-grid using fuzzy rule base approach. The proposed scheme starts with pre-processing of the retrieved current and voltage signals at both ends of the faulted feeder and adjacent feeder to compute the differential features. The differential features are used to build two separate decision trees (DTs) for the primary and backup protection. The differential features between immediate buses of faulted feeder are considered for primary protection and differential features between far end buses of faulted and adjacent feeders are used to build decision tree for secondary protection. From the developed decision tree classification boundaries, the fuzzy membership functions are generated and the corresponding fuzzy rule base is formulated for final relaying decision. The proposed scheme is tested for numbers of fault and no fault events simulated in the studied micro-grid with wide variations in system parameters and fault parameters in different operating mode. The extensive test results show the efficacy of the proposed protection scheme to provide a reliable protection measure to both primary and backup protection of micro-grid.

Keywords Micro-grid protection · DFT-pre-processor · Decision tree · Fuzzy rule base · Fault detection

1 Introduction

Integration of distributed generations (DGs) has been increasing significantly in the distribution network in recent years due to numerous benefits of renewable energy

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and rapid technological advances in renewable energy sector. The prominent benefits of renewable energy sources such as wind energy, solar energy and fuel cells are the reduced greenhouse gas emission, alternative solution to depleting fossil fuel based energy sources and growing energy demand [1–5]. Further, it offer on-site power generation at the distribution level to supply the industrial as well as domestic load, with reduced distribution losses. The low or medium voltage distribution network with DGs and controllable loads constitute a micro-grid, which can operate in grid connected mode or in islanded mode (grid loss). Thus, it provides improved supply reliability.

Despite the numerous benefits of micro-grid, the protection system may cease to operate due to the dynamic behavior of micro-grid [6,7]. Thus, achieving the desired protection measure becomes very challenging for safe micro-grid operation. The fixed setting overcurrent relays are normally employed for protection of distribution system. However, it may fail providing an adequate protection measure for micro-grid. The overcurrent relays may work efficiently in grid connected mode and may fail in islanded mode due to small fault current contribution in islanded mode [8]. The fault current in grid connected mode is comparatively high due to significant fault contribution from utility. Further, the fault current may vary with the types of DG present in micro-grid [7,8]. The inverter based DGs contributes 1.5 times the rated current of the inverter to the fault whereas synchronous and Doubly Fed Induction Generator (DFIG) DGs can contribute to fault 4–8 times greater than the inverter based DG [8]. Thus, the conventional over current relays employed for micro-grid protection is not an effective and reliable solution for safe operation of micro-grid against faulted conditions [8]. Further, the bidirectional power flows in micro-grid (due to presence of DGs) cease to operate current differential relay as the differential current may be very small or zero.

Several micro-grid protection techniques have been proposed previously. In [9], an adaptive relaying scheme for micro-grid is proposed considering high penetration of DGs, which does not consider the islanded mode of operation. A communication based protection schemes for grid connected micro-grids with an assumption of large amount of fault current contributed from utility grid is proposed in [10,11]. In [12] a microprocessor based protection scheme is proposed, however it does not consider standard micro-grid structure for study. The voltage based protection scheme is proposed in [13]. This technique uses synchronous reference frame to compare the reference of the phase voltage at the DG source [13]. A voltage deviation against the reference initiates the tripping of switching device [13]. In another scheme, the over current differential protection on each line with back up voltage and frequency protection at each DG is proposed in [14]. A differential energy based protection scheme is proposed in [15] which work for micro-grid in grid connected as well as in islanded mode. However, the same scheme suffers from the high computational burden of computing differential energy using S-transform, leading to slower response. Recently a data-mining model based differential protection scheme is proposed [16]. However, it does not consider the secondary protection.

The micro-grid protection technique must ensure safe and reliable operation of micro-grid in different operating mode. The aforementioned protection chal-

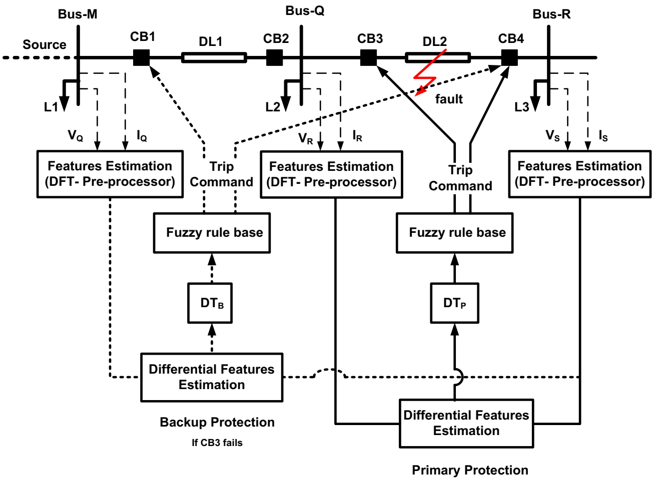

Fig. 1 Proposed comprehensive protection scheme

lenges induce a strong motivation to design a comprehensive protection scheme for micro-grid which can provide a reliable protection measure to primary protection and backup protection, when the primary protection relays fail. The paper presents a comprehensive relaying scheme using fuzzy rule base approach for micro-grid operation. The scheme considered all ten types of shunt faults (a–g, b–g, c–g, ab–g, bc–g, ab, bc, ca and abc) with fault resistance varies from 0.1 to 100 ohm at various locations of distribution lines in grid connected and islanded mode of micro-grid. Similarly, some no fault cases that have similar signature as the fault transient, such as sudden load change, capacitors switching, section cut-off, DG outage etc. are considered at different operating conditions.

The proposed scheme retrieves the voltage and current signals at ends of the feeders and pre-processes it through DFT-pre-processor [16] to extract fault sensitive parameters such as, the voltage (pu/s), the frequency (Hz/s), the power angle difference and the negative sequence Current at both end of the feeder. Further, two sets of differential features are estimated using the features estimated at ends of the faulted feeder and using features estimated at one end of the faulted feeder and far end of the adjacent feeder. Two DTs are generated using the estimated differential features for registering the fault status for primary and backup protection. The schematic diagram of the proposed comprehensive protection scheme for micro-grid is shown in Fig. 1. Bus Q and R are the buses present at two end of the faulted distribution line (DL2), whereas bus-M and Q are the buses associated with the adjacent distribution line (DL1), from source side. The voltage and current signal retrieved at bus R (V_R and I_R) and bus Q (V_Q and I_Q)are pre-processed to estimate the differential features for primary protection. The differential features for the backup protection are estimated using V_M and $I_{M(}$voltage and current signal retrieved at bus M) and V_R and I_R.

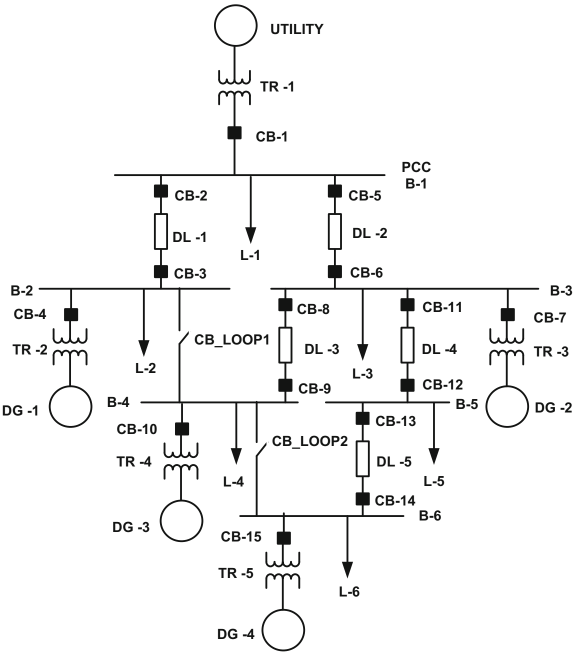

Fig. 2 Studied IEC micro-grid

2 System studied

The standard IEC micro-grid [17,18] structure with DG interfacing considered for the proposed protection scheme is shown in Fig. 2. The base power has been chosen as 10 MVA. The details of the studied system are given as follows:

- Utility: rated short-circuit MVA = 1000, f = 60 Hz, rated kV = 120, $V_{\text{base}} = 120$ kV.
- *Distributed Generations (DGs)*:
  - DG1, DG3: synchronous generator with rated MVA = 9, f = 60Hz, rated kV = 2.4, Inertia constant H = 1.07 s, friction factor F = 0.1 pu, Rs = 0.0036 pu, Xd = 1.56 pu, Xd′ = 0.296 pu, Xd″ = 0.177 pu, Xq = 1.06 pu, Xq″ = 0.177 pu, Xl = 0.052 pu, Td′ = 3.7 s, Td″ = 0.05 s, Tqo″ = 0.05 s.
  - DG2: Wind farm consisting of three 2 MVA wind turbines (6 MW, pf = 0.9), f = 60 Hz, rated kV = 575 V, inertia constant H = 0.62 s, friction factor F = 0.1 pu, Rs = 0.006 pu, Xd = 1.305 pu, Xd′ = 0.296 pu, Xd″ = 0.252 pu, Xq = 0.474 pu, Xq″ = 0.243 pu, Xl = 0.18 pu, Tdo′ = 4.49 s, Tdo″ = 0.0681 s, Tq″ = 0.0513 s. 575 V, 60 Hz. The synchronous generator with inverter interface to main grid has been considered for the proposed study (Type-4 detailed model in MATLAB/SIMULINK).
  - DG4: DFIG based wind farm consisting of six 1.5 MVA wind turbines (9 MVA, pf = 0.9), f = 60 Hz, rated kV = 575 V, Inertia constant H = 0.685 s, friction

factor F = 0.01 pu, Rs = 0.023 pu, Lls = 0.18 pu, $Rr' = 0.016$ pu, $Llr' = 0.16$ pu, Lm = 2.9 pu.

- *Transformers (TRs)*:
  - *TR1*: rated MVA = 50, f = 60 Hz, rated kV = 120 kV/ 25 kV, $V_{base} = 25$ kV,, $R_1 = 0.00375$ pu, $X_1 = 0.1$ pu, $R_m = 500$ pu, $X_m = 500$ pu.
  - *TR2 and TR4*: rated MVA = 12, f = 60 Hz, rated kV = 2.4kV/ 25 kV, $V_{base} = 25$ kV, $R_1 = 0.00375$ pu, $X_1 = 0.1$ pu, $R_m = 500$ pu, $X_m = 500$ pu.
  - *TR3* and *TR5*: rated MVA = 10, f = 60 Hz, rated kV = 575 V/ 25 kV, $V_{base} = 25$ kV, $R_1 = 0.00375$ pu, $X_1 = 0.1$ pu, $R_m = 500$ pu, $X_m = 500$ pu.

3 Features extraction

The proposed study retrieve one cycle post fault voltage and current signal samples at ends of the faulted feeder and feeder adjacent to the faulted feeder of the studied micro grid (in MATLAB/SIMULINK platform). A total number of 2300 fault and no-faults events (1300 for training and 1000 for testing) are simulated considering the various operating conditions mentioned as follows:

(a) Fault cases include the following conditions:
  - Faults on different distribution line (DL1, DL2, DL3, DL4, and DL5) at different location (10–90 %).
  - Fault resistance varies from 1 to 100 ohm.
  - All ten types of shunt faults (ag, bg, cg, abg, bcg, cag, ab, bc, ca and abc) are considered.
  - Fault cases simulated at different operating modes (grid-connected and Islanded) with radial and mesh topology.
  - Fault events are considered with varying the system loads.
  - Faults events are considered while some DGs are out (e.g. DG2 is out).
  - Faults events are considered while some sections are out (e.g. DL1 is out and fault occurs at DL5 with mesh topology).

(b) No fault cases include the following conditions:
  - Sudden load change at PCC and load buses (20 % overloading).
  - Capacitor switching at PCC and load buses.
  - Section cut-off (e.g. DL3 is isolated, R5 and R6 is open and micro-grid operating normally with mesh topology)
  - DG outage (DG1 is out but no fault event in any section of micro-grid)

The fundamental phasor such as amplitude, phase angle and frequency of the voltage and current signals retrieved at ends of the faulted feeder and feeder adjacent to faulted feeders are estimated using DFT based pre-processor [16]. The fundamental phasors estimated at ends of the target feeder are used to compute the fault sensitive differential features. The estimated differential features are used to generate the DTs (primary and backup protection). Further, the fuzzy rule base is developed from the classification boundaries of DT for final relaying decision. In the proposed study, 4 differential features (for both cases) that could be affected during the fault process are derived. These features are measured locally as follows: $Y_{iP} = |Y_{i,RP} - Y_{i,QP}|$ and $Y_{iB} =$

Table 1 The circuit breaker (CB) operate for primary and backup protection

Faulted line	Primary	Backup (radial, grid connected)	Backup (loop, grid connected)
DL1	2–3	**3–1**, 3–6, 2–4	**3–1**, 3–6, 2–4, 2–8, 2–10, 2–13, 2–15
DL2	5–6	**6–1**, 6–3, 5–7, 5–9, 5–12	**6–1**, 6–3, 5–7, 5–9, 5–12
DL3	8–9	9–5, 9–7, 9–12, 8–10	9–5, 9–7, 9–12, 8–10, 8–4, 8–15, 8–2, 8–13
DL4	11–12	12–5, 12–7, 12–9, 11–14	12–5, 12–7, 12–9, 11–14
DL5	13–14	14–11, 13–15	14–11, 13–15, 13–10, 13–4, 13–8, 13–2

The same set of circuit breaker will participate for fault protection in islanded mode except 3–1 and 6–1

$|Y_{i,RB} - Y_{i,MB}|$for primary and backup protection respectively. $Y_{i,P}$ is the ith feature (i = 0, 1, 2..., 5 no. of features) estimated for primary protection, and $Y_{i,B}$ is the ith feature estimated for backup protection. M, R and Q are the end points of the faulted feeder and adjacent feeder where voltage and current signals are retrieved, as shown in Fig. 1. The differential features estimated for primary and backup protection are as follows:

Y_{1P} = ΔV, the differential voltage (pu) for primary protection.
Y_{2P} = Δf, the differential frequency (Hz) for primary protection.
Y_{3P} = ΔPhi, the differential power angle difference for primary protection.
Y_{4P} = ΔIneg, the differential negative sequence current for primary protection.
Y_{1B} = ΔV, the differential voltage (pu) for backup protection.
Y_{2B} = Δf, the differential frequency (Hz) for backup protection.
Y_{3B} = ΔPhi, the differential power angle difference for backup protection.
Y_{4B} = ΔIneg, the differential negative sequence current for backup protection.

A total four data set are generated, out of which two data sets are used for training of the DT for primary and back up protection from which the rule base is developed. Further, the rule base is tested with other two data sets for validation of the proposed scheme. The possible pair of end points (circuit breaker location/bus) used to estimate the differential features are depicted in Table 1.

4 Implementation of the proposed scheme for primary protection

4.1 Building the DT for primary protection

The DT is an efficient and popular classification tool for high dimensional data spaces [19–23]. Being rule base, DT is more transparent and easy to implement as compared to the black-box solutions, such as neural network, random forest and support vector machine. Thus, it attracts wide spread attention in solving classification and decision making [21–23] problems of most engineering applications. The proposed work uses the open source data mining software package 'R' for generating the DT [24]. The schematic of the proposed protection scheme is shown in Fig. 1. The one cycle post fault instantaneous current and voltage signals are retrieved at ends of the faulted

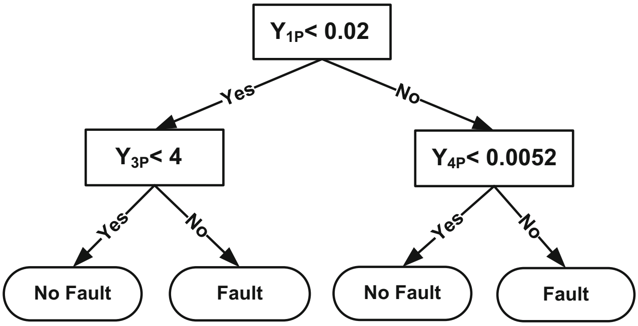

Fig. 3 DT generated for fault detection (primary protection)

feeder and pre-processed through DFT pre-processor [20] to estimates the differential features. The differential features are used to train the DT. Four differential features are used to build the DT for primary protection. All four features are set as input against one target output either of 1 (for fault) or 0 (for no-fault) for a particular instant. The feature set at particular instant is passed through the DT and the process continues till convergence. The DT is trained using the training data set generated considering the operating conditions mentioned in Sect. 3. Further, performance assessment is carried out using the testing data set.

The differential features (set) used to build the DT are computed using both end data of the faulted line, as depicted in Table 1. For a fault at DL2 primary protection parameters computed using buses 5 and 6 (5–6) only. Thus, the number of cases considered for training and testing of the DT is equal to the number of events generated. The proposed study (study of primary protection) considered a total of 1300 cases (1000 fault cases and 300 no-fault cases) for training and 1000 cases (800 fault cases and 200 no-fault cases) for testing generated considering the various operating conditions as mentioned in Sect. 3. The DT generated for primary protection is shown in Fig. 3. From Fig. 3, it is observed that $Y_{1P}(\Delta V)$, Y_{3P} (ΔPhi) and $Y_{4P}(\Delta \text{Ineg})$, features are participating in the final decision making process. Thus, these 3 features are the most significant features impacting the fault and no fault classification.

4.2 DT transformation to fuzzy rule base

The DT generated using the differential features provides initial rule base for fault and no fault classification with sharp boundaries. However, the sharp boundaries based rule base may susceptible to noise and uncertain conditions as expected in power system [25]. This problem is alleviated by applying fuzzy theory to the test node of DT (having crisp boundaries). Thus, the partitions become a series of fuzzy regions and the sharp boundaries used by the crisp DT cease to exist [25–29]. The proposed scheme is aim to relax the sharp decision boundaries of DT by introducing fuzzification. This introduces a pair of membership functions at each decision node, where each attribute (feature) is represented by a fuzzy set. The decision space is fragmented with a number of overlapping fuzzy regions (membership functions) [25,26]. For classification of a

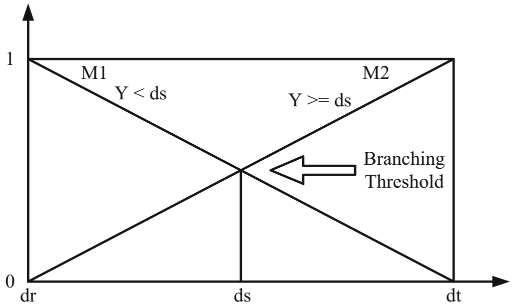

Fig. 4 Assignment of membership grades for two complementary membership functions M1 and M2 over domain dr. . .dt for attribute i

particular case, all branches are fired to some degree. The degree of membership at each branch for a given attribute value depends upon the coverage of the fuzzy set for that particular branch [26,27]. The fuzzy region around any decision node in a crisp DT is defined using a pair of complementary membership functions M_1 and M_2 around decision threshold ds as shown in Fig. 4 [25]. Figure 4 shows two complementary membership functions over the domain dr . dt of attribute i, where ds_i represents the branching threshold of attribute i. A specific value Y of attribute i, passing through the DT assigned a membership grade based on its proximity to ds_i [25,26]. Each membership function is having an associated domain (dr_i, dt_i) whose scope is determined by the attribute at each specific branch as defined as [25].

$$dr_i = ds_i - p_j \sigma_i \tag{1}$$

$$dt_i = ds_i + p_{j+1} \sigma_i \tag{2}$$

where σ_i, is the standard deviation of attribute i, p is a real number, $p \to [0.0, \infty]$ used to determine the effect of σ_i on the membership function domain and dr, dt are the lower and upper bounds of membership function, respectively. In practice ‘p’ remains typically small, $p \to [0.0, 5]$. This is because the large value of ‘p’ introduces too much fuzzification into the tree and the process of making the decision becomes too vague [25].

The fuzzy membership functions are developed from the partition boundaries of the DT and transform the DT to a fuzzy rule base. The triangular MFs [25] are developed for each independent variable from the DT boundaries. For the proposed protection scheme, a fuzzy interface models has been programmed in MATLAB environment. Each feature at test node ($\mathbf{Y}_{1P}$,$\mathbf{Y}_{3P}$ and $\mathbf{Y}_{4P}$) of the DT generated for primary protection are associated with two triangular membership functions [A_1, A_2], [B_1, B_2] and [C_1, C_2] respectively. All the membership functions are defined using (1) and (2). The fuzzy rule base is developed directly using the simple if-then-else decision logic at each and every test node of the trained DT. For example ‘If $\mathbf{Y}_{1P}$ is A_1 and $\mathbf{Y}_{3P}$ is B_1, then it is a No-fault situation (0)’. The proposed algorithm does not have any output membership function. The resulting classification is a mathematical combination of the rules. The developed fuzzy rule base for primary protection is depicted in Table 2. While testing with the same data set (as for DT) of 1000 cases (800 fault cases and 200 no-fault cases), the fuzzy rule base results, out of 800 fault cases 796 cases are

Table 2 Rule base developed for primary protection

Rules	$\mathbf{Y}_{1P}$	$\mathbf{Y}_{3P}$	$\mathbf{Y}_{4P}$	Fault (1)/no fault (0)
R-1	A_1	B_1	0	0
R-2	A_1	B_2	0	1
R-3	A_2	0	C_1	0
R-4	A_2	0	C_2	1

classified correctly and 4 fault cases are misclassified, whereas three no fault cases are misclassified as fault.

4.3 Results and analysis

The following reliability measures are used, to assess the performance of the proposed fault protection scheme.

- *Dependability* Total number of fault cases predicted/total number of actual fault cases. [16]
- *Security* Total number of no fault cases predicted/total number of actual no fault cases. [16]
- *Accuracy* Total number of correctly predicted (fault + no fault) cases/total numbers of actual (fault + no fault) cases. [16]

For fault protection relay, dependability is the important index to be assessed as it shows the “mis-detection” cases, which give the number of case, actually belong to fault but detected as no fault events. Security shows the “false-alarm” which indicates the number of no-fault cases predicted as fault [16]. “Mis-detection” is more critical compared with “false-alarm” in relaying task [19–25]. Finally, accuracy represents the measure of correctly predicted cases for both fault and no fault events.

The performance test results of the proposed relaying scheme (primary protection) for fault detection in different operating mode (grid connected or islanded) with radial network topology are shown in Table 3. The test data set includes a total number of 500 cases (200 fault events and 50 no fault cases in grid connected mode, whereas 200 fault events and 50 no fault cases) in radial topology. Table 3 depicted the performance test results in radial topology. It is observed from the Table 3 that the proposed scheme has accuracy of 100 % (with dependability 100 % and security 100 %) for fault detection

Table 3 Performance of the proposed scheme for fault detection in different operating mode with radial topology (primary protection)

	Grid connected	Islanded
Dependability (%)	100	99.5
Security (%)	100	98
Accuracy (%)	100	98.75

Table 4 Performance of the proposed scheme for fault detection in different operating mode with mesh topology (primary protection)

	Grid connected	Islanded
Dependability (%)	99.5	99
Security (%)	100	98
Accuracy (%)	99.75	98.5

in grid connected mode, whereas accuracy becomes 98.75 % (dependability 99.5 % and security 98 %) in islanded mode with radial topology.

Similarly Table 4 depicted the performance test results for fault detection in different operating mode with mesh topology. This performance assessment test include 500 cases (200 fault events and 50 no fault cases in grid-connected mode, whereas 200 fault events and 50 no fault cases in islanded mode) with mesh topology. It is observed from the Table 4 that proposed scheme has accuracy of 99.75 % (with dependability 99.5 % and security 100 %) for fault detection in grid-connected mode and has accuracy of 98.5 % (with dependability 99 % and security 98 %) in islanded mode with mesh topology. Thus, the proposed relaying scheme works reliably (with dependability more than 99 %) in different operating mode with radial and mesh topology of micro-grid (for primary protection).

5 Implementation of the proposed scheme for backup protection

5.1 Building the DT for backup protection

The previous section shows the efficacy of the proposed multiple features based differential protection scheme. However, the proposed differential protection scheme provide protection to the entire line with a protection measure (dependability) as high as 99 %, it may fail due to the failure of the circuit breaker, CT/PT and the relay (trip battery). Thus, to achieve a reliable protection measure, each primary protection relay must be equipped with a second line of protection (backup protection) to substantiate in case the primary protection fails. The primary and back up protection relay starts operating simultaneously [30,31]. However, normally the trip signal is sent to the backup protection relay after a time delay of 0.2 s [31]. The differential relaying needs a communication link between the both ends of the feeder to compute the relaying quantity (differential quantity). Thus, fiber optics link is a suitable candidate, which takes less than 0.1 ms for transmission under distance of 30 km (18 miles), and it needs no time synchronization between both the buses [32].

Similar process (as in primary protection) is carried out to build the DT for back up protection. The voltage and current signals at one end of the faulted feeder and distant end of the adjacent feeder (adjacent to the faulted feeder) are retrieved at same time stamp (after one cycle of fault event inception, as the primary protection and backup protection start operating simultaneously) and processed through DFT-preprocessor to estimate the differential features. Further, the estimated differential features are used to build the DT for backup protection. The features are set as input against one target output of 1 (for fault) or 0 (for no-fault situation). Two data sets are generated, one for training and other for testing from the fault and no-fault events simulated.

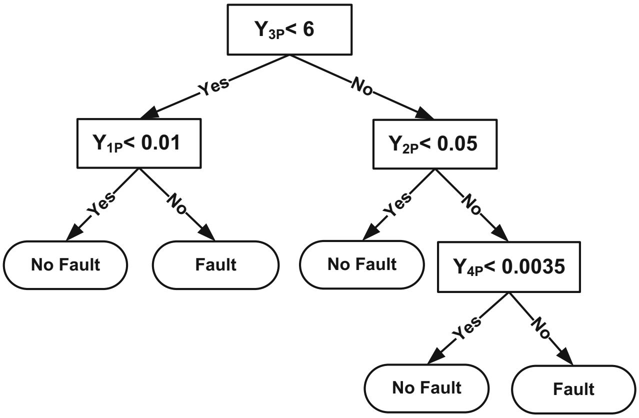

Fig. 5 DT generated for fault detection (backup protection)

The faulted line may have one primary relay (differential) and one or more than one backup relays. For a fault at DL1, it has one primary relay (2–3) and three backup relays such as 3–1, 3–6 and 2–4 (radial network topology with grid-connected mode) as depicted in Table 1. Thus, study of backup protection considered more number of cases compared to primary protection. The backup protection considered 5980 cases (4600 fault and 1380 no-fault) for training and 4600 cases (3680 fault and 920 no fault) for testing. The DT generated for Backup protection is shown in Fig. 5. From Fig. 5, it is observed that, four features as: $Y_{1B}(\Delta V)$, $Y_{2B}(\Delta f)$, Y_{3B} (ΔPhi) and Y_{4B} (ΔIneg) are participating in the fault and no fault classification for backup protection.

5.2 DT transformation to fuzzy rule base

Similar procedure is adopted (as used in primary protection) to generate the rule base from the crisp boundaries of developed DT for backup protection. Triangular MFs [23–27] are developed for each independent variable of the DT boundaries. Each features of DT for backup protection ($\mathbf{Y}_{1B}$, $\mathbf{Y}_{2B}$,$\mathbf{Y}_{3B}$ and $\mathbf{Y}_{4B}$) are associated with two triangular membership functions [E_1, E_2], [F_1, F_2], [G_1, G_2] and [H_1, H_2] respectively. Table 5 depicted the rule base developed for backup protection.

Table 5 Rule base developed for backup protection

Rules	$\mathbf{Y}_{1B}$	$\mathbf{Y}_{2B}$	$\mathbf{Y}_{3B}$	$\mathbf{Y}_{4B}$	Fault (1)/no fault (0)
R-1	E_1	0	G_1	0	0
R-2	E_2	0	G_1	0	1
R-3	0	F_1	G_2	0	0
R-4	0	F_2	G_2	H_1	0
R-5	0	F_2	G_2	H_2	1

Table 6 Performance of the proposed scheme for fault detection in different operating mode with radial topology (backup protection)

	Grid connected	Islanded
Dependability (%)	100	99.69
Security (%)	100	100
Accuracy (%)	100	99.845

Table 7 Performance of the proposed scheme for fault detection in different operating mode with radial topology (backup protection)

	Grid connected	Islanded
Dependability (%)	99.75	99.82
Security (%)	100	100
Accuracy (%)	99.875	99.91

5.3 Results and analysis

The performance assessment for backup protection is carried with the test data set of 4600 cases (3680 for fault + 920 for no fault). The test result in different operating mode (grid connected or islanded) with radial topology are depicted in Table 6. This test data set includes a total number of 900 cases (720 fault +180 no fault) in grid connected mode and 800 cases (640 fault + 160 no fault) in islanded mode with radial topology. It is observed that proposed protection scheme has accuracy of 100 % (with dependability 100 % and security 100 %) for backup protection in grid connected mode and accuracy of 99.845 % (with dependability 99.69 % and security 100 %) for backup protection in islanded mode with radial topology. Further, the performance assessment is carried out for fault detection in micro-grid with mesh topology. Table 7 depicted the performance results for backup protection in different operating mode of micro-grid with mesh topology. This includes 1500 cases (1200 fault + 300 no fault) in grid connected mode, and 1400 cases (1120 fault + 280 no fault) in islanded mode with mesh network. It is observed from the Table 7 that proposed technique has accuracy of 99.875 % (with dependability 99.75 % and security 100 %) in grid connected mode and has accuracy of 99.91 % (with dependability 99.82 % and security 100 %) in islanded mode of operation with mesh topology. This shows the potential ability of the proposed relaying scheme for backup protection in different operating mode and topology.

6 Discussion

The proposed fuzzy rule base approach of differential relaying scheme found an efficient fault detection technique for both primary and backup protection with dependability more than 99 % for micro-grid operating in different mode (grid connected and islanded mode) with radial and mesh network. A qualitative performance comparison is made (with SNR 20dB, as power system may have noise of SNR 20 dB) between the proposed (fuzzy rule base) relaying scheme with the existing current differential relay and DT based relay. Table 8 depicted the dependability comparison between the proposed relaying scheme and existing relays for fault detection (primary and backup)

Table 8 Dependability comparisons between proposed relaying scheme with existing relays, radial topology (with SNR 20 dB)

	Grid connected (%)	Islanded (%)
Primary protection		
Fuzzy rule base	98.5	98
DT based	89.5	85.5
Current differential	60.5	62
Over current	21	19
Backup protection		
Fuzzy rule base	98	97.5
DT based	92.5	88.5
Current differential	62.5	63.12
Over current	22.5	21

Table 9 Dependability comparisons between proposed relaying scheme with existing relays, mesh topology (with SNR 20 dB)

	Grid connected (%)	Islanded (%)
Primary protection		
Fuzzy rule base	98	96.5
DT based	92.5	91
Current differential	61	62.5
Over current	21.5	20
Backup protection		
Fuzzy rule base	98.61	97.96
DT based	90	89.29
Current differential	64	60.98
Over current	23	21.875

in different operating mode of micro-grid with radial network topology. It is observed that performance (dependability) of proposed relay (in both primary and backup protection) is low in islanded mode compare to grid connected mode for radial topology. However, dependability of the proposed relaying scheme is more than 97 % in both operating conditions for primary and backup protection, which is significantly high compare to other relays.

Table 9 depicted the dependability comparison between the proposed relay and existing relay for fault detection in different operating mode of micro-grid with mesh topology. It is observed that proposed relay provide dependability more than 96 % for fault detection in mesh topology. Thus, the proposed relay has better performance (for both primary and backup protection) than the existing relays for micro-grid in different operating mode with radial and mesh topology.

Table 10 Performance assessment of the proposed fuzzy rule base approach with the existing current differential relay

	Grid-connected mode		Islanded mode	
Fault conditions	CB at end-1	CB at end-2	CB at end-1	CB at end-2
Primary protection				
Current differential current relay				
a–g fault on DL3 (radial)	CB8 operates	CB9 operates	CB8 operates	CB9 operates
abg fault on DL4 (mesh)	CB11 operates	CB12 operates	CB11 fails	CB12 fails
Proposed data-ming based differential relay				
a–g fault on DL3 (radial)	CB8 operates	CB9 operates	CB8 operates	CB9 operates
ab fault on DL4 (mesh)	CB11 operates	CB12 operates	CB11 operates	CB12 operates
Back up protection				
Current differential current relay				
	While CB8 and CB11 fails due to some reasons			
a–g fault on DL3 (radial)	CB5 operates	CB9 operates	CB5 operates	CB9 operates
abg fault on DL4 (mesh)	CB5 operates	CB12 operates	CB5 fails	CB12 fails
Proposed data-ming based differential relay				
a–g fault on DL3 (radial)	CB5 operates	CB9 operates	CB5 operates	CB9 operates
abg fault on DL4 (mesh)	CB5 operates	CB12 operates	CB5 operates	CB12 operates
End 1	CB2, CB5, CB8, CB11, CB13			
End 2	CB3, CB6, CB9, CB12, CB14			

The aforementioned performance assessment is carried out using 2300 fault and no-fault events simulated at different operating conditions (as mentioned in Sect. 3) and it is observed that the proposed relaying scheme provides dependability more than 99 % (without noise) and more than 96 % with noise (SNR 20dB) at different operating conditions which is comparatively better than the performance of existing protection relays (over current and current differential relay). However, a large number of data can be used to build the DT for further improvement in the performance of the proposed scheme. Table 10 depicted the performance comparison of the proposed fuzzy rule base relay for both primary and backup protection with the existing current differential relay for specific fault situations.

7 Conclusion

A comprehensive protection scheme using fuzzy rule base approach has been proposed for micro-grid (primary and backup protection) operating in different mode with radial and mesh topology. The proposed relaying scheme is extensively tested for studied micro-grid model operating at different modes with changing system conditions. The performance assessment test indicates the effectiveness of the proposed relaying scheme. It provides performance (dependability) more than 97 % for radial topology and more than 96 % for mesh topology (considering a noise of 20dB SNR) with a relaying speed of less than 1 and 1/2 cycle (one cycle post fault data for preprocessing through DFT-processor, less than 1/2 cycle to derive differential features plus data-mining processing) for primary protection and 2 and 1/2 cycles (primary protection plus 0.2 s delay) for backup protection. Thus the fuzzy rule base relaying scheme is a reliable protection scheme for micro-grid operating in different mode with different network topology.

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