Abstract
The high impedance faults (HIF) in microgrids are characterized by low magnitude fault current with inherent non-linearity and random behavior. The possible weather intermittency in PV integrated microgrids and the intrusion of harmonics due to power converters and non-linear loading, further reduce the fault current during HIF. The insignificant fault current does not allow detection of HIF by conventional overcurrent relays. In this regard, a reliable and robust protection scheme based on the combined framework of probabilistic modelling, least square and Adaline algorithm, sine cosine algorithm (SCA) and support vector machine (SVM), has been proposed to perform the tasks of mode detection, fault detection/classification and section identification during HIF in microgrid. The algorithm involves online extraction of harmonic components and stochastic modelling of intermittency in solar irradiance. The performance of the proposed scheme has been analysed in terms of robustness against harmonics intrusion and weather intermittency during HIF. The performance comparison of the proposed scheme with the decision tree (DT) and classical SVM based techniques reflects its effectiveness with improved immunity against harmonic intrusion and weather intermittency. Further, the proposed scheme has been validated using OPAL-RT digital simulator for evaluating its appropriateness in real-time settings.

1 | INTRODUCTION

With the substantial growth in the power demand and rising awareness towards minimizing carbon emission, the concept of power generation has witnessed a steady shift from the bulk centralized generation to distributed generation [1]. The concept of distributed generation has led to the evolution of an alternative platform involving low or medium distribution network, comprising of distributed energy resources (DERs) and clustered loads commonly referred to microgrid [2, 3]. Microgrid operation offers a seamless transition between the two modes, i.e. grid-connected and islanded, based on the power exchange between the microgrid and utility grid at the point of common coupling. Among the renewable DERs, photovoltaic (PV) based sources are most commonly used due to their widespread availability, economic viability and ease of operation [4].

The wide utilization of DERs in the microgrid, causes several protection issues, due to intermittent operating characteristics of the weather-dependent renewable DERs. Further, the distinct level of fault current contribution from inverter-interfaced and synchronous DERs along with the divergent variation in the voltage–current profile during grid-connected and islanded modes of operation, makes the protection task difficult [5]. The low magnitude of fault current during islanded mode is further reduced during high impedance fault, thereby increasing the challenge in achieving reliable protection. High impedance faults generally develop because of the fault path arising due to the poor contact and incidental connection of the conductor with highly resistive surfaces such as sand, soil or asphalt. The magnitude of fault current during high impedance fault is insufficient to be sensitized by the classical overcurrent based protection devices. The fault current is further reduced if high
impedance fault is accompanied by harmonics, since the intrusion of harmonics contributes to the line impedance.

Harmonics in microgrid result from the high amalgamation of power electronic converters and non-linear loads.

In addition to this, the weather intermittency associated with PV-based DERs, cause random fluctuations in the solar irradiance levels, leading to subsequent variation in the current. If HIF during the islanded mode, is coupled with low PV irradiance levels, the insignificant/ minor variation in the fault current might be detected as a healthy scenario or a power quality disturbance, thus leading to relay maloperation. In this regard, the present work aims at the development of a reliable microgrid protection scheme for HIF with robustness against harmonic intrusion and weather intermittency.

In the past few years, several schemes have been proposed for the detection of high impedance faults in distribution networks. Some of the significant among them include the ensemble of decision tree-based approach [6], fuzzy-based detection methodology [7], wavelet transform based techniques [8–12] and decision tree based method [13]. However, all the above-reported techniques have been implemented for the power distribution networks, and none of them has been extended for microgrids. For the protection of microgrid against HIF, a comprehensive protection strategy for islanded microgrid [14] and Hilbert-Huang transform based scheme [15] have been proposed. However, the reliability of both the approaches have not been investigated during the presence of harmonics and weather intermittency of renewable DERs. A protection strategy based on the convolutional neural network for islanded microgrid [16] has considered the weather intermittency of PV-based DER. Another protection approach based on the probabilistic modelling of weather intermittency in renewable DERs has been validated for high resistance faults [17]. However, the developed schemes has not been extended for detection of HIF. Also the impact of harmonic intrusion on the performance of the protection scheme was not analysed.

The low magnitude of the fault current along with its dependence on the operating mode, the extent of harmonic intrusion, intermittent solar irradiance and the possible nature of connection between the conductor and surface which is conducive for high impedance faults, hinders the use of classical overcurrent relays based on fixed threshold settings. An adaptive protection scheme based on the continuous tuning of the threshold values, though capable of addressing the above issues over a certain range, may not offer reliable protection over wide and frequent variations in the irradiance levels and non-linear loading induced harmonic levels. Further, the high randomness in weather intermittency causes difficulty to the adaptive protection schemes in continuously updating the settings in accordance with the varying dynamics of the sources. Though the schemes proposed in [16, 17] have considered weather intermittency, however reliability is compromised during HIF due to the non-linear and random behaviour. The protection schemes utilizing RMS or fundamental voltage–current information, get adversely affected during the presence of harmonics. The use of harmonic information allows proper discrimination of healthy and faulty scenarios. Thus, achieving a high degree of reliability in detecting HIF during harmonics and solar irradiance variation, demands incorporating the randomness in weather intermittency and utilizing the harmonic information [18].

The review of existing literature on detection of high impedance faults reveals that none of the existing techniques have simultaneously addressed all the following issues:

(i) Imparting immunity to the protection scheme against weather intermittency for PV-integrated microgrids.
(ii) Maintaining reliability in relay operation by avoiding trip signal generation during wide variation in the loading condition.
(iii) Performing both HIF detection and section identification under islanded and grid-connected mode.
(iv) Utilizing harmonic information for rapidity in generating trip signal after inception of HIF.

In view of the above-mentioned concerns, an efficient protection approach utilizing the harmonic information of current has been adopted in the present work.

Motivated by the need to develop a protection scheme to address the twin issues, the fault detection and classification task has been achieved in the present work by modelling the stochastic variation in solar irradiance using meteorological data based probabilistic modelling and extracting the harmonic information in the post fault current profile using least square and Adaline algorithm. The parameter-less least mean square approach is used for estimating the harmonic attributes from the sampled current signals. The attributes calculated recursively in real-time are immune to noisy sensor measurement. Further to the acquisition of harmonic based attributes, the protection task has been framed as a classification problem that aims at the mapping between the feature space and state (healthy/faulty, type of fault) of the microgrid. Motivated by the effectiveness of support vector machines (SVM) in solving complex classification problems, it has been used in the present work to perform the intended protection tasks of fault detection/classification and section identification. The classical SVM, in spite of being effective for solving complex problems in multi-dimensional space, suffers from the limitation of being highly sensitive to the selection of their hyper-parameters. The selection is generally carried out on a trial and error with the aim of maximizing classification accuracy, which is a tedious and time-consuming process. In this context, a population based optimization technique, i.e. sine cosine algorithm (SCA) has been used in the present work for deriving the optimal architecture of the SVM.

The main contributions/highlights of the proposed work can be outlined as:

(i) A protection scheme based on the combined framework of least square and Adaline algorithm, SCA and SVM, has been proposed to perform the detection/classification and section identification of high impedance faults under both operating modes of microgrid (grid-connected and islanded).
(ii) The issues pertaining to the impact of weather intermittency and harmonic intrusion in microgrid protection has
been respectively addressed by modelling the randomness in weather intermittency and the extraction of harmonic information.

(iii) The developed scheme involves online estimation of harmonic component of the current signal using least square and Adaline algorithm and the stochastic modelling of intermittency in solar irradiance using a probability distribution function.

(iv) The performance of proposed protection scheme has been extensively validated in terms of its robustness against weather intermittency and harmonic intrusion.

The remaining portion of the paper is organized as follows: The brief description of microgrid system considered under study with HIF modelling is included in Section 2. The solar irradiance uncertainty modelling is discussed in Section 3. The development of joint framework of least square and Adaline algorithm, SCA and SVM based protection scheme is described in Section 4. The performance evaluation is carried out in Section 5, followed by the concluding remarks in Section 6.

2 STUDIED MICROGRID SYSTEM

The single line diagram of microgrid system considered under present study is depicted in Figure 1(a) [19]. It has been modelled and simulated, using MATLAB/Simulink environment. The studied microgrid system operates at 34.5 kV, 60 Hz with two DERs namely, photovoltaic (PV) and synchronous generator (SG) connected at buses B3 and B4 respectively. The transition between the two modes of operation is carried out using the static switch at the point of common coupling (PCC), which acts as a link between the microgrid and the utility grid for bidirectional power exchange.

The distribution network comprising a pair of lines is divided into four sections (S1, S2, S3 and S4) with each line stretched over a length of 20 km. The loads connected to the distribution network are represented by L1, L2, L3, L4 and L5. The parameter details of the microgrid system are listed in Table 1. To analyse the effect of harmonic intrusion due to non-linear load switching, the rectifier fed loads are considered in the system. The synchronous generator (SG) remains disconnected during grid-connected mode of operation whereas, during the islanded mode, both DERs are put into the operation to feed the loads.

The occurrence of high impedance faults are characterized by abnormal events involving non-linearity and arcing phenomena. In order to analyse the performance of the proposed protection scheme against high impedance fault scenarios, a simple 2-diode model of HIF [10] has been simulated as depicted in Figure 1(b). The HIF model contains a pair of anti-parallel diodes \( D_p \) and \( D_n \), non-linear variable resistors \( R_p \) and \( R_n \) and DC sources, \( V_p \) and \( V_n \). The DC sources in the HIF model represent the inception voltage of air in the ground surface (soil) and the conductor whereas the variable resistors represent the fault resistances. The distinct values of resistors allow the modelling of the asymmetrical profile of fault current. When the phase voltage \( V_{\text{phase}} \) is greater than \( V_p \), the direction of fault current is

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**TABLE 1** Parameter details of the microgrid system under study

| Component     | Parameter               | Specification                  |
|---------------|-------------------------|--------------------------------|
| Microgrid     | System parameters       | 34.5 kV, 60 Hz                 |
| Distribution line | Positive sequence impedance \((\Omega/km)\) | 0.0178 + j0.314 |
| Distribution line | Zero sequence impedance \((\Omega/km)\) | 0.295 + j0.04 |
|                | Length of sections S1 and S3 | 8 km                          |
|                | Length of sections S2 and S4 | 12 km                         |
| DER           | Rating of PV generator  | 9.2 MW                         |
| DER           | Rating of synchronous generator | \( Z_{sg} = 27.5 \angle 80^\circ \), \( \angle V = 0.5^\circ \) |
| Loads         | L1                      | 1 MW                           |
| Loads         | L2                      | 4.5 MW + 0.6 MVAR              |
| Loads         | L3                      | 3 MW + 0.3 MVAR                |
| Loads         | L4                      | 4.5 MW + 0.6 MVAR              |
| Loads         | L5                      | 6 MW + 0.15 MVAR               |

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**FIGURE 1** Microgrid under study (a) Single line diagram, (b) two-diode HIF model
FIGURE 2  (a) Variation in the level of current at bus B4 in the faulty phase ‘A’ due to non-linear load switching at 0.4 s followed by the inception of HIF at 0.5 s during islanded mode. (b) Corresponding RMS value and (c) fundamental component towards the ground whereas, the direction is reversed in case of $V_n$ being less than the phase voltage ($V_{\text{phase}}$). During the condition, $V_n \leq V_{\text{phase}} \leq V_p$, no fault current flows.

In order to demonstrate the variation in the level of fault current due to HIF inception with harmonic intrusion, distinct situations including, non-linear load switching and a line-ground HIF inception, has been simulated in Figure 2(a). The corresponding RMS value and fundamental component has been depicted in Figure 2(b) and (c) respectively. The HIFs display high degree of randomness with fluctuation in current levels. Unlike faults with medium or low resistance, the post-fault waveform in Figure 2 is characterized with unequal positive and negative half cycles. Also a substantial variation in the fundamental and RMS value of current is observed.

3 | SOLAR IRRADIANCE UNCERTAINTY MODELLING USING PROBABILITY DISTRIBUTION FUNCTION

As mentioned earlier, the uncertainty in solar irradiance level due to weather intermittency causes subsequent fluctuations in the current profile, which quite often leads to the mal-operation of classical overcurrent relays. So, in order to incorporate the randomness in solar irradiance into the proposed protection algorithm to avoid possible relay mal-operation, the present work involves stochastic modelling of solar irradiance using an appropriate probability distribution function (PDF). In this regard, the annual solar irradiance data [20] in the range of 100–1000 W/m² considered over a set of locations in the United States of America, has been recorded with hourly resolution and modelled using Gaussian distribution function [21] as:

$$f(\varphi) = \frac{1}{\sqrt{2\pi}\sigma^2} \exp\left[-\frac{0.5(\varphi - \mu)^2}{\sigma^2}\right]$$  (1)

where $\sigma$ and $\mu$ respectively represent the standard deviation and mean of the PDF. The number of healthy/faulty scenarios to be included in the training dataset corresponding to each irradiance level, is simulated in accordance with the derived PDF model (Figure 3) The total number of scenarios thus generated constitutes the input dataset for the SCA-optimized SVM classifier, to perform the intended protection tasks of fault detection/classification and section identification.

4 | MICROGRID PROTECTION USING STOCHASTIC WEATHER MODELLING AND ONLINE HARMONIC EXTRACTION

As discussed earlier, the intermittent operating profile of renewable DERs, distinct level of fault current contribution from DERs, divergent variation in current profile in the dual operating modes of microgrid, harmonic intrusion in the current...
profile due to non-linear loading make the protection task challenging. Further, the challenges pertaining to a very low level of fault current particularly in the islanded mode due to high impedance faults under the presence of harmonics and intermittency in solar irradiance, demand a fast and reliable protection scheme. In this regard, a protection scheme based on the combined framework of least square and Adaline algorithm, SCA and SVM has been proposed to perform the intended protection tasks for both grid-connected and islanded operation.

The proposed protection scheme involves the extraction of discriminatory attributes from the three-phase instantaneous current signals retrieved from the relaying bus, using least square and Adaline algorithm. The fundamental and harmonic components of post fault current signals, constitute the input feature vector for the training of the SCA-optimized SVM classification models to perform the tasks of fault detection, classification and faulty section identification under grid-connected and islanded modes of operation. The stages involved in the development of the proposed protection scheme are described in the following sub-sections:

4.1 Least square and Adaline algorithm based feature extraction

The harmonic information contained in the current signal post fault, gives an idea regarding the state of the microgrid (healthy/faulty). Keeping this in mind, the fundamental and harmonic components of current signal has been considered as the input attributes to discriminate among the healthy and faulty scenarios, since it can provide the distinct characteristics in both the situations. Thus, due to the effectiveness of fundamental and harmonic information in providing discriminatory information regarding the state of the microgrid, the proposed approach which is based on the combined framework of least square and Adaline algorithm, involves the estimation of the magnitude of harmonics (3rd, 5th and 7th) and fundamental component of the current signal.

The post-fault current signal can be represented as

\[
I(t) = \sum_{n=1}^{N} i_n \sin (\omega t + \theta_n) + A_0 + C(t)
\]

(2)

where \(T_s\) represent the sampling time of the current signal.

The harmonic estimation task involves the extraction of magnitude \(i_n\) and phase \(\theta_n\) of the harmonic frequency component of the measured samples \(I(k)\), for a given \(N\). The non-linearity introduced by the sinusoidal term does not allow the direct estimation of features by obtaining a closed form solution of Equation (3). In this regard, the tasks of estimating the fundamental and harmonic components from the discretized current signal Equation (3) have been formulated as the parameter estimation task and solved using a two-stage process involving Adaline neural network and the standard least square based algorithm. The first stage involves the estimation of phase corresponding to each frequency component using the Adaline network [22]. The initialization of single-layer network is carried out with random weights which is updated iteratively till the desired output is achieved. The input to network is given as

\[
X(k) = [i_1 \sin(k \omega T_s) \ i_1 \cos(k \omega T_s) \ ... \ i_n \sin(k \omega T_s) \ i_n \cos(k \omega T_s) 1]
\]

(4)

and the corresponding weight vector is assumed as

\[
W = [\omega \theta_1 \sin \theta_1 \ ... \ \omega \theta_n \sin \theta_n \ A_0]
\]

(5)

The estimation of phases \(\theta_1, \theta_2, ..., \theta_n\), involves the search for optimal weight vector, \(W\) for which the following objective function is minimized

\[
J = \sum_{k=1}^{N_s} (I(k) - X(k) W)^2
\]

(6)

where \(N_s\) represents the number of current samples. Initializing with a random weight vector, the objective function Equation (6) is minimized by iteratively updating the weight vector using modified Widrow–Hoff delta rule [23] till the convergence criteria is attained. Post convergence of the algorithm, the phases corresponding to each frequency component are determined from the weight vector as

\[
\theta_n = \tan^{-1} \left( \frac{|W|_2}{|W|_{2n-1}} \right)
\]

(7)

The estimation of phasor values is followed by obtaining the amplitude of the corresponding harmonic component using the standard linear least square algorithm.

The sampled Equation (3) can be rewritten as

\[
I(k) = H(k) X + C(k)
\]

(8)

where \(H(k)\) represents the system matrix and \(X\) corresponds to the vector of unknown parameters \((i_1, i_2, ..., i_n, A_0)\) to be estimated. Using a window of \(n+1\) measurements, Equation (8) can be further written as

\[
\begin{bmatrix}
\sin (2\pi f T_s + \theta_1) \\
\sin (2\pi f 2T_s + \theta_1)
\end{bmatrix} \cdots 
\begin{bmatrix}
\sin (2\pi f T_s + \theta_n) \\
\sin (2\pi f 2T_s + \theta_n)
\end{bmatrix} \cdots 
\begin{bmatrix}
\sin (2\pi f kT_s + \theta_1) \\
\sin (2\pi f kT_s + \theta_2)
\end{bmatrix} \cdots 
\begin{bmatrix}
\sin (2\pi f kT_s + \theta_n) \\
\sin (2\pi f kT_s + \theta_n)
\end{bmatrix} \begin{bmatrix}
i_1 \\
i_2 \\
i_n \\
A_0
\end{bmatrix}
\end{bmatrix} \begin{bmatrix}
i_1 \\
i_2 \\
i_n \\
A_0
\end{bmatrix}
\]

(9)
The performance of a classifier depends on the appropriateness of the intended classification tasks have been framed as an optimization problem and solved using SCA.

4.2 Development of hybrid SCA-SVM algorithm for fault detection/classification and section identification

For Equation (8), the estimation model is given by

$$\hat{y}(k) = H(k) \hat{X}$$

(10)

An estimate of $X$, i.e., $\hat{X}$ can be obtained by minimizing the covariance of estimation error as,

$$X = \left[ H^T H \right]^{-1} HH$$

(11)

The derived vector $X$, representing the state of the system (healthy/faulty), is further utilized as the input feature.

In order to demonstrate the discriminatory information contained in the derived features using least square and Adaline algorithm for the two difficult scenarios, the microgrid model (Figure 1) has been simulated during the islanding mode with non-linear load switching at $t = 0.5$ s followed by the inception of line-ground HIF at $t = 0.6$ s. (b) Corresponding harmonic spectrum (3rd, 5th and 7th harmonics) obtained for phase ‘A’ of line-ground HIF involving phase ‘A’ at $0.6$ s in section 3.

The resulting three-phase current waveform recorded at bus B1 and the corresponding harmonic spectrum of phase ‘A’ estimated using least square and Adaline algorithm, are depicted in Figure 4(a) and (b) respectively. As observed, the harmonic spectrum (magnitude of 3rd, 5th and 7th harmonic components) provides sufficient information to discriminate between the healthy (non-linear load switching) and faulty (inception of HIF) situations.

4.2.1 Sine cosine optimization algorithm

Sine cosine algorithm is a newly proposed population-based optimization algorithm, which aims at achieving the maximum probability of obtaining the globally optimal solution for an optimization problem [24]. This is achieved by initializing the algorithm with a set of random possible solutions and iteratively oscillates them around the best solution using trigonometric functions. The algorithm has been found to be useful in solving the complex non-linear multimodal functions. For the problem at hand, the SVM architecture selection task has been framed as an optimization problem and solved using SCA. The objective function has been formed by representing the classification accuracy as the function of SVM parameters represented as:

$$f(x) = \frac{\text{Number of correctly predicted test cases}}{\text{Total number of test cases}}$$

(12)

where $\hat{X} = [C, \gamma]$ represents the vectors comprising of the regularization parameter ($C$) and kernel coefficient ($\gamma$). The initialized random variables are iteratively modified using sine and cosine functions until the convergence criteria is achieved.

Like other population based heuristic algorithms, the overall task of achieving the optimal solution using SCA comprise of two steps, i.e. exploration and exploitation. The exploration involves random perturbation of probable solutions along different directions with the aim of finding the regions with lower value of the objective function while during the exploitation stage, comparatively lesser perturbations with reduced randomness are assigned to the solutions in order to direct them to move closer towards the globally optimal solution in the search space.

With the aim of solving the $D$ dimensional objective function $F(x)$ with $x = [x_1, x_2, ..., x_D]$, assuming the SVM is initialized with population size $N$ for $\text{iter}_{\text{max}}$ number of iterations, the $k^{th}$ solution ($k \leq N$) in the first iteration is represented as:

$$X_k = [x_{k1}^1, x_{k2}^1, ..., x_{kD}^1]$$

(13)

Iteratively, the solutions are updated as

$$X_{k,\text{iter}+1} = X_{k,\text{iter}} + r_1 \times \sin (\phi_2) \times \left| r_3 P_{k,\text{iter}} - X_{k,\text{iter}} \right|$$

(14)

$$X_{k,\text{iter}+1} = X_{k,\text{iter}} + r_1 \times \cos (\phi_2) \times \left| r_3 P_{k,\text{iter}} - X_{k,\text{iter}} \right|$$

(15)
where $X_{k,\text{iter}}$ represents the current position of $k$th solution at iteration $\text{iter}$ and $X_{k,\text{iter+1}}$ is the updated solution. The parameters $r_1$, $r_2$, $r_3$ are random numbers and $P_{k,\text{iter}}$ corresponds to the optimal solution obtained till $\text{iter}$ iteration.

The above equations can be combined using a random number $r_4$ as:

$$X_{k,\text{iter+1}} = \begin{cases} X_{k,\text{iter}} + r_1 \times \sin (r_2) \times |r_3 P_{k,\text{iter}} - X_{k,\text{iter}}| & r_4 < 0.5 \\ X_{k,\text{iter}} + r_1 \times \cos (r_2) \times |r_3 P_{k,\text{iter}} - X_{k,\text{iter}}| & r_4 \geq 0.5 \end{cases}$$

(16)

The parameters $r_1$, $r_2$, $r_3$ and $r_4$ play the role of carrying out the search for the global solution in $N$ dimensional search space. The parameter $r_1$ is responsible for deciding the direction of movement of the solutions i.e. it helps in regulating the extent of exploration and exploitation. In order to maintain the proper balance between exploration and exploitation, $r_1$ is adopted assuming large values in the initial iterations, followed by reducing it as:

$$r_1 = a - \frac{\text{iter}}{\text{iter}_{\text{max}}} \frac{a}{a_{\text{iter}_{\text{max}}}}$$

(17)

where $a$ is a constant. The selection of search direction is followed by the perturbation towards or away from the optimal solution, which is decided on the basis of control parameter $r_2(0 < r_2 < 2\pi)$. The influence of the destination point $P_{k,\text{iter}}$ on the distance from the present solution is taken into account by considering $r_3 > 1$ for emphasizing the effect and $r_3 < 1$ for deemphasizing the effect.

The optimal architecture details of each SVM module obtained using SCA along with their performance in terms of the training accuracy, are summarized in Table 2. The trained SVM modules using the optimal architecture, describes the most optimal mapping between the extracted features for distinct scenarios with the corresponding state (faulty/healthy), type of fault and faulty section.

4.2.2 Overview of the SCA-optimized SVM based protection scheme

As discussed earlier in Section 3, the pattern of input dataset has been generated on the basis of PDF model with wide variation in the shunt fault parameters (fault resistance, fault inception angle and fault location), HIF parameters and no-fault conditions (load variation and non-linear load switching and PV irradiance variation). The details of the operating scenarios with variation in the fault parameters, considered for framing the training and testing datasets are shown in Table 3. A total number of 479,500 training cases including 478,800 fault scenarios and 700 no-fault scenarios have been simulated in each operating mode of the microgrid. The process of obtaining an optimal architecture of the SVM classifier using SCA is described in Figure 5. The overall procedure of solar irradiance uncertainty modelling, feature extraction using least square and Adaline algorithm and further using them to train the SCA-optimized SVM classifiers to perform the tasks of fault detection/classification and section identification has been illustrated in Figure 6.

The proposed protection scheme is composed of different SVM models dedicated to perform the intended protection tasks. The distinct fault current characteristics possessed by the two operating modes of microgrid (GC and IM) require different relaying action, for which it is required to identify the correct mode of operation. So, prior to triggering the corresponding protection module for its execution, the mode detection task is performed by the model SVM-I to identify the operating mode.
TABLE 3  Details of simulated scenarios with variation in parameters

| Type of scenario                     | Parameters                              | Range       | Number of scenarios |       |
|--------------------------------------|-----------------------------------------|-------------|---------------------|-------|
|                                      |                                        |             | Training            | Testing |
| Fault (LG, LL, LLG, LLL, LLLG)       | Fault resistance, $R_f$ (in $\Omega$)   | 0–200       | 478,800             | 143,640 |
|                                      | PV Irradiance range, $G$ (W/m²)         | 100–1000    |                      |        |
|                                      | Inception angle, $\theta_f$             | 0–120°      |                      |        |
|                                      | Fault location, $L_f$ (in km)            | 1–19        |                      |        |
| No-fault (load variation)            | Balanced non-linear loading             | 5–40%       | 700                 | 300    |
|                                      | Unbalanced non-linear loading           |             |                      |        |

The occurrence of high-impedance faults (HIF) in the distribution networks results into the non-linear voltage–current characteristics with fault current of very low magnitude, which are quite difficult to be detected. Though the magnitude of current in HIFs is low, it cannot be left undetected, as the energized conductors touching the ground surface may pose a threat to the human life and the associated arcing phenomena may cause the fire hazards. Thus, in order to avoid such issues, the performance of proposed scheme has been evaluated in terms of detecting the HIF scenarios reliably. The performance analysis of each protection unit is described in detail in the following sub-sections.

5.1 | Performance of proposed scheme against high impedance faults (HIF)

5.1.1 | Mode detection

The detection of operating mode i.e. grid-connected or islanded, is the pre-requisite before putting the particular protection algorithm into action. Thus, the performance of the mode detection unit (SVM-I) has been analysed and compared with DT and classical SVM based mode detectors to examine the effectiveness in performing the task of identifying the
operating mode accurately. In this regard, a total number of 287,880 cases have been examined for both operating modes. The accuracy of the proposed mode detector has been found be 99.88% as compared to the DT and classical SVM based mode detectors achieving the accuracies of 91.44% and 90.18% respectively.

### 5.1.2 Fault detection/classification

The appropriateness of the proposed fault detection/classification units (SVM-II and SVM-III) has been evaluated in terms of accurately identifying the state of the system (healthy or faulty) and classifying the faults. In order to achieve the maximum classification accuracy of the units, SVM-II and SVM-III, the SCA was executed with a population size of 20 for 100 iterations. A total of 143,640 fault and 300 no-fault scenarios for each mode of operation, have been considered to analyse the performance of fault detector/classifiers. The performance of the proposed SCA-optimized SVM based fault detector/classifier has been evaluated and compared with the DT and classical SVM based classifiers in terms of the statistical indices (dependability and security) in Table 4. The classical SVM, has been implemented in MATLAB using the fitcsvm function, in which the kernel parameters are tuned to minimize the cross validation training error. As observed, the higher degree of dependability and security under each mode of operation indicates that the proposed fault detector/classifier outperforms the DT and classical SVM based schemes in reliably performing the intended tasks. The improved performance is attributed to the effectiveness of the SCA in providing optimal tuning parameters for the SVM modules (Table 2).

A power distribution network may encounter the fault events comprising low impedance fault (LIF) and high impedance fault (HIF). In this regard, the performance of proposed scheme has been examined in terms of its effectiveness in imparting suitable protection to the microgrid against LIF and HIF with variation in PV irradiance levels under both modes of microgrid operation (grid connected and islanded) in Table 5. The high degree of accuracy reveal the immunity of proposed scheme against weather intermittency for both LIF and HIF scenarios.

Applicability of the proposed protection scheme for practical settings, demands validating its appropriateness in terms of operation time for different fault types (phase to ground, phase to phase, and three phases to ground fault) under separate scenarios. The relay operation time representing the total time elapsed in the execution of the protection algorithm (feature extraction + operation of the SVM modules) has been estimated, and some prototypical fault scenarios are outlined in Table 6. For each of the considered case, the proposed algorithm has been found to perform the intended protection tasks well within the standard requirement of one cycle for both the operating modes of the microgrid.

### 5.1.3 Section Identification

In order to perform the task of faulty section identification, the optimal parameter selection task to obtain the maximum classification accuracy of dedicated section identification units (SVM-IV and SVM-V) has been achieved by executing the SCA with a population size of 20 for 100 iterations. The performance of section identification units has been analysed in terms of detecting the faulty section correctly. The performance of proposed SCA-optimized SVM based section identifier has been compared with the DT and classical SVM models under each mode of operation (grid-connected and islanded) in Table 7. As observed, the accuracy of proposed section identifier is higher than the other in both modes of operation, which indicates the effectiveness of proposed section identification unit in performing the intended task of identifying the faulty section appropriately.

As a representative case, a test scenario involving the inception of line-ground HIF (phase ‘A’ to ground) at $t = 0.5$ s
### Table 6: Response of the proposed protection scheme in terms of relay operation time

| Fault attributes | Fault parameters | Fault detector/classifier output | Relay operation time (ms) | Feature extraction | Detection | Total operation time |
|------------------|------------------|----------------------------------|--------------------------|-------------------|-----------|---------------------|
| Fault type       |                  |                                  |                          |                   |           |                     |
|                  |                  |                                  |                          |                   |           |                     |
| Grid-connected mode |                  |                                  |                          |                   |           |                     |
| LG AG            | R_f (Ω) = 50     | L_f (km) = 5                     | θ_f (°) = 0              | AG                |           | 8.3                 |
| LL BC            | 0                 | 7                                | 30                       | BC                |           | 8.3                 |
| LLG ACG          | 125               | 9                                | 60                       | ACG               |           | 8.3                 |
| LLL ABC          | 0                 | 13                               | 90                       | ABC               |           | 8.3                 |
| LLLG ABCG        | 150               | 18                               | 120                      | ABCG              |           | 8.3                 |
| Islanded mode |                  |                                  |                          |                   |           |                     |
| LG BG            | 75                 | 3                                | 0                        | BG                |           | 8.3                 |
| LL AC            | 0                 | 8                                | 30                       | AC                |           | 8.3                 |
| LLG BCG          | 100               | 10                               | 60                       | BCG               |           | 8.3                 |
| LLL ABC          | 0                 | 12                               | 90                       | ABC               |           | 8.3                 |
| LLLG ABCG        | 125               | 17                               | 120                      | ABCG              |           | 8.3                 |

### Table 7: Performance comparison of proposed section identifier with other techniques

| Sections | Grid-connected |          | Isolated |          |
|----------|----------------|----------|----------|----------|
|          | No. of test cases | Proposed scheme | DT | Classical SVM | Proposed scheme | DT | Classical SVM |
| S1       | 26,460          | 99.15    | 92.73    | 89.53    | 98.84    | 88.95    | 85.68    |
| S2       | 45,360          | 99.33    | 91.88    | 89.90    | 98.99    | 89.68    | 88.78    |
| S3       | 26,460          | 99.28    | 93.31    | 91.61    | 98.90    | 88.97    | 89.02    |
| S4       | 45,360          | 99.62    | 93.15    | 92.63    | 99.40    | 90.69    | 90.42    |
| Overall accuracy (%) | 99.35 | 92.77 | 90.92 | 99.03 | 89.57 | 88.48 |

In section S3 with L_f = 1 km, has been simulated. The current waveform of the faulty phase ‘A’ with the corresponding fundamental component and harmonic spectrum have been illustrated in Figure 7(a–c) respectively. The corresponding response of the proposed scheme generating appropriate trip signal at t = 0.5125 s (12.5 ms post fault inception) is shown in Figure 7(d).

### 5.2 Performance of proposed scheme against HIF under non-linear loading conditions

To further evaluate the robustness of the proposed scheme against non-linear loading conditions, it has been examined for some of the randomly simulated test scenarios in Table 8. The variation in non-linear loading during HIF has been considered from ±10% to ±40% in each of the two modes (grid-connected and islanded) of operation. From Table 8, it can be observed that the proposed fundamental and harmonic information based protection scheme performs reliably under both modes (grid-connected and islanded), irrespective of the wide variation in non-linear loading.

Even during the normal operation, the microgrids may not be perfectly balanced. The unbalanced loading conditions may influence the reliability and security of the protection system. In this regard, the performance of proposed scheme has been examined against unbalanced loading and the response has been analysed for no-fault scenarios with unequal variation in load across the three phases, as illustrated in Table 8. As observed, the proposed scheme has been found to be effective with regard to providing reliable protection against unbalanced faults with immunity against unbalanced non-linear loading. For all the test cases, the proposed scheme is found to provide the necessary response in minimum time (within one cycle). The overloading condition, often leads to fault current characteristics similar to the HIFs. The similar current profile may lead to false tripping of the conventional relays. To
TABLE 8  Performance of proposed scheme against varying and unbalanced non-linear load

| Input parameters | Response of proposed scheme |
|------------------|-----------------------------|
|                  | Grid-connected mode          | Islanded mode                     |
| Type of scenario | Variation in nonlinear      | SVM-II output | SVM-IV output | Relay operation time (ms) | SVM-III output | SVM-V output | Relay operation time (ms) |
|                  | loading | Section | SVM-II output | SVM-IV output | Relay operation time (ms) | SVM-III output | SVM-V output | Relay operation time (ms) |
| Fault scenarios  |         |         |               |               |                          |               |               |                          |
| LG AG            | +20%    | S2      | AG            | S2            | 12.5                     | AG            | S2            | 13.3                     |
|                  | −10%    | S1      | AG            | S1            | 11.7                     | AG            | S1            | 14.2                     |
| BG               | +20%    | S4      | BG            | S4            | 13.6                     | BG            | S4            | 12.5                     |
|                  | +10%    | S4      | BG            | S4            | 12.5                     | BG            | S4            | 14.6                     |
| CG               | +30%    | S3      | CG            | S3            | 11.7                     | CG            | S3            | 13.9                     |
|                  | −40%    | S1      | CG            | S1            | 14.2                     | CG            | S1            | 15.8                     |
| LLG ABG          | +20%    | S3      | ABG           | S3            | 13.3                     | ABG           | S3            | 14.3                     |
|                  | −30%    | S4      | ABG           | S4            | 11.7                     | ABG           | S4            | 16.7                     |
| ACG              | +10%    | S1      | ACG           | S1            | 14.9                     | ACG           | S1            | 13.3                     |
|                  | −20%    | S2      | ACG           | S2            | 14.2                     | ACG           | S2            | 14.8                     |
| BCG              | +40%    | S1      | BCG           | S1            | 13.6                     | BCG           | S1            | 15.2                     |
|                  | −10%    | S3      | BCG           | S3            | 12.9                     | BCG           | S3            | 14.8                     |
| LLLG ABCG        | +30%    | S2      | ABCG          | S2            | 14.2                     | ABCG          | S2            | 16.5                     |
| No-fault scenarios |         |         |               |               |                          |               |               |                          |
| Balanced loading |         |         | NF            | —             | 9.2                      | NF            | —             | 10.0                     |
|                  |         |         | NF            | —             | 10.8                     | NF            | —             | 11.7                     |
|                  |         |         | NF            | —             | 10.8                     | NF            | —             | 11.7                     |
| Unbalanced loading | Load variation in phase (%) |         |               |               |                          |               |               |                          |
|                  | A      | B     | C  |         |               |               |               |                          |
| +30    | +10 | 0     | NF            | —             | 10.1                     | NF            | —             | 9.8                      |
| 0       | +20 | +40   | NF            | —             | 11.2                     | NF            | —             | 10.6                     |
| +10    | 0   | +40   | NF            | —             | 10.4                     | NF            | —             | 11.5                     |

Further evaluate the effectiveness of the proposed scheme in distinguishing between overloading and HIF, the response of the relay has been evaluated for a prototypical overload and fault scenario. The scenario involves 40% increase in non-linear loading at $t = 0.5$ s, followed by the inception of line-ground HIF (AG) in section S1 at $t = 0.75$ s during the islanding mode. The harmonic spectrum derived from the current in phase ‘A’ is shown in Figure 8(a). Inspite of the intrusion of harmonics for both the scenarios, it can be observed that the magnitude of harmonic components differ for overload and HIF. The response of proposed scheme corresponding to the simulated scenario, is depicted in Figure 8(b).

The avoidance of the trip signal after increase in the load reflects the immunity of the scheme to overload. Further, the trip signal generated post 12.9 ms of the HIF inception, reflects the selectivity and rapidity in response of the scheme. The immunity of proposed scheme against overloading is attributed to the inclusion of harmonic information in executing the relaying action.

5.3 Performance of proposed scheme against HIF during weather intermittency

In order to evaluate the efficacy of proposed scheme against the weather intermittency, the performance of classification units in terms of accuracy (%) corresponding to each of the mentioned intervals of PV irradiance levels, has been analysed in Table 9. The obtained result (overall accuracy) confirms the effectiveness of the proposed scheme in providing reliable protection to the microgrid under both modes of operation with robustness against weather intermittency.

5.4 Comparison of proposed protection scheme with the existing microgrid protection techniques

Further, to demonstrate the robustness of the proposed protection scheme against harmonic intrusion and weather
TABLE 9  Performance of proposed scheme against HIF with variation in PV irradiance levels

| PV Irradiance | Type of HIF  | SVM-I     | SVM-II    | SVM-III   | SVM-IV    | SVM-V     | Overall Accuracy |
|---------------|--------------|-----------|-----------|-----------|-----------|-----------|------------------|
| 101–200       | LG, LLG, LLLG| 99.35%    | 99.58%    | 99.49%    | 99.10%    | 98.36%    | 99.18%          |
| 201–400       |              | 99.84%    | 99.76%    | 99.54%    | 98.86%    | 98.46%    | 99.29%          |
| 401–600       |              | 99.71%    | 99.56%    | 99.28%    | 99.72%    | 99.12%    | 99.48%          |
| 601–800       |              | 100%      | 99.89%    | 99.15%    | 99.92%    | 99.38%    | 99.67%          |
| 801–1000      |              | 100%      | 99.92%    | 99.62%    | 99.26%    | 99.26%    | 99.61%          |

FIGURE 7  HIF (BG) inception at $t = 0.5$ s in section S3 during islanding mode (a) Three-phase current waveform at bus B1 (b) Fundamental component (magnitude) of phase ‘B’ (c) Corresponding harmonic spectrum (3rd, 5th and 7th harmonics) for phase ‘B’ (d) Trip signal generated post 12.5 ms of fault inception

FIGURE 8  Increase in non-linear loading at $t = 0.5$ s followed by the inception of HIF (AG) at $t = 0.75$ s in section S1 during islanding mode (a) Corresponding harmonic magnitude (3rd, 5th and 7th harmonics) for phase ‘A’ (b) Trip signal generated post 12.9 ms of inception of HIF

intermittency, it has been compared with other protection techniques [25, 26] on different bases in Table 10. From the comparative assessment, it can be concluded that the proposed scheme outperforms other state-of-the-art microgrid protection techniques in providing efficient and reliable protection to the PV integrated microgrid against high impedance faults and is immune to the presence of harmonics and weather intermittency.

As mentioned earlier, fast and accurate fault detection is the key requirement of a reliable protection scheme in order to...
TABLE 10  Comparison of proposed ConvNet-based scheme with the reported microgrid protection techniques

| Basis of comparison          | Microgrid protection techniques                                                                 | Proposed protection scheme                                                                 |
|-----------------------------|--------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Adopted approach            | Hilbert-Huang transform and extreme learning machine                                             | Combined framework of least square and Adaline algorithm, sine cosine algorithm (SCA) and support vector machine (SVM) |
| Features selected           | Differential features of current signal                                                          | Synchronized phasor measurements of voltage and current                                      |
| Weather intermittency       | Not considered                                                                                    | Stochastic nature of PV based source modelled using an appropriate probability distribution function |
| Tasks performed             | Detection of HIF only                                                                             | Mode detection, HIF detection/classification and section identification                      |
| Total number of test        | Not available 831                                                                                 | Not available 143,940                                                                       |
| Robustness against          | Not validated                                                                                    | Validated against harmonic intrusion arising due to non-linear load switching               |
| Statistical analysis        | Not carried out                                                                                   | Carried out in terms of dependability and security                                           |
| Real-time validation        | Real-time study carried out using digital signal processor (DSP)                                  | Performed on OPAL-RT setup                                                                  |

TABLE 11  Quantitative comparison of the proposed protection scheme with other reported techniques in terms of speed and accuracy

| Mode of operation | Techniques   | Average relay operation time (ms) | Accuracy (%) |
|-------------------|--------------|-----------------------------------|--------------|
| Connected         | Proposed     | 11.6                              | 99.56        |
|                   | [26]         | 10.2                              | 92.77        |
|                   | [27]         | 6.2                               | 92.38        |
|                   | [28]         | 50                                | 91.25        |
| Islanded          | Proposed     | 13.4                              | 99.17        |
|                   | [26]         | 11.2                              | 91.04        |
|                   | [27]         | 6.9                               | 91.12        |
|                   | [28]         | 50                                | 90.70        |

restore the pre-fault scenario at the earliest. In this regard, the quantitative performance comparison of the proposed scheme has been carried out with other reported techniques in terms of the relaying speed and accuracy in Table 11. The comparison reveals that though some of the reported protection techniques responds faster to faults, their reliability is compromised during intermittency in solar irradiance and variation in other operating conditions of the microgrid. The relatively faster and simple approach of least square and Adaline algorithm in estimating the harmonic attributes helps in achieving the reduced relay operation time. The higher accuracy achieved by proposed scheme as compared to the other techniques ascertains its effectiveness in providing reliable protection to the microgrid. Thus, the overall observation on the comparative results demonstrates the merit of proposed protection scheme in detecting the HIFs quickly and reliably with immunity against the variation in non-linear loading conditions and weather intermittency.

5.5  Real-time validation using OPAL-RT digital simulator

For authenticating the suitability of a protection scheme for field applications, its performance has to be analysed in real-time. In this regard, the proposed protection scheme for PV-integrated microgrid (Figure 1(a)) has been implemented on OPAL-RT digital simulator (OP-5600) in order to obtain the real-time settings. OPAL-RT digital simulator facilitates the required interface between microgrid system modelled in MATLAB/Simulink environment to the RT-Lab software.

The multi-core processors and FPGA controllers present in the simulator provide parallel processing thereby facilitating real-time execution. The inherited features of flexibility and scalability in OPAL-RT make it appropriate for performing the transient studies on complex power system models.
and hence achieve precise results in real-time. The instantaneous current signals obtained through the real-time simulation are assessed through the customized input/output channels and processed through the least square and Adaline algorithm to derive the harmonic information, which are further utilized by the SCA-optimized SVM based protection units for taking the required relaying decision.

The experimental setup demonstrating the real-time implementation of proposed protection scheme on OPAL-RT digital simulator is depicted in Figure 9(a). In order to investigate the response of proposed scheme, a representative case involving high impedance BCG fault inception at \( t = 4 \) s in the presence of non-linear loading has been simulated in section S2 during the islanded mode with PV irradiance = 300 W/m\(^2\), and fault location = 11 km. The corresponding current signal recorded at bus B4 have been depicted in Figure 9(b). The response of the proposed protection algorithm in generating the trip signal at \( t = 4.013 \) ms (post 13 ms of the fault inception) as shown in Figure 9(c) confirms the effectiveness of proposed scheme in providing required protection to the microgrid with robustness against harmonic intrusion and weather intermittency.

6  |  CONCLUSION

The conventional overcurrent based microgrid protection schemes generally fail to detect HIF due to the low magnitude of fault current. The intrusion of harmonics and the stochastic variation in fault current level due to weather intermittency further contributes to the complexity of the protection tasks. In this regard, a protection scheme has been proposed for mode (grid-connected/islanded) detection, fault detection/classification and section identification during HIF, while maintaining improved robustness against harmonic intrusion and fault level variation arising due to mode variation and/or weather variation. The immunity against weather intermittency has been achieved by modelling the stochastic variation in PV-based generation by a probability distribution function, while the impact of harmonics has been incorporated by online estimation of harmonics magnitude from current signals. The scheme has been extensively validated for diverse operating scenarios involving wide variation in PV irradiance, fault parameters and non-linear loading. The proposed scheme has been compared with the DT and classical SVM based protection schemes. The proposed scheme has been found to outperform the other two in terms of performing the intended tasks accurately. The comparison reflects the superiority of the proposed scheme in performing the intended protection tasks with robustness against harmonics and weather intermittency under both grid-connected and islanded modes. The validation of the proposed scheme on real-time OPAL-RT digital simulation platform confirms its applicability for practical field operations.
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