SERBIAN JOURNAL OF ELECTRICAL ENGINEERING
Vol. 21, No. 3, October 2024, 327-343

UDC: 621.311.243:005.931.13 **DOI: https://doi.org/10.2298/SJEE2403327T**

An Intelligent Protection Scheme based on Support Vector Machine for Fault Detection in Microgrid Using Transient Signals in Protection Scheme

Shankarshan Prasad Tiwari[1]

Abstract: Fault detection in the microgrid is a crucial task due to the diversified fault conditions, and it must be rapidly identified to reduce any serious hindrance to the system. The fault current behaviour due to change in fault resistance of the touching point can damage the switches of integrated converters. In addition to the above, sporadic conditions can also affect the profile of voltage and current, in the system. Traditional protection schemes need modification to prevent relay maloperation of the microgrid. This paper presents a protection scheme based on support vector machines to detect faults under such tedious conditions. In this protection scheme, acquired samples of voltage and current from selected bus have been used and processed through the data processing tool discrete wavelet transform. The protection scheme is operating in two dissimilar operating modes, where initially mode was identified then fault detection/classification was done. Section identification task was performed to identify faulty sections under varying operating scenarios. The uncertain conditions of the renewable sources can affect the performance of the system, therefore some random cases have been considered to validate the protection scheme.

Keywords: AC faults, Fault detection, Fault resistance, Distributed energy resources, Section identification, Wind speed.

1 Introduction

In order to provide lighting for rural, urban, and suburban areas, the microgrid has evolved into a more sophisticated and intelligent power distribution system. The main components of the microgrid are distributed energy resources (DERs) which are rated at low scale, converters for converting electrical quantities (voltage and current) as per the need of the desired power output, and energy storage devices with precisely specified electrical limits [1 – 4]. In the traditional existing power generation system, the majority of the power plants are utilizing fossil fuels for the production of electrical energy. Majorly, coal is used, secondly nuclear fuel, and remaining electricity is generated from liquid fuels

[1]Ramdeobaba University, Department of Electrical Engineering, Nagpur, Maharashtra, India;
E-mail: shankarshan.tiwari20@gmail.com

such as diesel and petrol, but difficulties in the availability of such fuels as well as a reduction in their storage for a long period of time [5] for the generation of electrical energy make it intricate. Therefore, the attention of the power system engineers has paved towards the adoption of the microgrid. The microgrid offers many benefits when compared with traditional power systems, such as reliability, cost effective or effectiveness [6], better power quality, and environment friendly. Currently, three types of microgrids are available that are AC, DC, and hybrid microgrids [7 – 9]. Despite the advantages of microgrids in many cases as given above, protection remains a major concern because of a number of factors related with protection of microgrid, such as current fluctuation in grid and islanded modes, converter unit failure, the bidirectional behaviour of converters, and unnecessary /unwanted disconnections.

In addition to the above fault scenarios, protection becomes more difficult when a fault occurs in the system due to the varying nature of the fault resistance. The value of the fault resistance can be low or high, depending on the contact of the conductor with different surfaces, such as sand, wet, and dry surfaces, as well as contact with metal or branches of trees. In all conditions, the value of the fault resistance can change between low and high, therefore it is mandatory to mitigate such problems by identifying fault occurrences rapidly. In addition to the above difficulties, fault detection can be more difficult when the operational dynamics of the microgrid change due to changes in the atmospheric conditions. Such conditions can vary the output level of the current, which will affect the voltage-current profile of the microgrid. Traditional protection schemes based on threshold value-based overcurrent relays are unable to sense the operational dynamics of the system. To understand the basic concept of impact in the current due to wind intermittency, wind speed has been changed from 15 to 6 m/s in the microgrid, and the simulated outcome is demonstrated in Fig. 1. In the proposed figure, it can be observed that the current level is changes due to variations in wind speed. A total of the three zones in the figure, where initially the microgrid is operates in a normal condition with constant speed, the current level is the same while it is changes in the second zone due to changes in the wind speed. Further in the third zone, it is again constant, which shows that variations in wind speed affect the operational dynamics of the system. In addition to above protection, it becomes tricky under varying nature of the fault resistance due to the dissimilar fault conditions. The same event can be observed for photovoltaic (PV) integrated or PV and wind (interconnection of the both) integrated microgrid.

In existing literatures variety of works for protection of the microgrid is available including here: an enhanced voltage relay based protection scheme for microgrid in [10], a protection scheme based on travelling wave in [11] where learning based protection scheme is designed for protection of the microgrid. A low cost communication based protection scheme for microgrid in [12], deep belief network based protection scheme in [13], where time-time transform has been considered in the analysis of the microgrid. A transient wavelet energy based protection scheme in [14], wavelet transform and taguchi-based artificial neural network based protection scheme for microgrid in [15]. Based on power flow direction, magnitude of the current and voltage sag a protection scheme is proposed in [16], and based on S-transform a differential protection scheme in [17] where differential current has been measured in two ends to get signal then energy of the signal versus time is extracted for identification of the fault condition. However, existing protection schemes in the literature do not consider varying fault resistance (low and high) under varying operational dynamics of the renewable sources of energy as well as majority of the protection schemes are limited for fault detection task only.

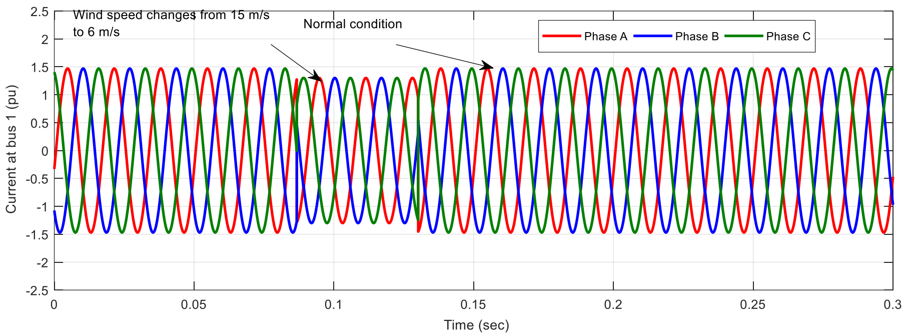

Fig. 1 – *Variation the level of current during change in wind speed.*

Motivated by the above difficulties in the microgrid, in this paper, a support vector machine-based protection scheme is proposed to detect faults in the microgrid under diversified fault conditions. In the proposed work, three main tasks have been performed, which are mode detection or mode identification, identifying and classifying AC faults, and faulty section identification. For comparative analysis purposes, k-nearest neighbour (kNN) and decision tree (DT) based algorithms have been also used while discrete wavelet transform (DWT) has been used for processing of the signals. The major contribution of the work can be summarized as follows:

- Developing a protection scheme for mode identification in grid and islanded modes. Identifying faults and faulty sections for dissimilar classes of faults in the microgrid.
- Validating the protection scheme under stressed fault conditions and dissimilar load changes in the microgrid.
- A Comparative analysis with kNN and DT-based classifiers during validation of the algorithm.
- Considering some random variations in the wind speed for the analysis of the protection scheme.

The remaining portions of the manuscript are structured as follows: A single-line representation of the microgrid has been given in Section 2, and discrete wavelet transform overview for data processing in Section 3. Algorithm overview with figure is given in Section 4, and the protection scheme in Section 5. A performance analysis in Section 6 and Section 7 illustrates the limitations and future scope of the work, followed by conclusions in Section 8.

2 Single Line View of the Microgrid

Fig. 2 shows the single-line view of the microgrid, where integration of the DER, utility grid, and other units is given. The frequency of the system is 60 Hz, and a total of eleven loads are connected at the different locations.

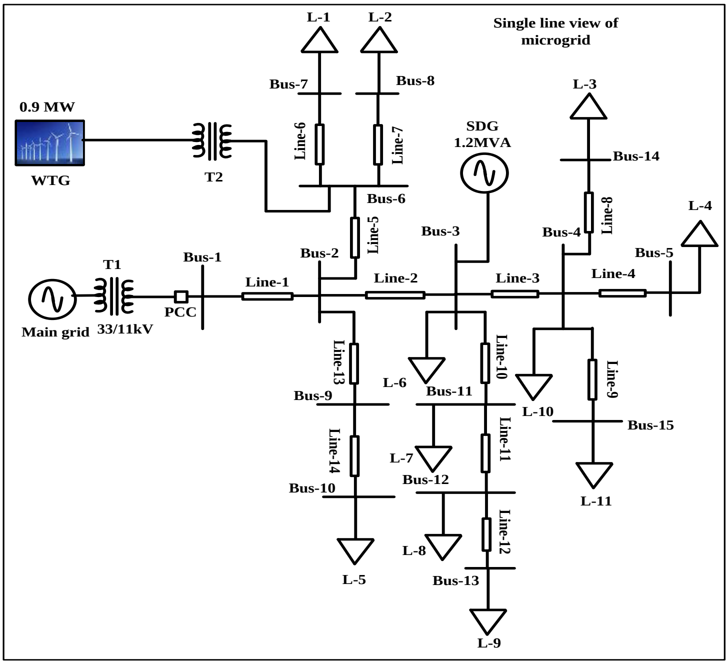

Fig. 2 – *Single line view of the microgrid.*

As demonstrated in the figure below, the utility grid of 2 MVA 33kV/11kV is integrated at bus-1. Therefore, a point of common coupling has been used to connect the system. In cases of faulty condition, the point of common coupling (PCC) helps in the operation of the microgrid in islanded mode. Apart from the above, a total of fourteen lines and fifteen numbers of buses have been used in the system. A synchronous diesel generator (SDG) based unit is connected to bus-3 with a rating of 1.2 MVA, while a wind turbine generator (WTG) is connected to bus-6 through a transformer. The length of each section is 0.5 km. Loads have been assumed to consume constant power with a three-phase arrangement. T1 and T2 are two transformers that are used to integrate grid- and wind turbine-based units.

3 Feature Extraction through DWT

The discrete wavelet transform has been widely used for removal of the extra information from the collected signals of the voltage and current. The DWT has become a proficient and smart data processing tool in time as well as in the frequency domain. The db3 mother wavelet has been used for signal decomposition, which is significant for transient analysis in the power system. In recent years, the proposed data processing tool has been found that it is significant for the analysis of the power system, such as ultrafast transmission line fault detection [19], condition monitoring of wind turbine [20], and analysis of harmonic distortion [21].

A time domain signal is decomposed into its approximation coefficients using a scaling function (ϕ_{jk}) which can be given as:

$$\phi_{jk}(t) = 2^{-j/2}\phi(2^{-j}t - k) \tag{1}$$

where j and k are the integers in the equation.

Further, calculated coefficients can be used when calculating the standard deviation of the signals and it can be expressed as:

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

where $i = 1, 2, \ldots, N$ and x_i represents the data in the series.

The authors of the numerous research studies have considered a number of features (using characteristics) for the analysis of the work. The same concept has been analyzed in the present work also.

Suppose if the features are the $F_{et1}, F_{et2}, F_{et3}, F_{et4} \ldots, F_{etn}$, then they can be expressed as follows:

$$[F_{et1}, F_{et2}, F_{et3}, F_{et4}, \ldots, F_{etn}]\,. \tag{3}$$

These futures can be used in the protection scheme for analysis of the training of the dissimilar modules.

4 Overview of the Support Vector Machine

The appropriateness of the SVM for classification of the datasets has attracted researchers to adopt it as a proficient data analysis tool in various types of applications, such as the classification of power quality events [22] and the automatic classification of power quality events [23]. The SVM is a binary classifier and works on the principle of pattern recognition. The algorithm identifies class of the data which is based on the distance between the data points in an infinite space hyperplane (Fig. 3). If the distance between two points will be greater, probability of the error will be less.

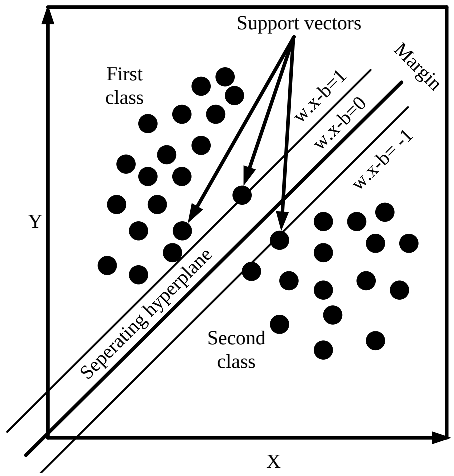

Fig. 3 – *Presentation of support vector machine.*

For T (training) dataset (4) is used to show the distribution of data points from multi dimensional input which is given below:

$$T = (a_i, b_i) < i < n\,, \tag{4}$$

where a_i shows the real vector and b_i represent values that can be +1 or –1 to represent class. Further, the hyperplane equation for class separation (two classes) can be represented as:

$$\boldsymbol{wx} - b = 0\,. \tag{5}$$

Here *w*, *x* and *b* are the normal vector at the origin point, set of data points and bias respectively.

The distance between the hyperplane is significant to increase greater classification accuracy by removing the probability of the data lying. If margin is higher, accuracy of the data classification may be appropriate. To avoid data lying below equations can be used:

$$\boldsymbol{wx} - b \geq +1 \quad \text{for class 1,} \tag{6}$$

$$\boldsymbol{wx} - b \leq -1 \quad \text{for class 2.} \tag{7}$$

Suppose if margin is *m* then separation margin is given by:

$$m = \frac{2}{\|\boldsymbol{w}\|}\,. \tag{8}$$

To achieve a large margin value of the m and w can be adjusted at the time of the training that can be higher and lower, respectively.

5 Development of the Protection Scheme

The development of the protection scheme for the proposed microgrid under both operating modes has been demonstrated in this section. For a clear visualisation of the sequence of the operation, Fig. 4 has been used, where many SVM-based modules are used in both modes.

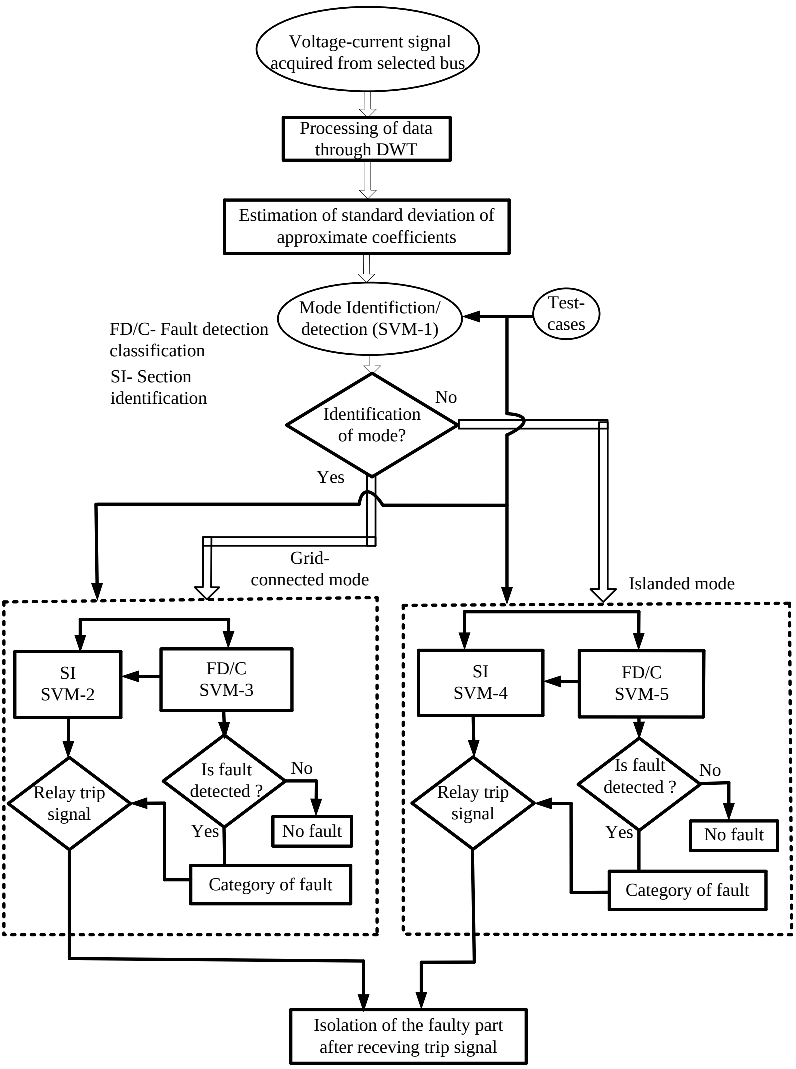

Fig. 4 – *Protection scheme architecture under grid connected and islanded mode.*

The sequence of the protection scheme for operation during a fault can be analysed as follows: After acquiring signals of voltage and current, feature extraction using DWT was performed, and the extracted signals were further used to determine the standard deviation of the signals. These signals were fed into the SVM-1 module, which is dedicated to the task of the mode identification. Once the mode is identified (grid or islanded), the protection scheme automatically activates the remaining modules dedicated for given tasks after fault in the microgrid in both of the modes. Modules SVM-3 and SVM-5 were utilized for fault detection and classification, while the remaining modules SVM-2 and SVM-4 are for section identification. After fault identification, the relay is activated to operate the circuit breaker. In the case of a normal or healthy condition, the protection scheme shows no fault condition.

6 Performance Evaluation

Performance plays a crucial role for stable and dependable operation of the power distribution system. The performance should be adequate and greater for uninterruptable and reliable operation in connected areas. Therefore, in this section, the performance has been analyzed under varying scenarios to observe invulnerability of the modules when evaluating for given task. A total of 45028 fault cases in grid and islanded modes in the given microgrid through simulation were generated with given parameters. **Table 1** indicates the details of the parameters that were considered during the generation of the datasets. The ratio used to divide the entire dataset is 70% and 30%, where later is used in testing and former in the training of the modules. The validations of the protection scheme were carried out under subsections in this section.

Table 1

Dataset used for training and testing under given parameters.

<table>
<tr><th>Used parameters in data generation</th><th>Total cases used data generation</th><th>Total-generated cases</th><th>Total cases for training of the modules</th><th>Total cases for testing of the modules</th></tr>
<tr><td>Fault category/class</td><td>8</td><td rowspan="7">For single section total cases (8*3*3*12*2*1) =1728*13=22464 in each mode

Total generated cases 22464*2=44928 44928 +100=45028</td><td rowspan="7">31519</td><td rowspan="7">13509</td></tr>
<tr><td>Resistance of fault (Ω)</td><td>3 in each section</td></tr>
<tr><td>Total length considered during fault (km)</td><td>3 in each section (Total 13 section)</td></tr>
<tr><td>Variation in wind speed (m/s)</td><td>12 in each section (Random cases)</td></tr>
<tr><td>Fault inception angles (degree)</td><td>2 case (30^0, 90^0)</td></tr>
<tr><td>Operating mode</td><td>Each mode (2 case, grid connected and islanded)</td></tr>
<tr><td>Cases used under no-fault condition</td><td>100 (Variation in wind speed)</td></tr>
</table>

6.1 Mode identification/mode detection (Module SVM-1)

The differences in fault current magnitude in grid and islanded modes should be quickly identified to trigger operation of the next modules in the microgrid, for continued operation. Thus, in order to assess accuracy of the SVM-1 module performance was analyzed in both of the modes in this subsection. For testing of the proposed module, a total of 6440 test cases under both of the operating modes were used. The achieved accuracy for grid-connected mode is 98.86%, while it is 100% rest of operating mode (islanded). Further, the performance of the module was compared with k-nearest neighbour (kNN) and decision tree (DT)-based modules in the same dataset. To clearly demonstrate differences in the percentage accuracy graph, it is plotted in Fig. 5 using MATLAB software. The responses in the **Table 2** clarify that module used for mode identification is dependable for the same task.

Table 2
Percentage accuracy achieved after validation of the SVM-1.

Techniques used for comparison	Operating modes		
	Grid connected (%)	Islanded (%)	Overall accuracy (%)
SVM	98.16	100	99.08
kNN	96.83	97.74	97.28
DT	95.88	96.96	96.89

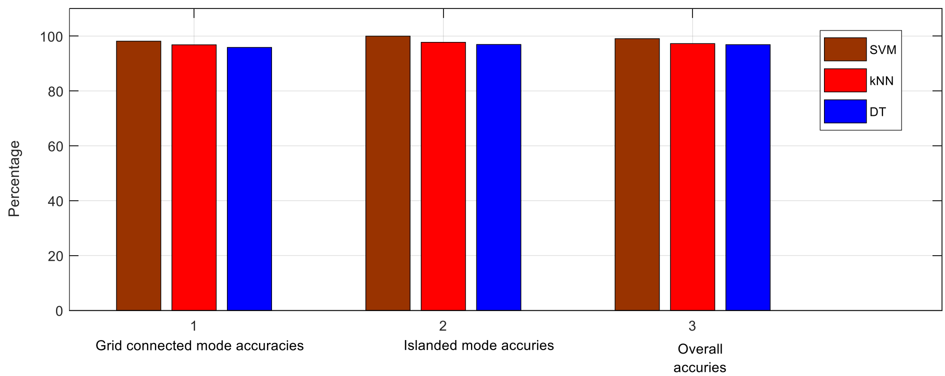

Fig. 5 – *Comparison of the accuracy after mode detection with other algorithms.*

6.2 Fault detection/classification (Modules SVM-3 and SVM-5)

This subsection evaluates performance of the classifier module for fault detection/classification to analyze its capability during fault detection. Reliability indices are significant for a brief statical analysis therefore performance has been observed through these indices in and islanded modes. The robustness of SVM-3 and SVM-5 module was observed through testing using a total of 4360 test cases, with 30 no-fault cases in grid connected as well as islanded operating modes in the microgrid. After analysis of the reliability indices (dependability and security) through fault and no fault cases [24], it was observed that fault detector classifier in both of the operating modes was efficiently performing the task of the fault detection/classification. Fault misdetection as well as classification can be avoided by knowing dependability while generation of the false alarm signals can be analyzed through security.

Table 3
Reliability analysis and comparison with other algorithms.

Algorithms used for comparison	Mode of operation					
	Grid connected			Islanded		
	Dependability (%)	Security (%)	Overall accuracy (%)	Dependability (%)	Security (%)	Overall accuracy (%)
SVM	98.73	100	99.36	98.28	99.31	98.79
kNN	97.88	98.94	98.41	96.28	97.51	96.89
DT	96.14	95.47	95.80	95.46	93.49	94.47

6.3 Faulty section identification/faulty line identification (Modules SVM-2 and SVM-4)

In a practical power system, a number of sections are required to transmit and distribute power from one end to another. Therefore, the probability of the section fault cannot be ignored. The rapid fault clearance after investigation of the faulty section helps to smoothly run power distribution system by removing the faulty part that can be achieved through proper predictive planning. Faulty sections after occurrence of the dissimilar AC faults have been analyzed in this subsection in both modes of the microgrid. To test both of the faulty section identifier modules, dissimilar AC faults in dissimilar sections were used and tested with 3718 cases in both of the operating modes. The test results in **Table 4** indicate that section identifier modules are accurately operating when identifying faulty sections. The achieved accuracy after faulty section identification is 99.04% for SVM-2 module and 98.31% for module SVM-4. The authors of the existing research work have also considered other modules when analysing their work. Therefore, to examine the authenticity of the proposed module, two other algorithms have also been used that have been tested on the same dataset. To show differences in achieved accuracy, Figs. 6 and 7 has been considered where performance can be easily observed.

Table 4
Performance of SVM-2 and SVM-4 for section identification.

Operating modes	Section	Section wise given test cases	Fault type	SVM (%)	kNN(%)	DT (%)
Grid connected	Sect-1	261	AG	98.86	96.54	94.96
	Sect-2	260	BCG	99.54	95.94	94.35
	Sect-3	264	ACG	99.18	97.88	94.48
	Sect-4	270	ABCG	98.37	96.46	95.81
	Sect-5	280	AB	98.73	96.84	94.48
	Sect-6	260	BC	99.28	96.66	95.76
	Sect-7	264	ABC	99.34	96.24	95.34
	Overall accuracy (%)			99.04	96.65	95.02
Islanded	Sect-1	261	AG	98.11	95.24	94.14
	Sect-2	260	BCG	98.12	93.88	92.16
	Sect-3	264	ACG	98.24	97.06	93.34
	Sect-4	270	ABCG	98.18	96.24	93.88
	Sect-5	280	AB	98.36	95.84	93.29
	Sect-6	260	BC	98.55	95.92	93.13
	Sect-7	264	ABC	98.62	95.27	94.62
	Overall accuracy (%)			98.31	95.63	93.50

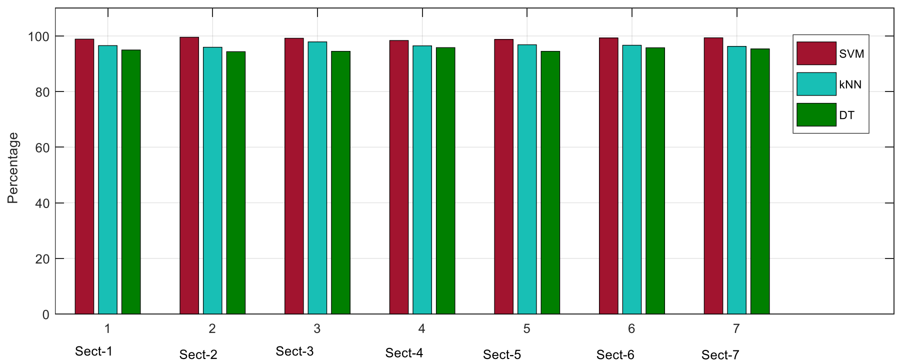

Fig. 6 – *Section identifier performance and comparison during grid connected mode.*

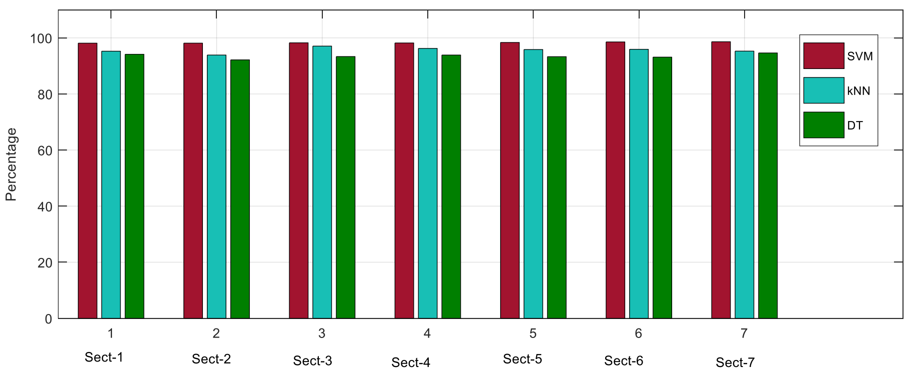

Fig. 7 – *Section identifier performance and comparison during islanded connected mode.*

6.4 Validation of the protection scheme under varying levels of the fault resistance, dissimilar ac faults and uncertain conditions

As demonstrated in Section 2, one unit of the wind-based DER is integrated in proposed microgrid system. Therefore, the probability of uncertainty cannot be ignored due to weather based conditions. This subsection describes authenticity of the scheme under dissimilar wind speed and AC faults as dealt in the **Table 5**. The speed of the wind is taken between 4 m/s to 15 m/s, and its fault resistance ranges from 4 Ω to 100 Ω. The main reason behind the inclusion of the varying range of fault resistance and its validation under dissimilar fault resistance is its wide changes when contacting dissimilar surfaces.

To clearly show the changes in magnitude during both operating modes, Figs. 8 and 9 have been used, where Figs. 8a and 8b show the difference in the magnitude of the level of fault current as depicted in figure. An ACG fault under the same fault resistance has been created in the microgrid to get information about the changes in the microgrid fault current level during both of the operating modes. Fig. 9 depicts the effect of the fault resistance on the BCG fault in islanded mode. Due to the high value of the fault resistance (80 Ω), it can be investigated that magnitude of the fault current is too much varying as compared to Fig. 8. According to results in **Table 5** it is clear that performance is greater and efficiently operating.

Table 5

Response of the protection scheme analysed after some random variation in wind speed and fault resistance.

Types of mode	Type of fault	Resistance of the fault point (Ω)	Changes in wind speed (m/s)	Length of the fault (km)	Protection scheme response	Relay response time (ms)
Grid connected mode	BG	80	8	0.5	BG	0.012
	ACG	70	10	1	ACG	0.013
	BCG	80	11	1.5	BCG	0.012
	ABCG	100	12	1	ABCG	0.010
	BG	60	15	2.5	ABG	0.012
	AB	10	10	3	AB	0.014
	BC	4	4	3.5	AC	0.010
	ABC	6	13	5	ABC	0.014
Islanded mode	BG	80	8	0.5	BG	0.013
	ACG	70	10	1	ACG	0.014
	BCG	80	11	1.5	BCG	0.013
	ABCG	100	12	1	ABCG	0.012
	BG	60	15	2.5	ABG	0.014
	AB	10	10	3	AB	0.015
	BC	4	4	3.5	AC	0.012
	ABC	6	13	5	ABC	0.014

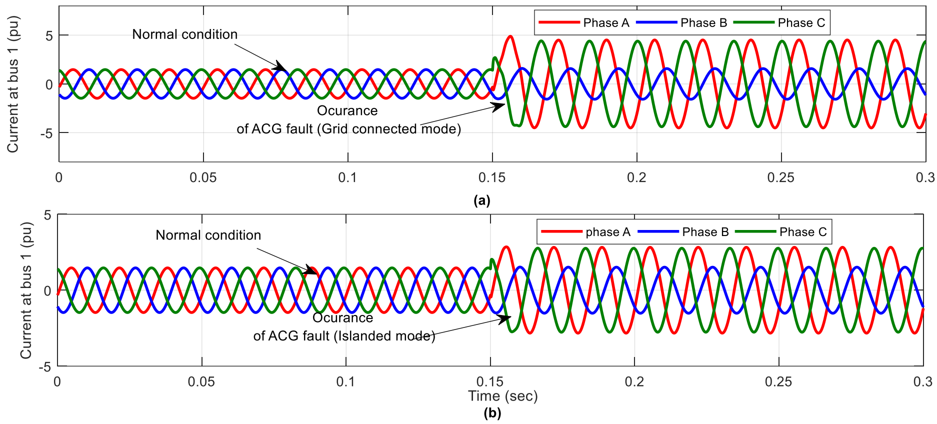

Fig. 8 – *Level of the fault current after occurrence of ACG fault:* (a) *Grid connected mode;* (b) *Islanded mode.*

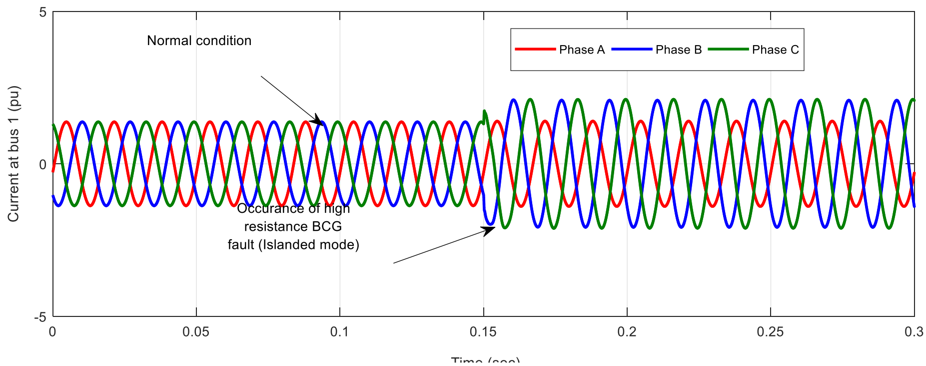

Fig. 9 – *Fault current variations when fault resistance is changing with BCG fault in islanded mode.*

6.5 Validation of the protection scheme when load is changing and fault occurs under grid connected and islanded mode

Sudden changes in load condition that are connected from microgrid can result into some erroneous tripping operations in the microgrid. For traditional protection schemes, such conditions are not significant when protecting against such variations. The other serious problem can be harmonic injection in the system. As a result, this subsection validates protection scheme to check, the immunity of the classifier against change in load condition. **Table 6** is given to demonstrate the complete range of the load changes and variety of the faults. The results in Table in this subsection show that responses are accurate and effectively identified in grid and islanded mode. Results after careful evaluation in the below table indicate that protection scheme efficiently operates in these conditions.

Table 6
Classifier response during load variation for dissimilar loads.

Types of mode	Load variation	Type of fault	Protection scheme response
Grid connected	±20 in L1	BG	BG
	±30 in L4	ABCG	ABCG
	±40 in L6	ABG	ABG
	±50 in L8	AB	AB
	±55 in L10	AC	AC
	±60 in L5	ABC	ABC
Islanded mode	±20 in L1	BG	BG
	±30 in L4	ABCG	ABCG
	±40 in L6	ABG	ABG
	±50 in L8	AB	AB
	±55 in L10	AC	AC
	±60 in L5	ABC	ABC

6.6 Comparison with existing protection schemes under dissimilar parameters

A comparative analysis of the proposed protection scheme is examined in this subsection using several given parameters. **Table 7** shows complete details of the parameters and reported tasks in the existing and proposed protection schemes. After observation it is found that reported SVM-based approach is efficient and performs better when comparing it with existing schemes.

Table 7
Comparative assessment of different existing techniques.

Used parameters	Existing schemes given in literature			
	[13]	[14]	[17]	Proposed scheme
Input-features	Current	Current	Current	Voltage and current
Fault-parameters	Fault resistance at a particular instant	Fault-Resistance (some cases)	Fault-resistance and distance	Many cases of the fault resistance under, length of fault
Performed work	Fault detection and classification	Fault-detection	Fault-detection and fault classificatio n	Mode identification, Fault detection /classification, Section identification
Test-cases	Not-taken	Not-taken	Not-taken	Considered (13509)
Intermittent conditions	Not considered	Not considered	Not considered	Considered

7 Limitations and Outlook of the Research

In order to detect and classify faults in the AC microgrid, a protection scheme is given which is operates in dissimilar operating conditions. To observe the robustness of the protection scheme, uncertainty has been considered; however, dissimilar geographical locations affect the output of renewable energy sources as per weather conditions. Therefore, the propose work can be extended under wide dissimilarities in locations around the world, and the performance of the protection scheme can be analyzed under dissimilar faults with distinct grounding conditions in the any type of power distribution system.

8 Conclusion

The microgrid adoption to connect load centres is significant over traditional power distribution system but due to variety of random challenges its protection is the main difficulty. In this research, a support vector machine-based protection scheme is used to protect it from such fault challenges under varying operating scenarios. A discrete wavelet transform-based data processing tool was utilized to process voltage and current signals collected from selected bus. A number of diversified fault conditions were considered under the grid-connected and islanded modes of operation. The fault current level according to fault location and its resistance can vary therefore validation was carried out under a variety of AC faults in grid and islanded mode. Among the reported existing literature, the proposed SVM-based protection scheme was found to be good when observing its performance. The achieved accuracy after mode detection was 98.16% and 100%, while for fault detection and classification, it was 99.36% and 98.79%, respectively, under grid-connected and islanded modes. The overall performance of section identifier modules with achieved accuracy of 99.04% and 98.31% indicates that the protection scheme is invulnerable and operates efficiently.

9 References

[1] A. Muhtadi, D. Pandit, N. Nguyen, J. Mitra: Distributed Energy Resources Based Microgrid: Review of Architecture, Control, and Reliability, IEEE Transactions on Industry Applications, Vol. 57, No. 3, May-June 2021, pp. 2223 – 2235.

[2] M. Naderi, Y. Khayat, Q. Shafiee, F. Blaabjerg, H. Bevrani: Robust Synchronization of Multiple Converter-Based Weak Microgrids for Smooth Interconnection, IEEE Transactions on Power Systems, Vol. 39, No. 2, March 2024, pp. 2763 – 2774.

[3] M. Imran Azim, L. Ali, J. Peters, M. H. Shawon, F. R. Tatari, S. M. Muyeen, A. Ghosh: A Proportional Power Sharing Method Through a Local Control for a Low-Voltage Islanded Microgrid, Energy Reports, Vol. 8, December 2022, pp. 51 – 59.

[4] M. H. Mousavi, H. M. CheshmehBeigi, M. Ahmadi: A DDSRF-Based VSG Control Scheme in Islanded Microgrid Under Unbalanced Load Conditions, Electrical Engineering, Vol. 105, No. 6, December 2023, pp. 4321 – 4337.

[5] M. Ahmadi, M. H. Mousavi, H. Moradi, K. Rouzbehi: A New Approach for Harmonic Detection Based on Eliminating Oscillatory Coupling Effects in Microgrids, IET Renewable Power Generation Vol. 17, No. 14, October 2023, pp. 3536 – 3553.

[6] G. Mirzaeva, D. Miller: DC and AC Microgrids for Standalone Applications, IEEE Transactions on Industry Applications, Vol. 59, No. 6, November-December 2023, pp. 7908 – 7918.

[7] N. Khosravi, R. Baghbanzadeh, A. Oubelaid, M. Tostado-Véliz, M. Bajaj, Z. Hekss, S. Echalih, Y. Belkhier, M. Abou Houran, K. M. Aboras: A Novel Control Approach to Improve the Stability of Hybrid AC/DC Microgrids, Applied Energy, Vol. 344, August 2023, p. 121261.

[8] W. Yang, S. Miao, Z. Liu, J. Han, Y. Xiong: Control of Parallel Bidirectional Converters Under Unbalanced Conditions in an AC/DC Hybrid Microgrid, Electric Power Systems Research, Vol. 226, January 2024, p. 109952.

[9] Z. Lyu, J. Yi, J. Song, B. Liu: Coordinated Optimal Control and Dispatching Operation of Grid-Connected AC/DC Hybrid Microgrid Group, Electric Power Systems Research, Vol. 221, August 2023, p.109430.

[10] G. P. Santos, A. Tsutsumi, J. C. M. Vieira: Enhanced Voltage Relay for AC Microgrid Protection, Electric Power Systems Research, Vol. 220, July 2023, p. 109310.

[11] D. A. Etingov, P. Zhang, Z. Tang, Y. Zhou: AI-Enabled Traveling Wave Protection for Microgrids, Electric Power Systems Research, Vol. 210, September 2022, p. 108078.

[12] J. Nsengiyaremye, B. C. Pal, M. M. Begovic: Microgrid Protection Using Low-Cost Communication Systems, IEEE Transactions on Power Delivery, Vol. 35, No. 4, August 2020, pp. 2011 – 2020.

[13] O. A. Gashteroodkhani, M. Majidi, M. Etezadi-Amoli: A Combined Deep Belief Network and Time-Time Transform Based Intelligent Protection Scheme for Microgrids, Electric Power Systems Research, Vol. 182, May 2020, p. 106239.

[14] D. Liu, A. Dyśko, Q. Hong, D. Tzelepis, C. D. Booth: Transient Wavelet Energy-Based Protection Scheme for Inverter-Dominated Microgrid, IEEE Transactions on Smart Grid, Vol. 13, No. 4, July 2022, pp. 2533 – 2546.

[15] Y.- Y. Hong, M. T. A. M. Cabatac: Fault Detection, Classification, and Location by Static Switch in Microgrids Using Wavelet Transform and Taguchi-Based Artificial Neural Network, IEEE Systems Journal, Vol. 14, No. 2, June 2020, pp. 2725 – 2735.

[16] J. O. C. Pereira Pinto, M. Moreto: Protection Strategy for Fault Deection in Inverter-Dominated Low Voltage AC Microgrid, Electric Power Systems Research, Vol. 190, January 2021, p. 106572.

[17] A. Langarizadeh, S. Hasheminejad: A New Differential Algorithm Based on S-Transform for the Micro-Grid Protection, Electric Power Systems Research, Vol. 202, January 2022, p. 107590.

[18] S. C. Vegunta, M. J. Higginson, Y. E. Kenarangui, G. T. Li, D. W. Zabel, M. Tasdighi, A. Shadman: AC Microgrid Protection System Design Challenges – A Practical Experience, Energies, Vol. 14, No. 7, April 2021, p. 2016.

[19] A. Abdullah: Ultrafast Transmission Line Fault Detection Using a DWT-Based ANN, IEEE Transactions on Industry Applications, Vol. 54, No. 2, March-April 2018, pp. 1182 – 1193.

[20] A. A. Ogaili, M. N. Hamzah, A. Ab. Jaber, E. Ghane: Application of Discrete Wavelet Transform for Condition Monitoring and Fault Detection in Wind Turbine Blades: An Experimental Study, Engineering and Technology Journal, Vol. 42, No. 1, January 2024, pp. 104 – 116.

[21] J. Barros, R. I. Diego, M. de Apraiz: Applications of Wavelet Transform for Analysis of Harmonic Distortion in Power Systems: A Review, IEEE Transactions on Instrumentation and Measurement, Vol. 61, No. 10, October 2012, pp. 2604 – 2611.

[22] A. A. Abdoos, P. K. Mianaei, M. R. Ghadikolaei: Combined VMD-SVM Based Feature Selection Method for Classification of Power Quality Events, Applied Soft Computing, Vol. 38, January 2016, pp. 637 – 646.

[23] H. Erişti, Y. Demir: A New Algorithm for Automatic Classification of Power Quality Events Based on Wavelet Transform and SVM, Expert Systems with Applications, Vol. 37, No. 6, June 2010, pp. 4094 – 4102.

[24] S. P. Tiwari: Artificial Neural Network Based Algorithm for Fault Detection in a Ring DC Microgrid Under Diverse Fault Conditions, Distributed Generation & Alternative Energy Journal, Vol. 38, No.1, December 2023, pp. 23 – 40.