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A Teager Kaiser Energy Operator–Based Novel Differential Energy Technique for the Detection of Very High Impedance Faults in AC Microgrid Feeder

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Protection of AC microgrids is difficult due to bidirectional power flow, inverter-based distributed generation, and significantly reduced fault currents, especially in islanded operation.*
- *Conventional overcurrent and impedance-based protection schemes struggle to detect high-impedance faults and often fail under non-fault transient conditions such as load or capacitor switching.*
- *Advanced signal-processing and differential protection techniques have been explored to improve sensitivity and selectivity in microgrid fault detection.*

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ABSTRACT

It is quite challenging to protect AC microgrids that operate in both islanded and grid-connected modes due to the large differences in fault currents between the two modes. Microgrid protection is a challenging task, as traditional overcurrent relays do not function effectively with integrated renewable distributed power due to the bidirectional flow. When it comes to power supply, solar-based distributed generators (DGs) are quite reliable; however, when they are integrated with inverters, the fault current is limited, making protection challenging. This article proposes a novel protection scheme that uses differential current followed by a Teager Kaiser Energy Operator with a dual filtering method. The scheme is able to detect faults with high impedances up to 1000 Ω in grid-connected mode and 500 Ω in islanded mode. The scheme was also tested for load switching, capacitor switching, nonlinear loading, and DG outages and is able to differentiate between the non-fault transient events and fault events. The scheme's efficiency was checked in radial and mesh configurations. The scheme is able to detect faults within 1.3 ms. Rigorous simulations were conducted to validate the scheme's efficiency, including evolving faults, simultaneous faults, and composite faults. The scheme performed very well in detecting these faults.

***Index Terms*—**Distributed generators, high impedance fault, Microgrid feeder protection, Teager Kaiser Energy Operator

I. INTRODUCTION

Electricity consumption has significantly increased in recent years due to the rapid expansion of nations. Increasing demand cannot be met by conventional fossil fuel-based power generation, and major environmental issues are associated with it, such as air pollution, the greenhouse effect, and global warming. In order to ensure a sufficient supply of electricity and environmental sustainability, there is a major shift toward the use of renewable energy sources (RES) to attain net-zero emissions of greenhouse gases. However, traditional power systems have become more complex due to the increasing integration of RES into the grid [1]. Renewable energy sources like solar energy, wind energy, fuel cells, and energy storage are compact and independent and form a decentralized power system, i.e., a Microgrid (MG). It can be operated as a single unit with a direct user connection. It functions as a responsive power source that can swiftly adapt to fulfill transmission and distribution demands for larger networks [2]. The MG offers many benefits to the consumer and utilities, including high efficiency and improved energy, optimized energy consumption, reliability, and power quality, and it can be operated in Grid-Connected Mode (GCM) or IM (Islanded Mode) [3]. Topological changes in the operating state can disable the general fixed setting of over current relay-based protection (GCM to IM and vice versa). When operating in GCM and off-grid modes, the fault current magnitude changes. In the off-grid mode of operation, the MG may contribute a different fault current than it does in the GCM. Also, MG protection becomes extremely difficult due to the growing use of inverter-integrated distributed generation, which is the cause of the low fault current level and

WHAT DOES THIS STUDY ADD ON THIS TOPIC

- *Introduces a novel differential energy–based protection scheme that combines differential current measurement with the Teager–Kaiser Energy Operator (TKEO) and dual filtering.*
- *Demonstrates reliable detection of very high impedance faults (up to 1000 Ω in grid-connected mode and 500 Ω in islanded mode) while accurately distinguishing them from non-fault transients.*
- *Validates fast and robust fault detection (within 1.3 ms) across multiple operating conditions, network topologies (radial and mesh), and complex fault scenarios such as evolving, simultaneous, and composite faults.*

may make the protection schemes imprecise and unreliable by failing to detect high impedance faults (HIFs).

Fault analysis is a study that aids in detecting, comprehending, and treating issues in power systems. The distribution network has an inherent tendency to experience faults in a power system network, and fault detection is essential to minimizing power supply interruptions and safeguarding costly industrial equipment [4].

An important objective of all protection systems is to provide a high degree of service continuity in the event that the power system network experiences malfunctions. To avoid false relay tripping, the protective strategy needs to be precisely designed for both grid-integrated and off-grid modes of operation.

To overcome these obstacles and guarantee MG's secure and dependable operation, ongoing research and development activities concentrate on creating robust protection strategies, standardizing protocols, and enhancing interoperability. Researchers have devised a number of protection strategies, which are discussed in the literature review.

In recent years, a lot of research has been done on creating a protection plan specific to MGs. In addition to conventional voltage and current-based methods, researchers have employed a wide range of additional criteria for this goal. [5] presented a protection mechanism based on differential frequency. Numerous articles in the literature have discussed the problems and difficulties the MG faces in terms of protection [6] and speak in great detail about the protection issues with the MG, both direct current and alternating current (AC), which additionally propose methods for protection using substitute alternatives.

In [7], a fault detection method for AC MGs based on the Teager Kaiser energy operator (TKEO) is described. The proposed technique examines the current signal to identify faults in the MG. The combination of squared three-phase currents recorded at one end of the line is the foundation for the method. This article discusses different symmetrical and unsymmetrical faults. Both grid-integrated mode and off-grid mode simulations are performed. However, the suggested plan does not take into account the effects of simultaneous, evolving, and composite faults.

In [8], a differential transient current-based fault detection technique for the MG was proposed. Still, the primary disadvantage is that when there is a DER outage or capacitor and load switching, the switching transients may cause issues, and backup protection is necessary to safeguard the MG.

Afterward, an MG's positive-sequence current-based technique, as described in [9], can only be used in a low-resistance fault. [10] suggests a further adaptive strategy that uses a current signal and a cycle-to-cycle comparison.

Primary and backup protection should be supplied by monitoring the change in fault current in a steady condition, as suggested in [11]. This plan might not, however, provide good results in the case of high resistance defects, and its effectiveness is limited to low distributed generator (DG) penetration. The problem may not be correctly identified by the distance-based [12] and two overcurrent [13] approaches. A steady state change in the fault current-based system is introduced for primary and backup protection. Nonetheless, this technique might not be able to detect a HIF. Choosing appropriate fuzzy rules and membership functions could become challenging when using this method. In [14], differential energy is calculated, and the fault is subsequently identified using an empirical mode decomposition-based method for the current. In [15], a protective method was developed based on incremental voltage and current signals and utilizing the short-time correlation transform concept. A Clarke transformation-based adaptive protection plan for an MG was proposed in [16]. This plan requires an expensive phasor measurement instrument. Furthermore, the effects of switching transients, HIF, etc., have not been taken into account. A machine learning-based plan and Hilbert-Huang transform have been proposed in [17] for MG protection. In this technique, the fault categorization is done using a model decomposition of the current. However, the suggested scheme's actual implementation is extremely complex.

A differential method utilizing Hilbert-Huang and S-transforms is suggested in [18] for determining the differential spectral energy content at the protected feeder ends. The DG transients and unbalanced loads could cause the scheme to fail. Furthermore, a high sampling rate is necessary for the method based on traveling waves, as described in [19].

A strategy based on the support vector data description algorithm is put out in [20] to locate the distribution network issue with a variable degree of DG penetration. However, this approach is challenging for the real system due to the database's requirement for more memory and reliance on system settings.

In [21], a novel auto-encoder and fuzzy C-means-based single line-to-ground fault detection technique was developed. However, this method has not been checked for faults during the IM of operation.

In [22], a novel approach using an optimal hybrid bell algorithm is discussed, which uses a combination of standard normal distribution and Poisson distribution method for fault analysis, and it is tested on 9-bus and 39-bus systems. The algorithm can terminate fault within 0.55 sec. Further, with the use of the Routh-Hurwitz criteria, the method was authenticated.

According to the literature review, several present techniques fail to meet required expectations, such as different non-fault scenarios and off-grid operating modes, essential for efficient MG protection. Furthermore, complicated fault conditions, like simultaneous, evolving, and composite faults, are neglected while designing protection strategies. This paper suggests a novel fault detection system for an inverter-based MG. First, sum of relay currents (SRCs) is obtained by taking the differential current from both ends. A TKEO-based technique is applied to SRC signals to identify a fault, and a moving RMS filter with a median filter is used to obtain the fault detection index (FDI) signal. Because TKEO only takes two samples of historical data for computation, it offers superior time resolution and less computation load.

The following lists the main contributions of the suggested scheme:

- The proposed scheme only requires current measurement at both ends.
- The scheme remains unaffected by fault inception angle (FIA), location, and type.
- It can detect faults within 1.3 ms.
- It does not require any training, unlike machine learning and AI methods.
- Symmetrical and unsymmetrical faults with up to 1000 Ω fault resistance can be detected.
- It works successfully for evolving, simultaneous, and composite faults.
- It is robust against switching transients such as capacitor switching, load switching, and nonlinear loading.
- The suggested protection strategy effectively differentiates internal and external faults or disturbances.
- The scheme accurately works for GCM and off-grid modes.

II. METHODOLOGY

A simple system used for distribution system testing is the IEEE 13 bus feeder. Shunt capacitors, a regulator, many short unbalanced transmission lines, and one source are its components, and they run at 4.16 kV. At buses 634 and 680, powered DGs are included in the standard IEEE 13-bus network. Single-phase or two-phase systems are the cause of the imbalance laterals in the IEEE 13-bus test system. The remaining buses are balanced three-phase buses, whereas buses 645, 646, and 684 are two-phase (i.e., only A and C), and bus 611 is single-phase only. Engineers and researchers frequently use the IEEE 13-bus system to evaluate their distribution system analysis models and techniques. It is essential to the creation of complex distribution management systems. The test system's one-line diagram is displayed in Fig. 1. The parameters of the system are referenced from [23].

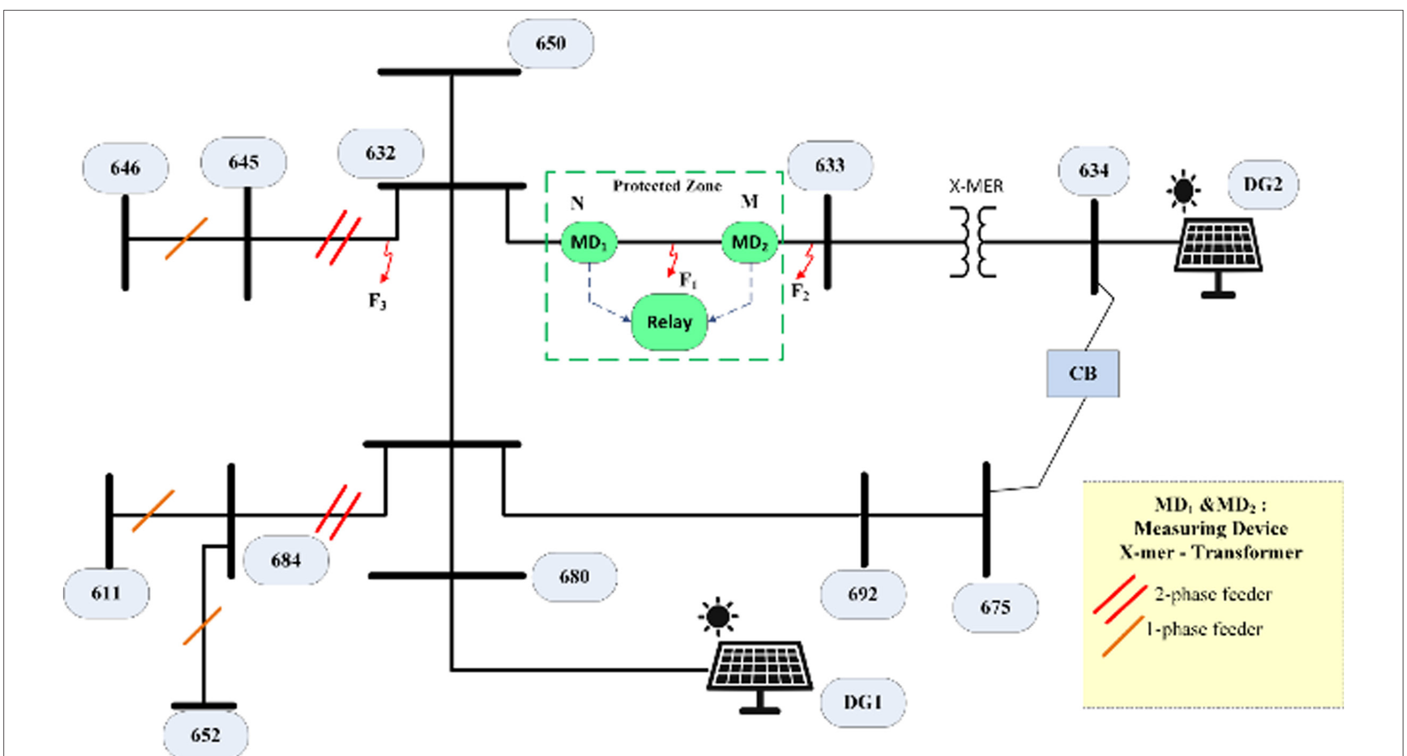

Fig. 1. IEEE 13 bus modified system.

The M-side, which stands for the DG terminal, and the N-side, which is the grid connection point, are the two separate locations in the MG where three-phase currents are measured in the suggested scheme. The main goal is to determine whether faults are present by determining the difference in current between these two points. First, the grid-side current i_{an}, i_{bn}, i_{cn} is subtracted from the dg-side current i_{am}, i_{bm}, i_{cm} to determine the differential current phase-wise. I_{da} i.e, differential current for Phase A is obtained using (1) by subtracting i_{an} and i_{am}. Similarly, differential current I_{db} for Phase B is obtained by subtracting i_{bn} and i_{bm} and Phase C by subtracting i_{cn} and i_{cm} using (2) and (3). After that, SRC is obtained using (4) by adding differential currents, i.e., I_{da} as shown in (1), I_{db} in (2), and I_{dc} in (3). The discrete form of TKEO is represented in (6)

and continuous form in (5). The TKEO is applied to the SRC signal in order to increase the sensitivity of detection, which is evaluated using (7). After applying TKEO, it is passed through a moving RMS filter which is obtained using (8). The filter removes the fluctuation and gives a steady value. Where *RMSV*(*n*) is the filtered output, *TKEO*(*SRC*(*n*)) is the input signal, and N is the window size. After applying the RMS filter, a median filter is used to handle the energy signal as shown in (9). It eliminates transient noise, and this stage makes fault identification more robust. With $n \in \{1,2,\ldots,N\}$ and N being the signal length, the one-dimensional median filter works on a discrete-time signal *RMS*[*n*]. The filtered output signal $F_{rmsv}[n]$ is generated by sliding a window of odd length L = 2k + 1 across the input signal and calculating the median of the samples inside the window centred at *RMSV*[*n*]. Equation (10) represents the FDI.

$$I_{da} = |I_{an}| - |I_{am}| \tag{1}$$

$$I_{db} = |I_{bn}| - |I_{bm}| \tag{2}$$

$$I_{dc} = |I_{cn}| - |I_{cm}| \tag{3}$$

During fault events, the grid side contributes considerably more current than the DG side. Because the current difference becomes more noticeable during disturbances, this behavior is the foundation for fault identification.

Then, SRC is obtained using:

$$SRC = I_{da} + I_{db} + I_{dc} \tag{4}$$

The TKEO is applied to the differential current signal in order to increase the sensitivity of detection. The TKEO accurately collects the signal's immediate energy content. Any continuous-time signal's TKEO [24] is defined as:

$$TKEO\left(S(t)\right) = \left[\frac{dS(t)}{dt}\right] - \left(S(t)\right)\left(\frac{d^2\left(S(t)\right)}{dt^2}\right) \tag{5}$$

TKEO can now be rewritten in the discrete form as follows:

$$TKEO\left(S(n)\right) = \left(S(n)\right)^2 - \left(S(n-1)\right)\left(S(n+1)\right) \tag{6}$$

Where (*S* (*n*–1)) is the past value, *S* (*n*) is the present value, and (*S* (*n* + 1)) is the upcoming value. It can be seen from the formula that three successive sample values are required. Thus, it is simple to use and provides great accuracy for protecting power systems. In order to better observe the point of change during a fault scenario, TKEO was applied to the SRC signal.

$$TKEO\left(SRC(n)\right) = \left(SRC(n)\right)^2 - \left(SRC(n-1)\right)\left(SRC(n+1)\right) \tag{7}$$

The system is stable when the energy value is close to zero under normal, non-fault conditions. However, abrupt changes in current magnitude during a failure cause a noticeable energy spike.

$$RMSV(n) = \sqrt{\frac{1}{N}\sum_{K=0}^{N-1} TKEOSRC(n-k)^2} \tag{8}$$

$$f_{rmsv}(n) = median\left(\{RMS[n-k], x[n-k+1], \ldots, x[n], \ldots, x[n+K]\}\right) \tag{9}$$

Where:

- f_{rmsv}[n]: Output of the filtered signal at index n
- *RMS*[n]: Input signal
- k: Half the window size (i.e., k = (L-1)/2)
- median{.}: Middle value of the sorted sequence

$$FDI = f_{rmsv} \tag{10}$$

The final indicator of fault existence is the median-filtered output, and the FDI is set according to this value. If FDI > threshold (Th) value, the fault is detected, the trip signal is 1, and if the system is healthy, the trip signal remains zero. The flow diagram for methodology can be seen in Fig. 2.

A. Threshold Selection

After conducting thorough simulation studies, the Th selection in this article was determined. Various fault types have been taken into consideration, including different-phase faults (L-L-L/L-L-L-G), LG, L-L-G, and L-L. Non-fault scenarios and external three-phase faults have also been considered for Th selection. Additionally, the MG was analyzed in both off-grid and grid-integrated operating modes. The current is measured in all three phases from both ends of the protected feeder, and a summation of the three-phase differential current is carried out. The TKEO operator was then applied to calculate energy, followed by a one-dimensional median filter. In the protected feeder, multiple short-circuit faults took place at different sites. The fault resistance for a double line-to-ground fault in a range from 0.1 Ω to 1000 Ω is analyzed. Threshold selection is essential for the relay-tripping mechanism. For internal faults, the lowest value of FDI is taken into consideration, and for external faults, the maximum value of FDI is considered. The minimum value of FDI is found at AG fault to be 0.17 A^2, and the maximum value of FDI is found to be 0.005 A^2 under non-fault conditions. In order to keep the MG safe from outside faults, this action was taken. Therefore, the Th value to detect HIF (up to 1000 Ω) is taken as 0.1 A^2, considering an approximate safety margin of 100%.

III. RESULTS AND DISCUSSION

The performance assessment for different types of faults and non-fault cases is added below.

A. Performance Assessment for Different Locations with Varying Fault Resistance

Fig. 3 illustrates an A-G on internal fault in the center of the protected feeder with R_f = 1 Ω at 0.2 s. Fig. 4 provides FDI for an A-G on internal

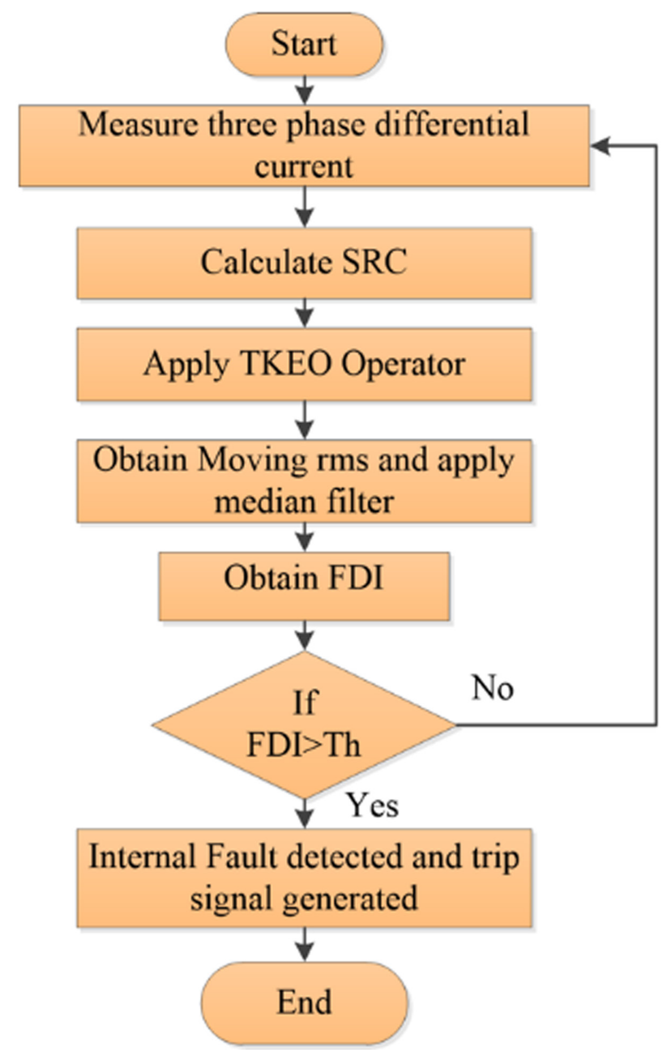

Fig. 2. Flow chart of the scheme.

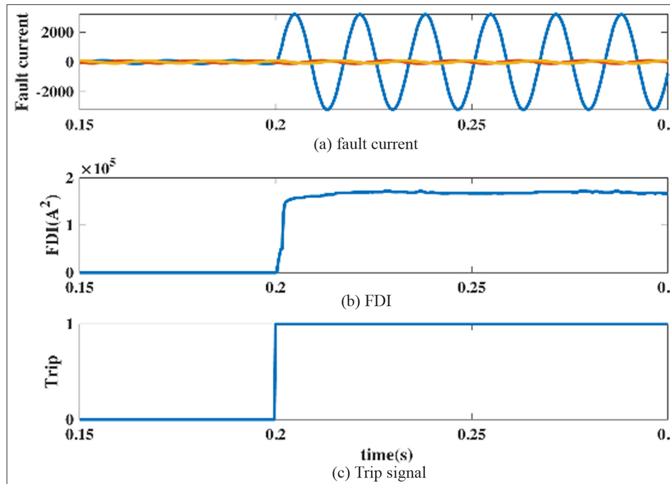

Fig. 3. Internal A-G fault with fault resistance $R_{f=}$ 1 Ω.

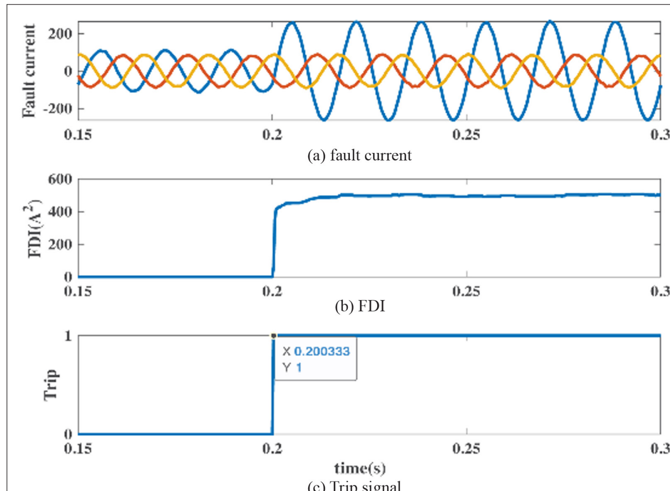

Fig. 4. A-G fault at 0.2 s with fault resistance R_f = 20 Ω.

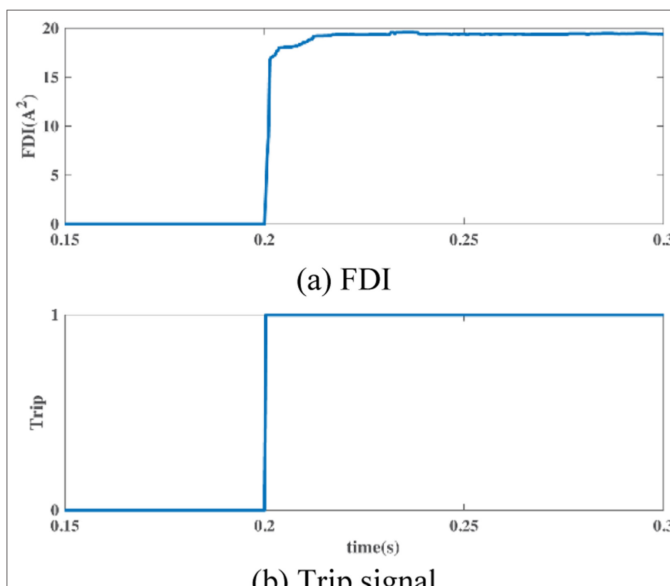

Fig. 5. A-G fault at 0.2 s with fault resistance R_f = 100 Ω.

fault in the center of the protected feeder with R_f = 20 Ω at 0.2 s. Fig. 5 provides FDI for an a-g on internal fault in the center of the protected feeder with R_f = 100 Ω at 0.2 s. Similarly, R_f = 500 and R_f = 1000 are provided in Figs. 6 and 7. A trip signal is produced at 0.20033 s because FDI exceeds the Th for all the cases. Similarly, AB-G fault was conducted for 500 Ω and 1000 Ω fault resistances. It can be seen in Figs. 8 and 9 that the FDI value increases with the fault occurrence at 0.2 s, and the trip signal becomes 1, showing the fault is detected. The fault case for the ABC-G fault can be seen in Fig. 10, with a fault resistance of 1000 Ω.

If FDI is less than Th, the trip signal turns 0, i.e., for external fault occurrences, and if it is greater than Th, the trip signal turns 1, i.e., for internal fault events. The results obtained indicate that the suggested technique can successfully detect internal faults.

B. Performance Assessment for Different Inception Angles

Because faults can happen at any time, the FIA may impact how well protective systems work. Table I includes a variety of outcomes for various FIAs in order to analyze the impact of the FIA. It demonstrates that the recommended technique's functionality is unaffected by modifications to FIAs. Table I shows that every fault is accurately detected with an average fault detection time (T_d) of 4.5 ms.

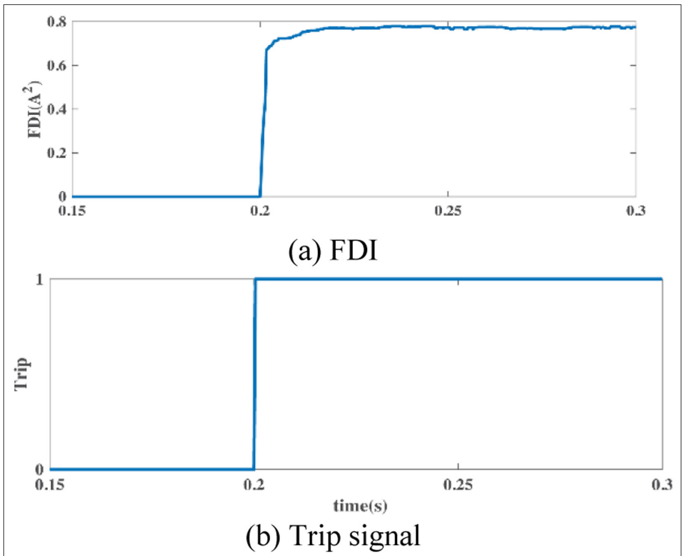

Fig. 6. A-G fault at 0.2 s with fault resistance $R_f = 500\ \Omega$.

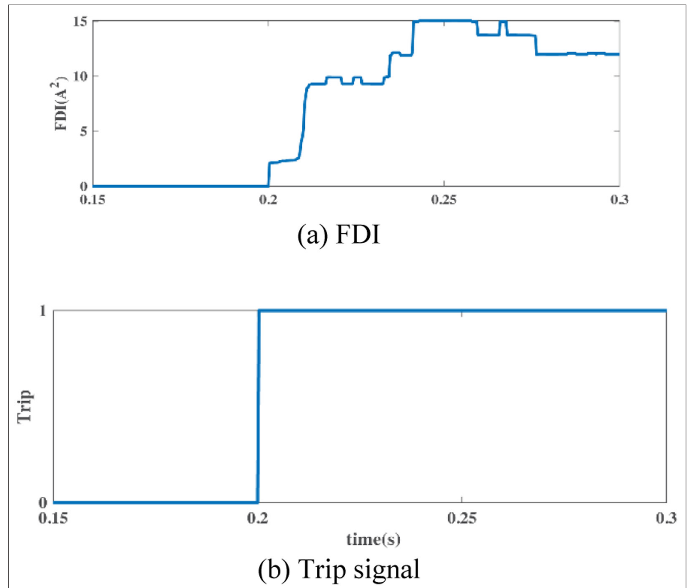

Fig. 8. AB-G fault at 0.2 s with fault resistance $R_f = 500\ \Omega$.

C. Performance Assessment for Change in Topology

The amount and direction of the current may change when the MG topology shifts from radial to mesh and vice versa. Consequently, the different fault current levels and behavior may affect the protection mechanisms. With the use of CB, buses 634 and 675 were connected to transform the simulated MG's topology from radial to mesh, as seen in the IEEE 13 bus system Fig. 1. Fig. 11 shows the performance of the suggested strategy for an AC-G internal fault in the center of the protected feeder with mesh type topology and $R_f = 100\ \Omega$ at 0.2 s. The results for different faults at different fault location sites in mesh-connected mode are noted in Table II.

D. Performance Assessment for Simultaneous, Composite, and Evolving Faults

The term "evolving fault" refers to a power system fault that, over a brief time, progresses from a single-phase or phase-to-phase fault, which involves a limited number of phases, to a more severe multi-phase or three-phase fault. Conventional protection schemes have difficulties detecting these types of dynamic behavior, which could delay precise identification and isolation as the fault characteristics change over time. In an evolving fault, two faults emerge at different times at the same network fault location. The proposed scheme has been tested for an evolving fault with an A-G fault at 0.2 s and BC-G fault at 0.22 s with 10 Ω resistance, and it is found that the scheme is able to operate the relay correctly, and the fault can be detected. From Fig. 12, it can be seen that the FDI crosses the set Th and that the trip signal is high.

In the real world, power system faults often occur as part of a chain of events. In certain instances, two or more faults can happen at the same time, either in one place or at different points over the network. Simultaneous faults refer to when two or more faults act at

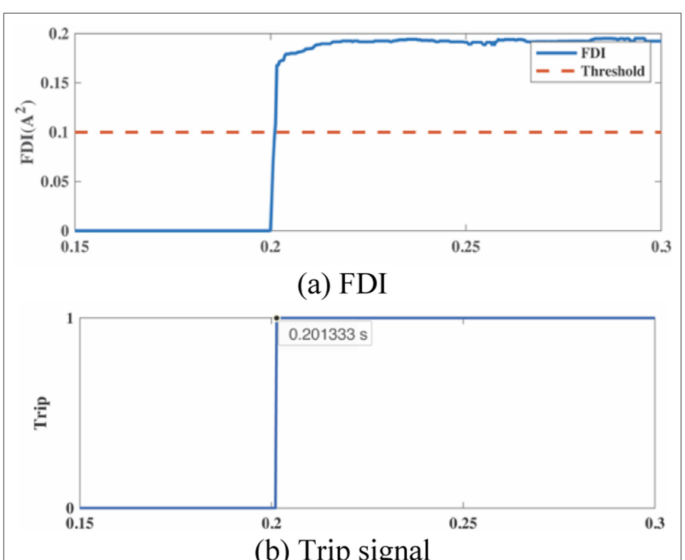

Fig. 7. A-G fault at 0.2 s with fault resistance $R_f = 1000\ \Omega$.

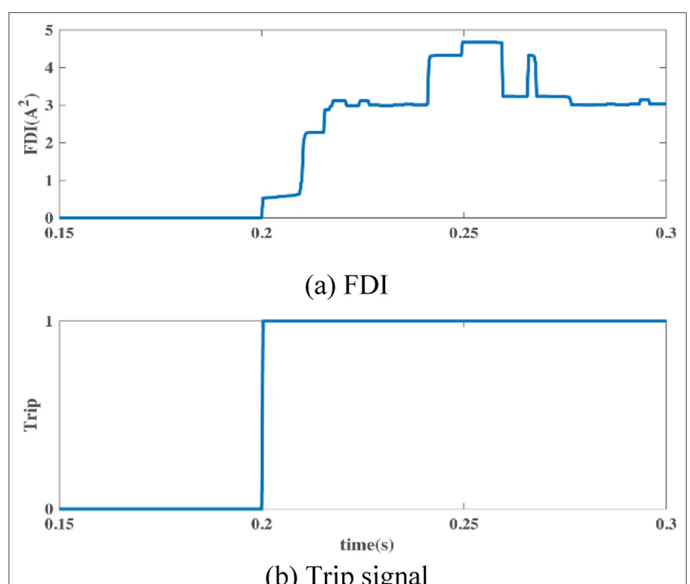

Fig. 9. AB-G fault at 0.2 s with fault resistance $R_f = 1000\ \Omega$.

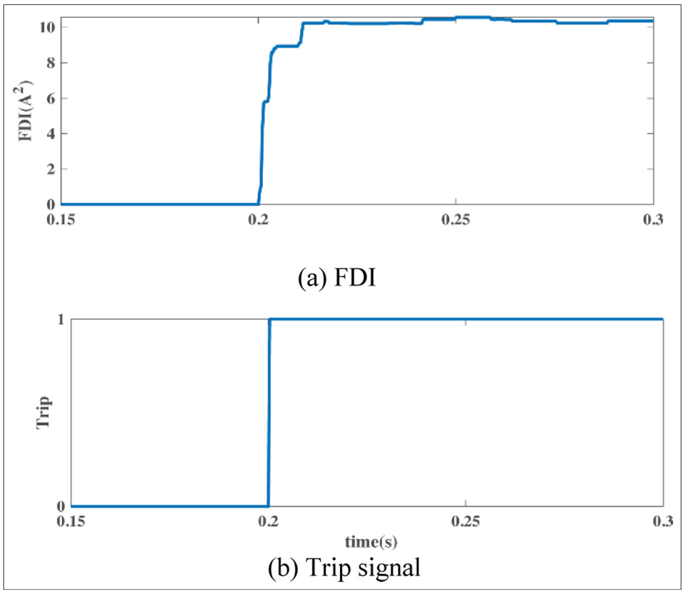

Fig. 10. ABC-G fault at 0.2 s with fault resistance R_f = 1000 Ω in the middle of the protected feeder.

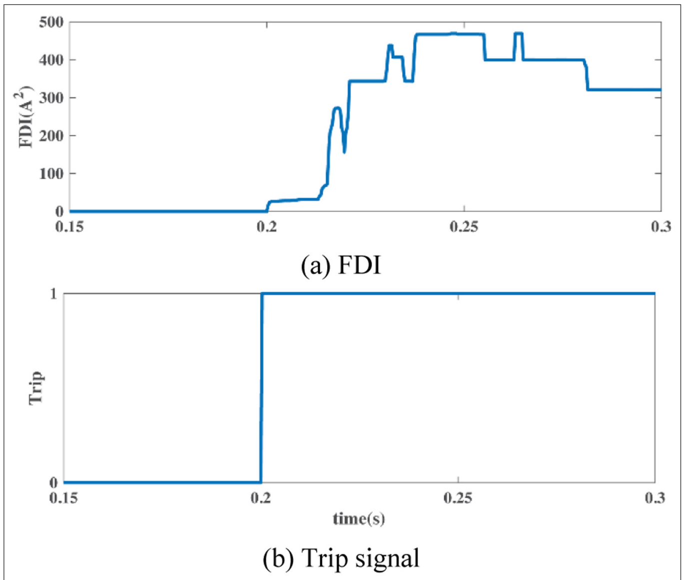

Fig. 11. AC-G fault in the middle of the protected feeder with fault resistance R_f = 150 Ω and mesh topology.

the same time. L–G and L–L faults can occur together or as discrete faults occurring in different parts of the grid. Though simultaneous faults rarely occur, they are challenging to detect because their current paths vary. Due to their bi-directional power flow and many dispersed power sources, AC MGs make it extremely challenging to classify simultaneously occurring faults. As a result, it is critical that AC MGs have strong protection systems that can manage several fault occurrences simultaneously.

Simultaneous fault with AB-G fault of 150 Ω at 0.2 s and AG fault at 0.2 s with 0.01 Ω resistance is conducted, and it can be seen in Fig. 13 that the devised scheme is able to detect the fault.

A composite fault occurs when an MG internal fault and a non-fault event, such as a DG outage, happen at the same time. To prevent damage to the other components of the MG, the relay must detect an event of this kind. The scheme is also able to detect composite faults. To verify this, a test case has been taken into consideration, and an AB-G fault with 10 Ω at 0.2 s and DG tripping at the same time is carried out, and the results can be seen in Fig. 14.

TABLE I. RESULTS FOR DIFFERENT FAULT INCEPTION ANGLES

FIA	FT	R_f	FDI	T_d
0	A–G	100	17.032	0.33 ms
20	A–G	100	17.04	1 ms
60	A–G	100	16.95	3 ms
90	A–G	100	17.00	4.33 ms
180	A–G	100	17.15	8.33
210	A–G	100	17.20	10 ms

*FT = Fault type.
*FIA = Fault inception angle.
*R_f = Fault resistance.
*FDI = Fault detection index.
*T_d = Fault detection time.

E. Performance Assessment for Off-Grid Mode

The proposed scheme has also been tested for off-grid mode. The fault current level is limited in the islanded mode of operation. The traditional dI-based technique cannot detect the fault because the fault current is not contributed by the grid in the off-grid mode,

TABLE II. DIFFERENT RESULTS (OF INTERNAL FAULTS) FOR MESH-CONNECTED MODE

FT	FS	R_f	FDI (A^2)	T_d (ms)	Trip
A–G	76.20	100	9.90	0.33	1
A–G	76.20	150	4.34	0.67	1
B–G	0.3048	100	16.82	0.33	1
B–G	76.20	50	41.03	0.33	1
B–G	0.3048	50	68.76	0.67	1
A–G	91.44	100	10.59	1	1
AC–G	91.44	10	4713	1.33	1
BC–G	91.44	0.1	612994	2.33	1
ABC–G	30.48	30	1042	0.67	1
ABC–G	149.35	30	985	1	1
ABC–G	149.35	0.001	781887	1	1
AC–G	149.35	1	121332	2	1
C–G	137.16	5	8419	1.67	1
AB	91.440	120	7.46	23.33	1
BC	45.720	7	2297	3	1

*FT = Fault type.
*FS =Fault site in meters from Bus 632.
*R_f = Fault resistance.
*FDI = Fault detection index.
*Td = Fault detection index.

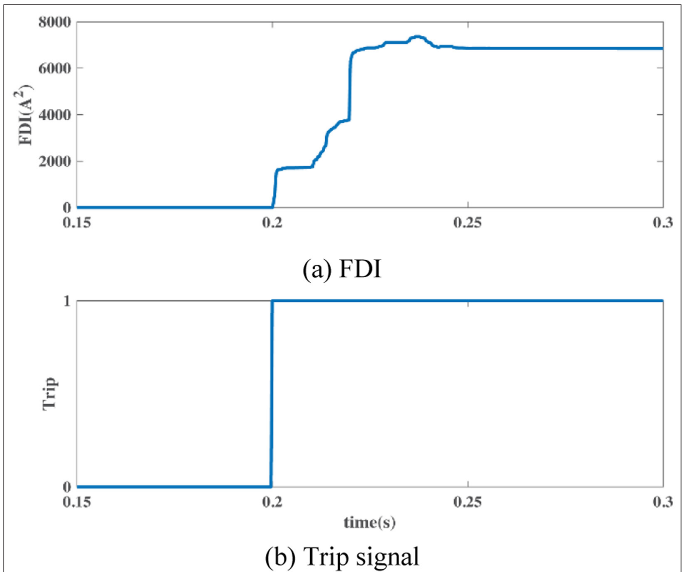

Fig. 12. Result for evolving fault, AG fault at 0.2 s and BC-G at 0.22 s with $R_f = 10\ \Omega$.

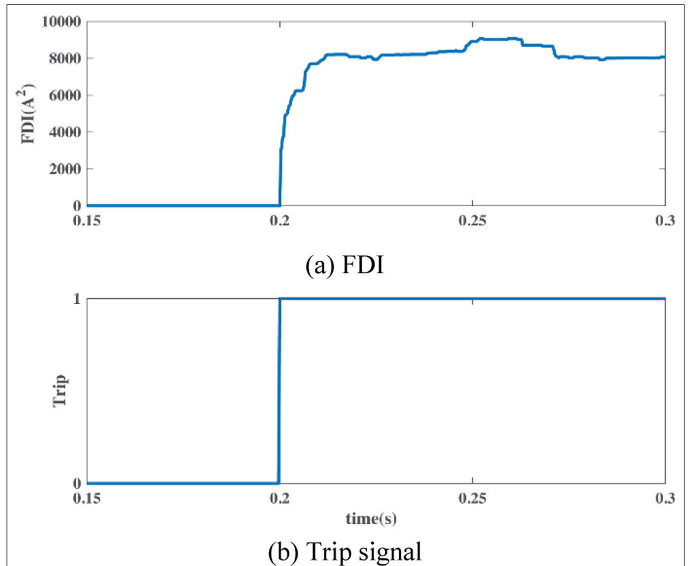

Fig. 14. Result for composite fault, ABG fault with 10 Ω, and DG tripping occurs at the same time.

resulting in a lower fault current level. Therefore, the ability of a protection approach to detect the fault in a connected or disconnected grid is essential. An AG fault with $R_f = 100\ \Omega$ resistance during the islanded mode of operation at 0.2 s in the midst of the protected feeder is intentionally done to evaluate this condition. The result is evaluated, and it is found that the scheme can detect faults in both modes. Fig. 15 shows that the value of FDI exceeded the Th and made the trip signal 1.

F. Performance Against Capacitor Switching

Transients are produced when capacitors are connected or disconnected inside a distribution network [25]. Capacitor switching is carried out at bus 633, close to the measurement device, to differentiate between faults and transients. The capacitor switching is done using capacitive loads of 100 kVAr, 200 kVAr, and 300 — kVAr corresponding results are shown in Figs. 16–18, respectively. It was found that the trip signal remains low, which shows the scheme's robustness.

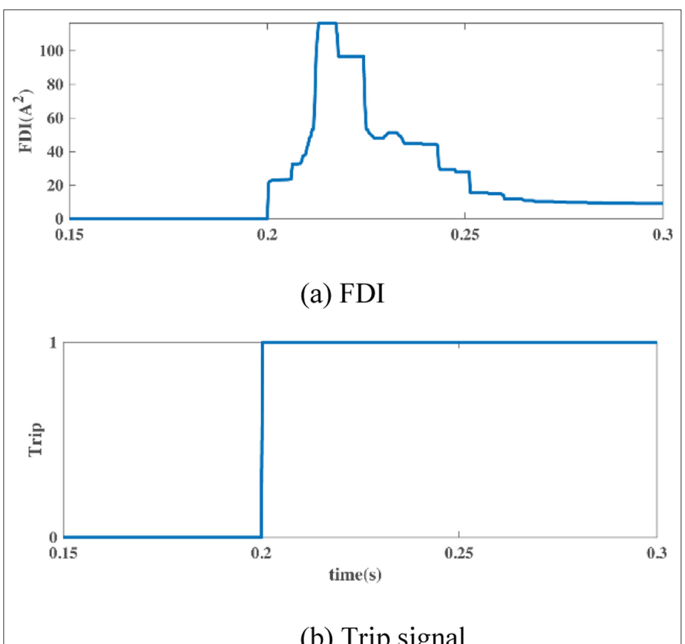

Fig. 13. Result for simultaneous fault, ABG fault with 150 Ω at 0.2 s and AG with $R_f = 0.01\ \Omega$.

G. Performance Against Load Switching

Transients occur when the load is switched in a practical distribution network because the load is continuously changing [26]. These temporary situations must be avoided by the protection scheme that is put in place, and it should also prevent accidental tripping in these situations. Figs. 19–21 show that the proposed scheme remains unaffected by load switching with 100 kW, 200 kW, and 300 kW, respectively.

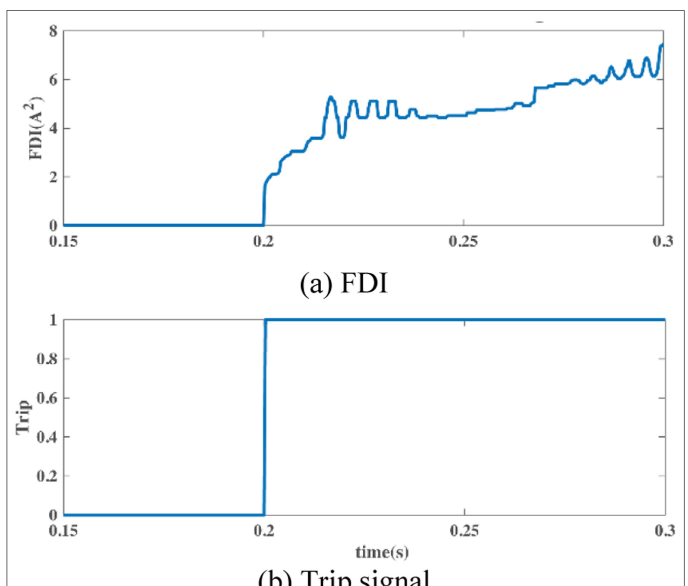

Fig. 15. Result for AB-G fault with $R_f = 100\ \Omega$ with off-grid mode.

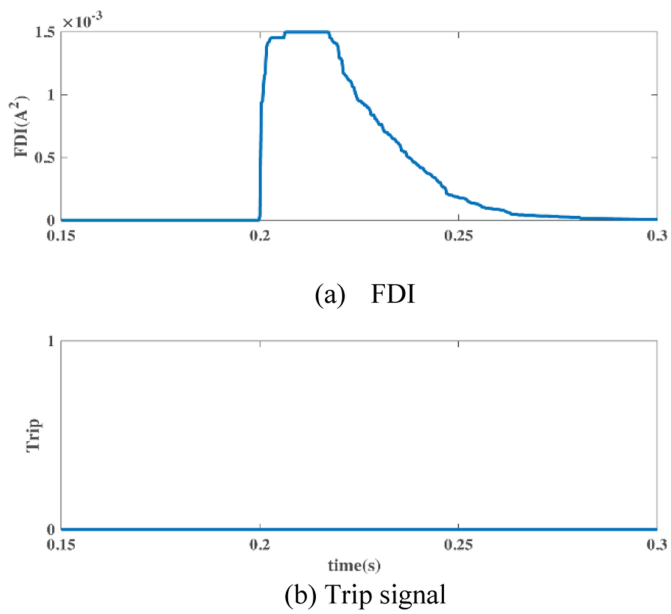

Fig. 16. Results for capacitor switching with 100 KVAR.

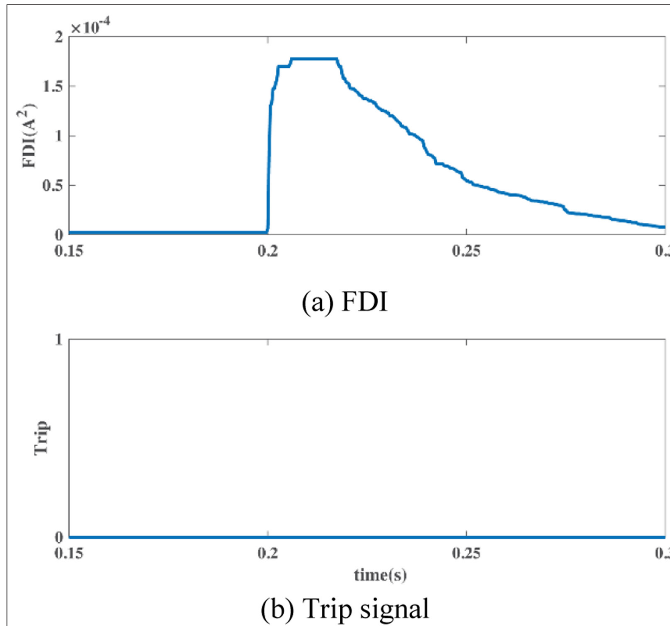

Fig. 18. Results for capacitor switching with 300 KVAR.

H. Performance Against Distributed Generator Outage

In distribution systems, DGs are best placed near the end consumer to minimize power losses while improving the voltage profile and system efficiency. The DG was tripped at 0.2 s to check the protected scheme's performance. The result shown in Fig. 22 is that the DG outage did not cause the tripping of the relay by the proposed scheme.

I. Performance Against Nonlinear Loading

Performance against nonlinear loading is also checked by adding an uncontrolled rectifier with light loads to heavy loads, and it can be seen in Fig. 23 that the trip signal remains zero. Hence, the scheme can effectively differentiate between fault cases and non-fault cases.

J. Comparative Assessment

Several different well-known protection schemes have been compared to the suggested approach. The comparative study provides the uniqueness of the proposed scheme. The observation is expressed in tabular form in Table III.

When creating the protection system, the authors of [8] and [27] considered the current samples, but maximum fault resistances are not discussed. Similarly, in [21], [28, 29], voltage and current samples are considered. However, the recommended protection strategy only made use of current signals. The system's complexity is reduced since voltage-sensing devices are not required.

For the MG's off-grid mode, the effectiveness of the protective methods has not been examined in [21]. The suggested method, however, successfully identifies the problem in the MG's off-grid and GCMs.

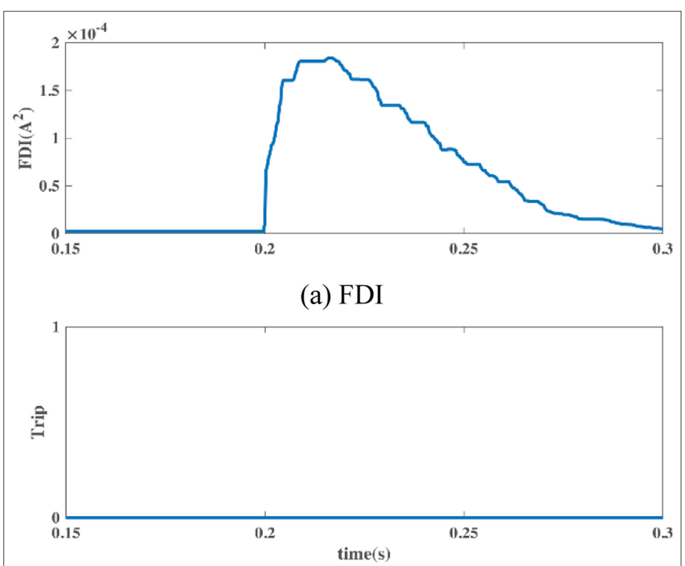

Fig. 17. Results for capacitor switching with 200 KVAR.

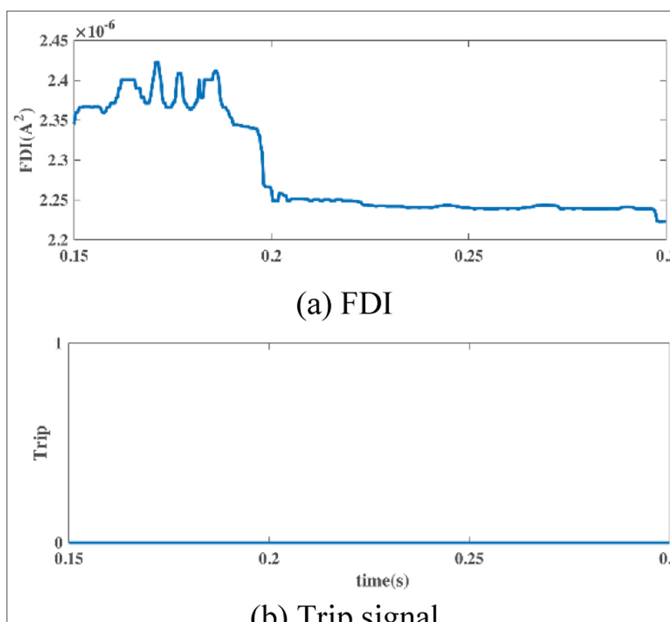

Fig. 19. Results for load switching with 100 kW.

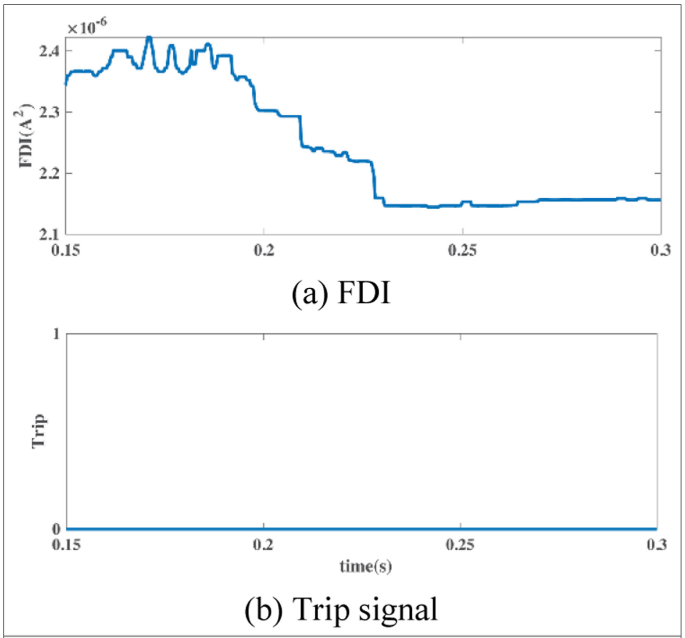

Fig. 20. Results for load switching with 200 kW.

While schemes [8] and [28] do not specify the maximum fault resistance at which systems detect faults. References [30, 31], [7], and [32] discovered that the protection scheme was effective for lower values of fault resistances, i.e., up to 100 Ω only. But the method suggested in this paper is able to identify faults up to 1000 Ω.

A few existing protection strategies can identify faults up to 1000 Ω, but do not take into account some of the significant internal faults, such as simultaneous, composite, and evolving faults [8], [32], [19]. However, the suggested scheme successfully identifies these faults.

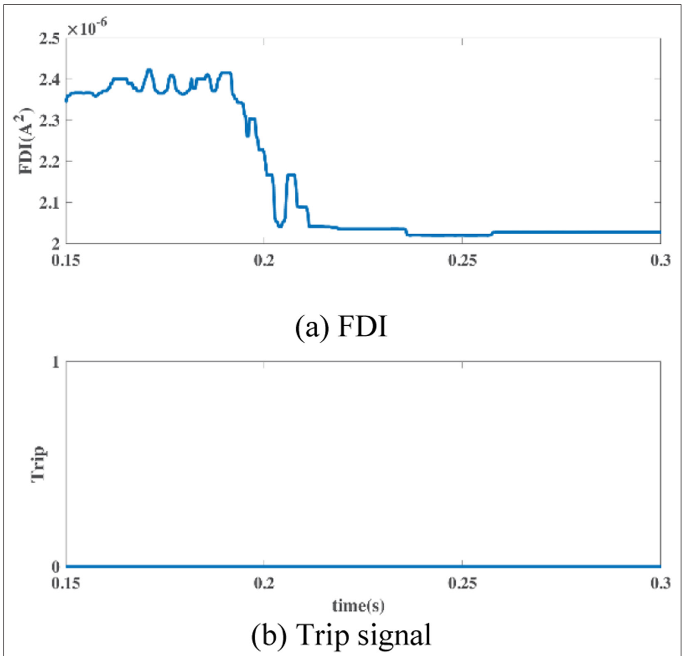

Fig. 21. Results for load switching with 300 kW.

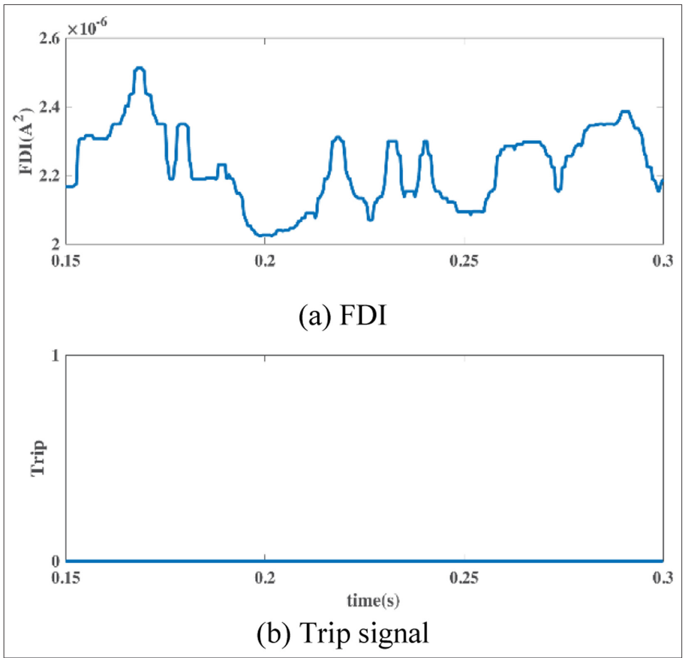

Fig. 22. Results for DG outage.

The scheme of [33] introduces a novel protection strategy for MG based on the estimated differential energy of fault currents. Different symmetrical and unsymmetrical fault cases have been taken into consideration in a 33-bus MG test system. The method has been tested for different non-fault conditions such as DG outage, DG intermittency, overloading cases, non-fault conditions, and FIAs. However, the scheme can detect HIF fault up to 100 ohms only during GCM and IM, and fault scenarios that rarely occur but are complex, such as simultaneous fault, evolving fault and composite fault, are not evaluated in this scheme.

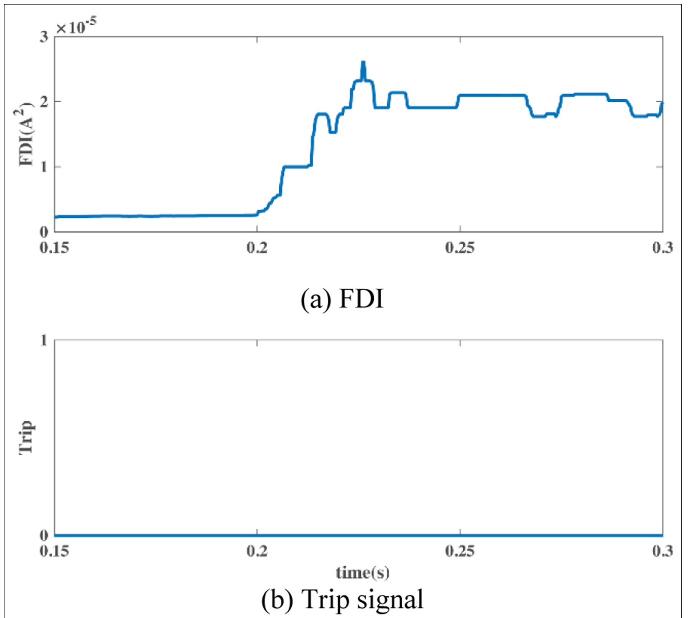

Fig. 23. Results for nonlinear loading.

TABLE III. COMPARATIVE ASSESSMENT WITH OTHER SCHEMES

Criteria	[30]	[8]	[31]	[27]	[7]	[32]	[19]	[28]	Proposed Scheme
Maximum value of R_f (Ω)	27	ND	25	ND	100	50	1000	ND	1000
Tested for fault location variation	Yes	ND	Yes	Yes	Yes	Yes	No	Yes	Yes
Tested for no-fault events	Yes	Yes	Yes	Yes	No	ND	Yes	Yes	Yes
Simultaneous fault considered	Yes	No	No	Yes	Yes	No	No	Yes	Yes
Evolving fault considered	Yes	No	No	Yes	Yes	No	No	Yes	Yes
Fault detection during islanding	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Data used—voltage or current	Current	Current	Both	Current	Current	both	ND	Both	Current
Operating voltage (KV)	0.4	0.4	12.47	25	12.47	ND	20	4.16	4.16
Fault detection time(in ms)	ND	3	2	58.33	0.3	7	522	22.74	1.3

*ND = Not defined.

The scheme of [7] presented a novel change detection and fault classification scheme. In this scheme, TKEO at one end of the protected line is applied for fault current, and then three-phase squared relay currents, whose energy calculation using TKEO is used for fault detection. 0.01 A^2 is a Th for fault detection; however, this Th can only detect faults up to 100 ohms. This scheme seems beneficial in terms of cost-effectiveness; however, it does not consider complex fault situations such as simultaneous fault, composite fault, and evolving fault. Also, the scheme can detect faults in the islanded mode of operation, but the value of HIF it can detect is not mentioned.

Non-fault events such as load switching, capacitor switching, and nonlinear loading are considered in every scheme except [7]. However, the schemes can only detect fault resistance up to 100 Ω [19]. The proposed scheme effectively detects faults up to 1000 Ω with non-fault event considerations.

The existing protection strategies, given in [34, 35], [23], are complex since they require voltage and current signals from both ends of the feeder to be measured. The scheme is robust against false tripping, nonlinear loading, and capacitor switching and can detect fault resistance up to 500 Ω without considering off-grid mode. However, the proposed scheme is easy to implement and can identify faults with off-grid systems up to 1000 Ω.

The scheme is able to quickly detect HIF within 1.3 ms as compared to other schemes.

Unlike machine learning or artificial intelligence-based methods, the suggested strategy does not require data training to detect fault conditions, which can occasionally become complicated due to many repetitions.

IV. CONCLUSION

The test was carried out in an IEEE 13 bus modified system in a MATLAB/Simulink environment. A new high impedance fault detection scheme, based on the differential energy using the TKEO operator, is proposed in this paper, and the scheme's performance was examined for high resistance faults for symmetrical and unsymmetrical faults. It was shown that it could identify faults up to R_f = 1000 Ω in GCM and can detect faults up to 500 Ω in off-grid mode. The method has also been tested for faults in the MG's radial and looped/meshed topologies, and it was found that only one relay Th for both GCM and off-grid modes of operation is required. The scheme has also been tested for external faults and a variety of non-fault scenarios, such as load switching, capacitor switching, and DG outages. The scheme can detect the fault scenarios and differentiate non-fault ones. The limitation of the scheme is that it is not tested on real time simulator. The scheme can also be tested on Hybrid AC MG model, different DG penetration levels and noise immunity measurement.

Data Availability Statement: The data that support the findings of this study are available on request from the corresponding author.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – T.N.M., S.A.; Design – T.N.M.; Supervision – O.M.G.; Resources – O.M.G.; Materials – S.A.; Data Collection and/or Processing – T.N.M.; Analysis and/or Interpretation – S.A.; Literature Search – T.N.M., S.A.; Writing – T.N.M.; Critical Review – O.M.G.

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