INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIELD
ISSN(O): 2455-0620 [Impact Factor: 9.47]
Monthly, Peer-Reviewed, Refereed, Indexed Journal with IC Value : 86.87
Volume - 11, Issue - 07, July - 2025

DOIs:10.2015/IJIRMF/202507014 --:-- Research Paper / Article / Review

Fault detection using combined Variational mode decomposition and Teager energy operator-based approach

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Abstract: *Identification of faults in distribution system connected with distribution generation (DG) is challenging due to the low magnitude variations. To design a fault detection logic (FDL), the suitable features need to be extracted from the current signals of the relay location. This paper used variational mode decomposition (VMD) to extract the features associated with faults and other events after processing the instantaneous current data through VMD. The 2nd mode of VMD is opted as useful feature to detect the faults in DG connected distribution lines with Teager energy operator (TEO). The value of TEO is continuously monitored and compared with pre-set threshold to detect various faults in the system and to generate the trip command to the circuit breaker. Different types of faults are simulated on the test system and the performance of the FDL are validated under those conditions.*

Key Words: *faults, distribution generation, VMD, features.*

1. INTRODUCTION:

Fault detection is a challenging task when limited number of classical diesel generators and renewable units (wind or solar) generating few MW of power exports to grid through distribution system. The faults currents are significantly low for such systems and therefore, overcurrent and classical protection schemes are not reliable to detect the faults [1]-[2]. Hence, improved protection schemes are necessary to enhance the power system security during faults and other disturbances [3]. In the fault detection process of the distribution networks included with distribution generation, dynamic behaviour of system included with magnitude and direction changes of the current and voltage initiates significant problems [4]. Several approaches were proposed to mitigate these issues in order to enhance the detection process.

The algorithms monitor the quantities like amplitude and phase to detect various faults in the distribution system with distributed generation (DG) according to the literature provided in [5]-[6]. Phase angle of current information comparison scheme [5], impedance angle-based comparison approach [6], differential components [7], total harmonic distortion (THD)-based scheme [8] and energy-based scheme [9] are few examples for regular protection schemes of distribution systems with DGs or microgrid protection in grid connected and islanding modes. These schemes are implemented based on the variation of certain components with initiation of faults. For example, the current phase changes at each node due to inception of fault and it is compared with the previous information to detect the faults as reported in [5]. In [6], impedance angle is considered which has the merit of both voltage and current features during the faults. In [7], the energy is calculated from the differential value of the superimposed component of the positive sequence impedance to detect the faults as an extension of the work presented in [6]. The events are analysed with THD information since the presence of a particular level of THD may change according to the event initiated in the system [8]. One common feature of majority of these schemes is estimating the energy associated with corresponding system measurement is the key to detect the abnormalities from the normal events. The reliability is one key attribute of the protection schemes enhanced when aforementioned techniques are assisted with wavelet transform (WT) like signal processing tools [10]. Because the signal processing techniques are used extensively in the protection schemes for fault detection tasks of the transmission and distribution networks to improve the efficacy of the FDLs. In [11], a full study of the use of various signal processing were used to detect the islanding situation of the DG coupled to a distribution network to export power to the grid. In [12], WT is used for fault detection in a DG-penetrated electrical power system. The features from WT like tools not only help to enhance the FDL performance, but also useful to extend for classification tasks. The features of the either direct voltage/current associated quantities or outputs of these components of the signal processing tools are used for machine learning models such as support vector machine (SVM) to detect faults and to discriminate the faults from islanding events [13]. In [14], extreme learning machine (ELM) is applied to protect the microgrid in presence of wind speed intermittency. Apart from these intelligent techniques, approaches designed from the signal variations are imposed on features extracted using signal processing techniques [15]-[16]. In [17], Hilbert-Huang transform (HHT)-based differential protection scheme is proposed to detect the faults. Most of these methods are capable of detecting faults due to their significant change in voltage/current and associated parameters. Empirical wavelet transform (EWT) is investigated in [17] to detect faults with high impedances in distribution system. The features associated with time-frequency transform enable the process of detection of faults with high impedance in an inverter interfaced distribution system. Variational mode decomposition (VMD) technique is used in [19] to detect faults with high impedance with an energy metric known as TEO.

In this paper, variational mode decomposition (VMD) technique is used to detect the faults in DG connected distribution lines. The process initiated with the measuring the 3-phase currents and processed through VMD technique. The VMD technique decompose the signal into set of modes and dominated mode is selected to compute the energy metric. TEO is adopted to estimate the energy and compared with pre-set threshold to detect the faults. The performance of the proposed scheme is tested on different faults by varying location, inception and resistance values of the faults. The rest of the article organizes as follows: section 2 provides methodology, section 3 provides test system information, section 4 discusses various case studies and finally conclusions are presented in section 5.

2. PROPOSED METHOD:

Because of its strong mathematical foundation, resistance to noise, and absence of mode mixing effects, variational mode decomposition (VMD) is a very dependable technique for signal decomposition in a variety of fields. By addressing important drawbacks like mode mixing and noise sensitivity, which frequently impair the quality of decomposition in EMD, VMD provides greater accuracy and stability than conventional techniques like Empirical Mode Decomposition (EMD). In particular, the input signal y(t) is broken down into a finite number of Intrinsic Mode Functions (IMFs), which is comparable to EMD but has improved characteristics because of its distinct algorithmic design [27]. VMD is unique in that it uses a variational optimization framework that includes three key constraints: frequency mixing to guarantee that the modes are well-separated in the spectral domain, Wiener filtering to reduce noise and improve mode extraction, and the Hilbert Transform (HT) to examine the signal in the frequency domain. VMD is a flexible technique in signal processing applications because of this mix of limitations, which not only guarantee a more accurate decomposition but also permit adaptation to various signal types. The VMD algorithm's applicability is further increased by the user's ability to alter the number of modes and customize the decomposition process to meet particular needs thanks to its iterative nature. VMD is the perfect option for this study because of these qualities, which provide a trustworthy and the idea behind VMD can be seen as a constrained variational issue, expressed as

$$\min \binom{\omega_n}{v_n} \left\{ \sum_n \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_n \right] e^{-i\omega_n t} \right\|_2^2 \right\}$$
$$\text{subject to } \textstyle\sum_n v_n = y(t) \qquad (1)$$

where v_n = n[th] mode, δ = Dirac distribution, ω_n = center frequency. Here constrained problem is converted as an unconstrained one by introducing a Lagrangian multipliers (λ) and penalty factor (α).

$$L(v_n, \omega_n, \lambda) = \alpha \textstyle\sum_n ||\partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * v_n \right] e^{-i\omega_n t} ||_2^2 + \; ||y(t) - \textstyle\sum_n^v v_n||_2^2 + (\lambda, y(t) - \textstyle\sum_n^v v_n) \quad (2)$$

In Eq, (1) and (2), modes are decomposed using the expression using Equation (3)

$$v_n^{m+1}(w) = \frac{y - \sum_{i<n} v_i^{m+1}(\omega) - \sum_{i>n} v_i^m(\omega) + (\lambda^m(\omega)/2)}{1 + 2\alpha\,(\omega - \omega_n^m)^2} \qquad (3)$$

The center frequency is determined by

$$\omega_n^{m+1} = \frac{\int_0^\infty \omega |v_n^{m+1}(\omega)|^2 d\omega}{\int_0^\infty |v_n^{m+1}(\omega)|^2 d\omega} \qquad (4)$$

Additionally, λ will be updated using

$$\lambda^{m+1} = \lambda^m + \tau(y - \sum_n v_n^{m+1}) \quad (5)$$

here τ = update parameter. The updating process concludes after convergence criteria is satisfied.

$$\frac{||v_n^{m+1} - v_n^m||_2^2}{||v_n^m||_2^2} < \varepsilon \quad (6)$$

The VMD is iterative process and step-by-step, modes are decomposed until the residual component is sustain similar to EMD. After processing the current information measured at the relay location through VMD, IMFs are extracted, and the detection procedure follows the below steps:

- The current will be extracted at the relay location.
- The VMD is used to process the current signal and extract the relevant IMFs, and the dominant features are identified to detect the events. After examining the several cases, IMF-2 is adopted in this work as dominant IMF to detect the faults and to discriminate the faults from normal conditions.
- Teager energy operator (TEO) is applied to IMF-2 in order to calculate the signal's energy. The TEO uses three consecutive samples to calculate the energy of IMF-2,

$$y(m) = y^2(m) - y(m-1)\, y(m+1) \quad (7)$$

Where, $y(m-1)$, $y(m)$, and $y(m+1)$ are the three consecutive samples.

- This TEO is compared with a predetermined threshold, and faults are recorded when it is exceeded to generate the trip signal. The complete flow of the proposed approach is represented in Fig. 2

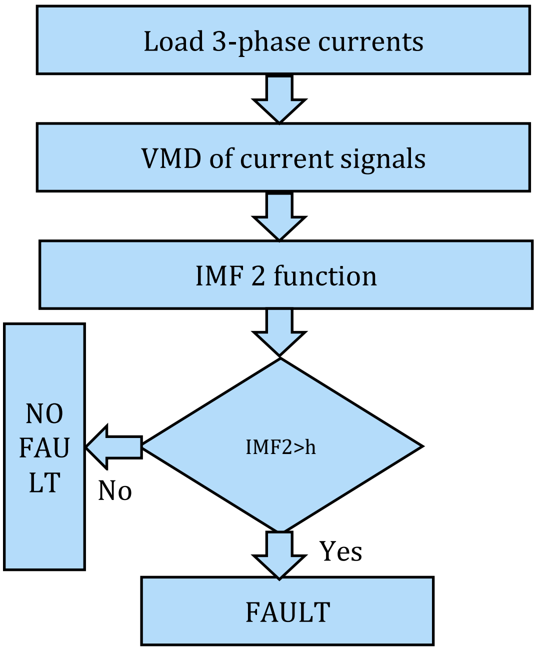

Figure 1. Algorithm of proposed fault detection mechanism

3. TEST SYSTEM:

The proposed VMD-TEO scheme is tested on grid connected DG system whose single line diagram is presented in Fig 2. The distribution line is at 33 kV connected to a 132 kV substation. A distributed generator, namely synchronous generator, is connected to this system. The system's details are based on [20] and the current information is measured at bus-2 to assess the performance of the VMD-TEO scheme.

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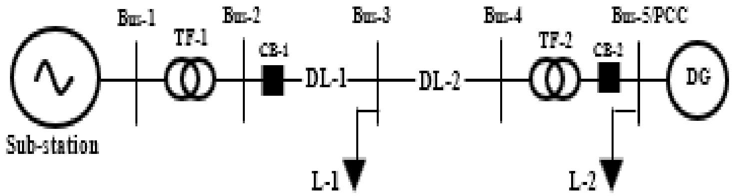

Fig. 2. Single line diagram of the test system.

4. SIMULATION RESULTS :

To test the outputs of the suggested protection scheme under different faults scenarios in presence of DGs, a test system shown in Fig. 2 is chosen and simulations are performed in MATLAB/SIMULINK. All 11-types of faults are simulated on test system by varying the location of the fault, inception of the fault and resistance of the fault. Later, few typical cases are investigated to test the efficacy of the proposed scheme.

4.1. Single line-ground faults

The ground faults involved with single phase of transmission/distribution are mostly occurring according to the statistics and the performance of proposed VMD-TEO scheme is tested under three different line-to-ground faults. First, at 15 Km from the grid connected point, an A-g fault is initiated at inception time of 2.7 sec with a fault resistance of 10 Ω. Fig. 3 shows the combined plots of the instantaneous currents, IMF 2 of the VMD after processing phase-A current and TEO is the corresponding energy value. At the fault initiation, the TEO exceeds the pre-set threshold and therefore the A-g fault is detected by the VMD-TEO method. The B-g fault located at 12 Km from the relay point with inception time of 2.92 sec and fault resistance of 20Ω is simulated in the test system and the corresponding instantaneous current information is recorded and plotted in Fig. 4(a).

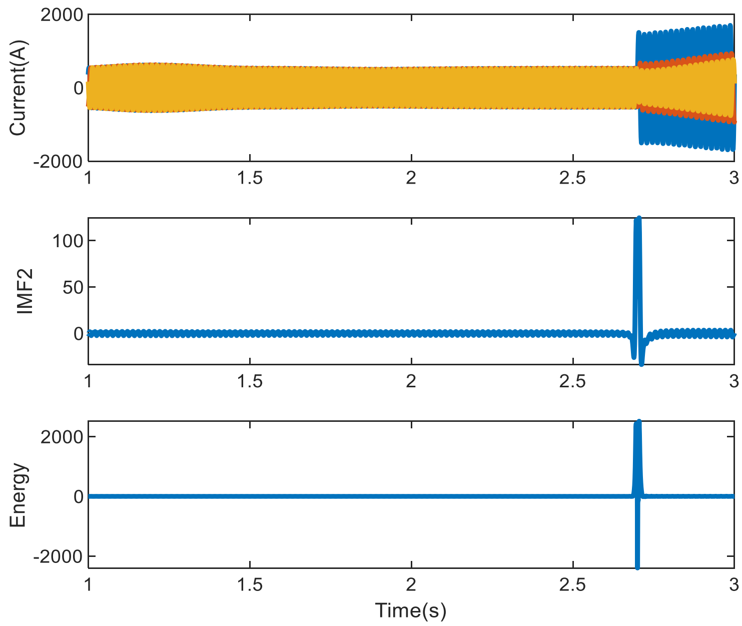

Fig. 3: Outputs VMD-TEO scheme during A-g Fault, a. currents, b. IMF2, c. TEO

This current data is processed through VMD and IMF2 is extracted and provided in Fig. 4(b). The TEO calculated from the IMF2 information is provided in Fig. 4(c). For IMF2 and TEO calculations, only phase-B current is considered. Furthermore, a C-g Fault located at 8 Km from the relay point with inception time of 2.8 sec and fault resistance of 30Ω is simulated and results are plotted in Fig. 5. The instantaneous current signal measured at the relay location is plotted in Fig. 5(a). The phase-C current data is processed through VMD and IMF2 is extracted and provided in Fig. 5(b). The TEO calculated from the IMF2 information is provided in Fig. 5(c). These three cases are (A-g, B-g and C-g faults) simulated at different fault parameters like location, inception and fault resistances to validate the behaviour of VMD-TEO scheme and the responses presented in Figs 3, 4 and 5

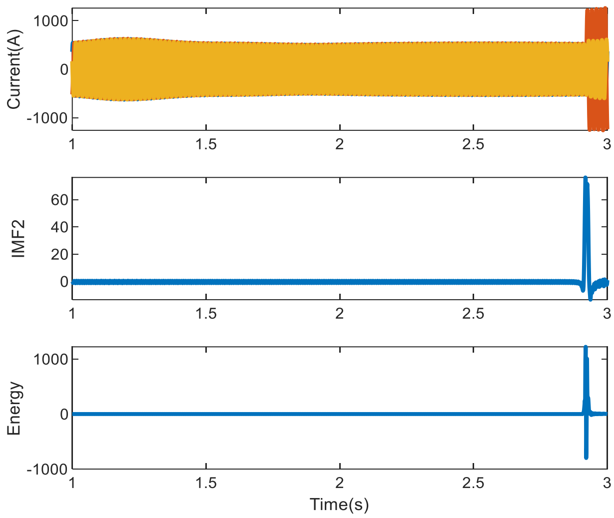

Fig. 4: Outputs VMD-TEO scheme during B-g Fault, a. currents, b. IMF2, c. TEO

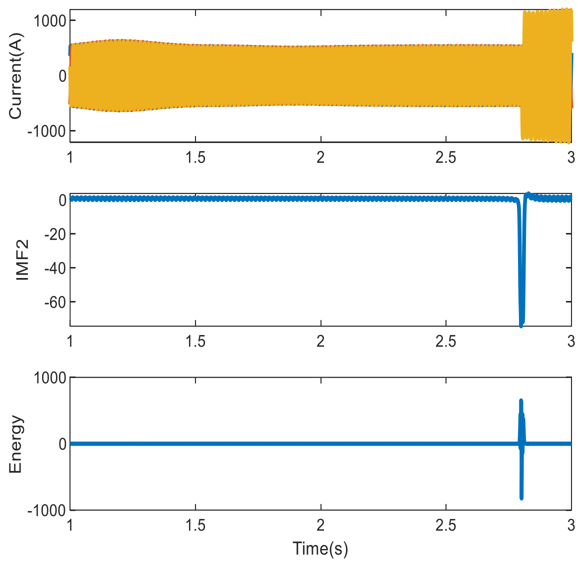

Fig. 5: Outputs VMD-TEO scheme during C-g Fault, a. currents, b. IMF2, c. TEO

4.2. Double line and Double line-ground faults

To evaluate the performance of the proposed fault detection scheme under various multi-phase fault conditions, six distinct fault scenarios are simulated in a test power system. These scenarios include both line-to-line (L-L) faults—A-B, B-C, and A-C—and line-to-line-to-ground (L-L-g) faults—A-B-g, B-C-g, and A-C-g. Each fault simulation is conducted under varying conditions, including different fault locations, inception times, and fault resistances, to comprehensively assess the robustness of the VMD-TEO algorithm. The current data generated from these faults is processed using the VMD technique to extract the IMFs, which serves as the core of the proposed approach for fault detection and classification. The detection performance is measured in terms of detection time and the ability to accurately identify the faulted phases. The results of this evaluation are detailed in Table 1, which summarizes the fault type, fault location (in kilometers), fault inception time (in seconds), fault resistance (in ohms), detection time (in milliseconds), and the classification output specifying the identified faulted phases. The results indicate that the proposed scheme achieves rapid fault detection, with detection times consistently within 3–4 milliseconds across all fault cases, regardless of variations in fault location, timing, or resistance. Moreover, the scheme demonstrates accurate classification of faulted phases for both L-L and L-L-g faults, correctly identifying the phases involved in all six scenarios. For example, in the A-B fault at 10 km with a resistance of 5 Ω occurring at 2.65 seconds, the algorithm detects the fault in 4 milliseconds and identifies the faulted phases as A and B (Fig. 6). Similarly, in the B-C fault at 2 km with a resistance of 1 Ω occurring at 2.68 seconds, the algorithm detects the fault in 3 milliseconds and correctly classifies the faulted phases as B and C (Fig. 7 (a)). For A-C, A-B-g, B-C-g and A-C-g, the VMD-TEO results are presented in Fig. 7(b), 7(c), 7(d) and Fig. 8.

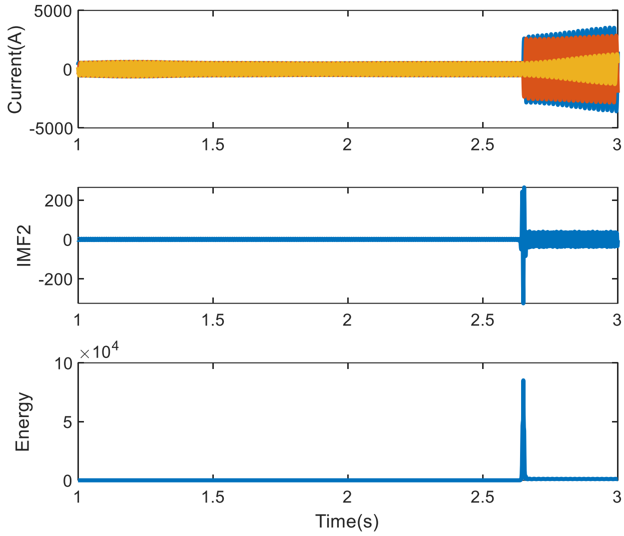

Fig. 6: Outputs VMD-TEO scheme during A-B Fault, a. currents, b. IMF2, c. TEO

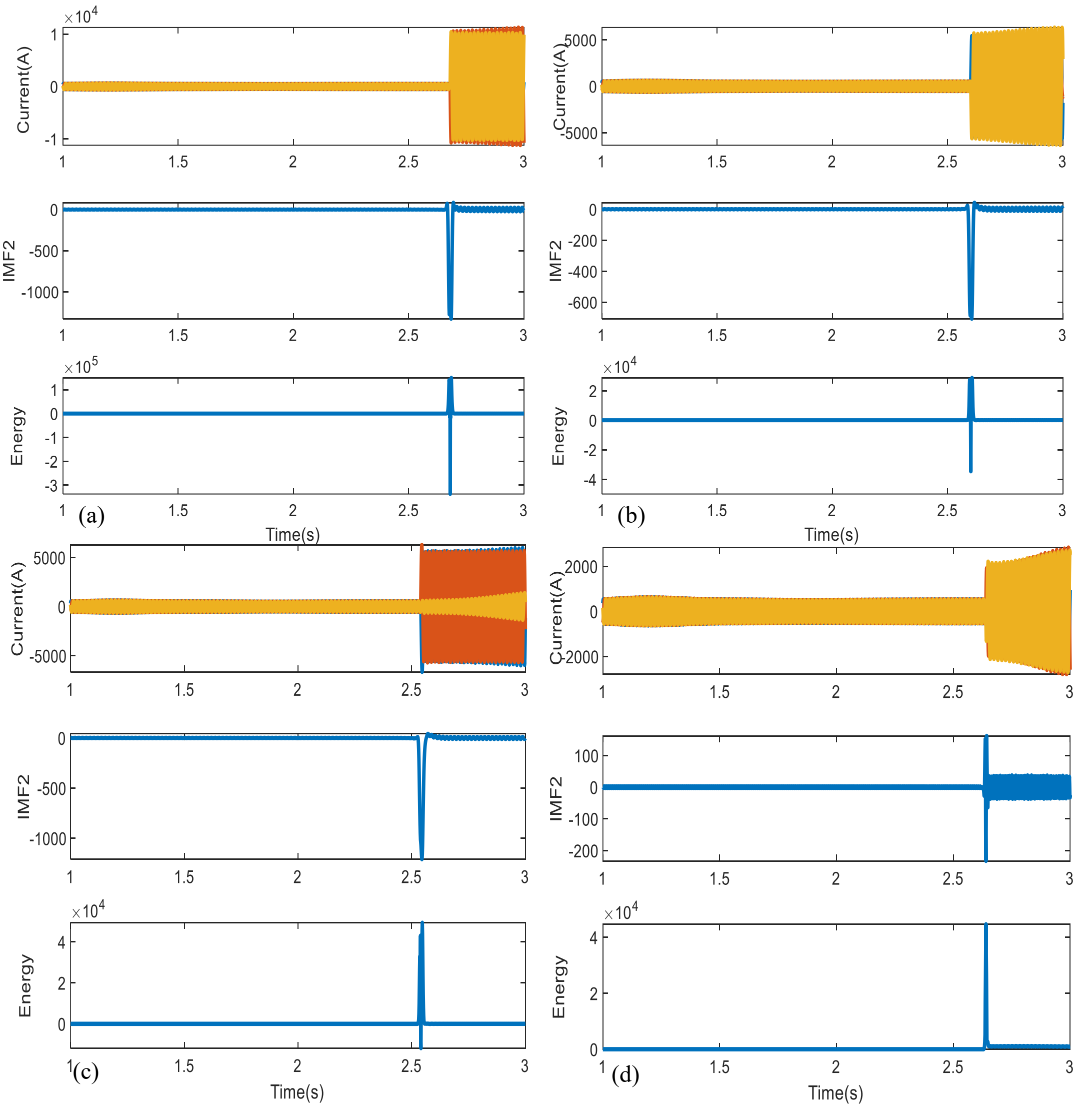

Fig. 7: Outputs VMD-TEO scheme during a. B-C fault, b. A-C fault, c. A-B-g fault, d. B-C-g fault

Table 1. Detection times and faulty phase identification outputs for different L-L and L-L-g faults.

Type of fault	Location (Km)	Inception (Sec)	Resistance (Ω)	Outputs	
				Detection in time (msec)	Classification
A-B	10	2.65	5	4	A, B
B-C	2	2.68	1	3	B, C
A-C	3	2.6	3	3	A, C
A-B-g	7	2.54	1	4	A, B
B-C-g	17	2.64	5	4	B, C
A-C-g	8	2.62	3	3	A, C

4.3. Symmetrical faults

For the symmetrical faults, the result of VMD-TEO is provided in Fig. 9. These results are obtained when the fault component parameters are fixed at fault location of 13 km, inception time of 2.6 sec and fault resistance of 5 Ω. For this simulated case, the method successfully performed both detection and faulty phase identification as shown in results provided in Fig. 9. Irrespective of values of the parameters like location, resistance and inception, the symmetrical faults are detected in less time by the proposed method.

4.4. High resistive faults

The response of the VMD-TEO scheme against high resistive fault is validated in this case study. The fault current during the high resistive fault is extremely low and it is always challenging to detect such types of faults in distribution systems. To illustrate the advantages of the VMD-TEO scheme, an A-g fault with a fault resistance of 75 Ω is simulated in the test system (fault location of 10 km from the bus 2 and fault inception time of 2.55 sec) and results are provided in Fig. 10. In Fig. 10(a), the three phase current signals are provided, and phase-A information is processed through VMD to extract the IMF 2 presented in Fig. 10(b). The final result of VMD-TEO is available in Fig. 10(c) shows the ability of the scheme to detect the typical faults along with normal faults.

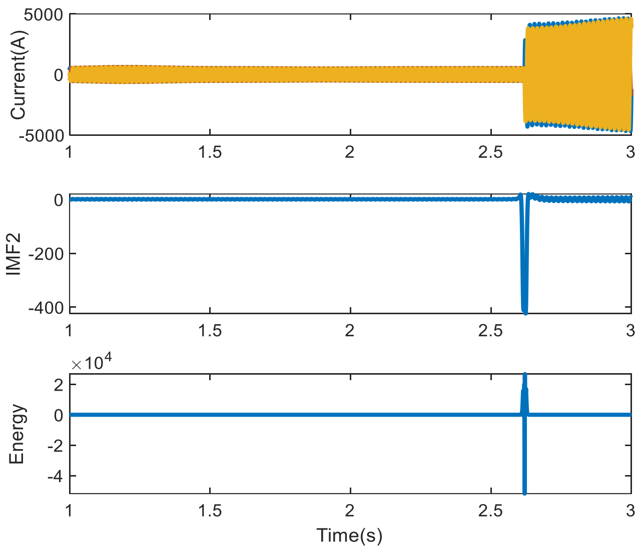

Fig. 8: Outputs VMD-TEO scheme during A-C-g Fault, a. currents, b. IMF2, c. TEO

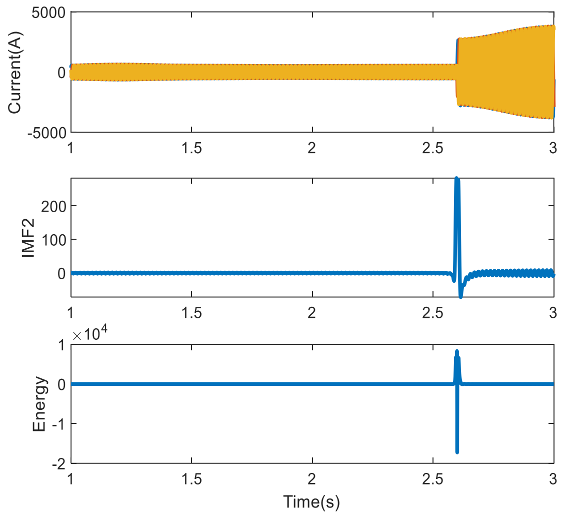

Fig. 9: Outputs VMD-TEO scheme during A-B-C-g Fault, a. currents, b. IMF2, c. TEO

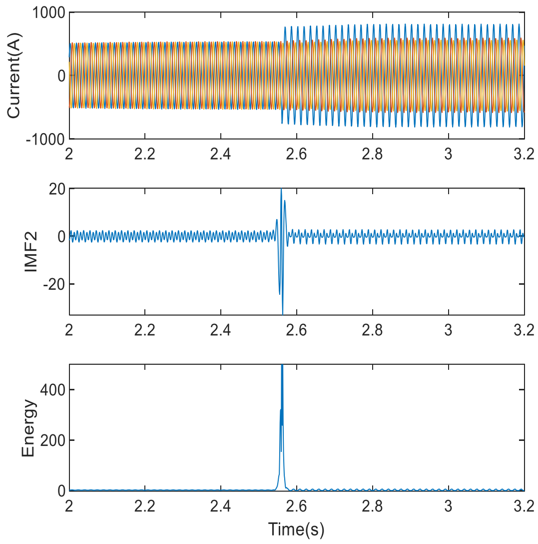

Fig. 10: Outputs VMD-TEO scheme during A-g high resistive fault, a. currents, b. IMF2, c. TEO

5. CONCLUSION

This work proposes a VMD-TEO approach for detecting various faults in DG-connected distribution lines when in grid linked mode. The scheme's reliability is confirmed for faults such as L-g, L-L, L-L-g, and L-L-L-g, which are reproduced on the test system by changing the fault conditions such as position, initiation, and resistance. The VMD-TEO approach generated trip signals in all of the test situations. Furthermore, the suggested method detects typical high resistive defects quickly, which is another advantage of the algorithm. In the future, the approach needs to be validated to detect the islanding circumstances and distinguish them from defects.

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