DISCRETE WAVELET TRANSFORM AND DECISION RULES SUPPORTED METHOD FOR DETECTION OF FAULTY EVENTS IN DISTRIBUTION NETWORK WITH RENEWABLE ENERGY

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Abstract— This paper has designed a current based method using db4 mother wavelet of Discrete Wavelet transform (DWT) and decision rules for detection of faulty events incident on the distribution network (DN) where penetration level of both the wind and solar energy is present. Algorithm can be used for protection of the DN by continuously monitoring the current signals. Investigated faulty events are phase to ground (LG) fault, phase to phase (LL) fault, two phases to ground fault (LLG) and three phases to ground (LLLG) fault. Study is performed on a test DN modeled using IEEE-13 node test system in MATLAB where a solar photovoltaic (PV) power plant and wind power plant (WPP) are integrated. Performance of algorithm is established by comparing with a method reported in literature which is also based on DWT but using different features.

Keywords— *Discrete Wavelet transform; Distribution network; Faulty event; Renewable energy; Solar energy; Wind energy.*

1. Introduction

Number of grid connected large size Renewable energy (RE) power plants are continuously increasing. These plants help to meet the increased load demand by environmental friendly energy with reduced carbon emission. However, these energy sources generate power which is variable in nature and also uncertain to generate power. This resulted to initiate technical challenges for the power utilities like variations in the grid frequency, voltage variations, reduced efficiency of equipment, power quality (PQ) problems, deterioration in grid stability, reduced power reliability, and protection issues [1]-[3]. Protection issues need to be investigated for increasing the performance of protection schemes by the use of signal processing and intelligent techniques. Fault identification and their classification is a key issue which can be analysed using the signal processing techniques. Ola et al. [4], presented a method for detection and categorization of faults incident on the power network where generation from WPP is available using Stockwell transform (ST) based median feature. This technique has demerits of high computational complexity. In [5], authors has designed a techniques which is effective for identification and categorization of faulty scenarios incident on the grid of utilities where solar energy integrated by the application of DWT and rule based decision tree (RBDT). This method has not been tested for generation from various types of the RE generators in the hybrid grids. In [6], authors have proposed a scheme for the protection of transmission lines using the K-means clustering and linear regression techniques. Method is effective for identification and classification of faults incident on the transmission line. In [7], a technique for identification of faults incident on the transmission line to provide effective protection using hybrid combination of Wigner distribution function (WDF) and DWT is investigated. A technique using the combination of DWT and HT for identification and classification of faulty events incident on the DN in the presence of solar energy by processing the voltage and current signals is presented by the authors in [8]-[9]. Combination of features computed using the ST and HT to detect faults on transmission line feeding the dynamic loads for designing protection scheme is introduced in [10]-[11]. Transmission line fault detection method using ST for utility grid with wind energy generation is introduced in [12]. In [13], authors investigated a method for detection of faults incident on the network of power system when Thyristor Controlled Reactor (TCR) devices are used in the network to control the reactive power. In [14], authors designed a current supported scheme using Harmonic Wavelet Transform (HWT) and RBDT to provide effective protection to the transmission lines. ST supported technique using median features is designed for transmission line protection by the authors in [15]. Various techniques for fault detection in the utility grids with and without the presence of RE generation to design protection schemes are reported in [16]-[25]. Following are main contributions of this paper:-

- A current based technique using DWT and decision rules is introduced for detection of faulty events incident on the DN where penetration level of both the wind and solar energy is high.
- Investigated faulty events are LG, LL, LLG and three phases to ground (LLLG) fault.
- Performance of algorithm is established by comparing with a method reported in literature which is also based on DWT but using different features and study is performed on IEEE-13 nodes test system in MATLAB/Simulink environment.

The paper is divided into seven sections. Introduction of the research activity is included in Section 1. Test system with integrated wind and solar power plants is described in Section 2. Proposed techniques for faulty event recognition are illustrated in Section 3. Results of simulation and their discussion is included in Section 4. Fault classification is described in Section 5. Section 6, describes the performance comparative study. Section 7, includes the conclusion of the research activity.

2. Test Distribution Grid with RE Generators

IEEE-13 bus test feeder is utilized for the proposed study of fault estimation. A solar PV system of capacity 1 MW integrated on bus 680 and two wind generators of capacity 1.5 MW are integrated on buses 646 and 675 of the test IEEE-13 bus test system. It is operated at a frequency of 60 Hz. The original test system is rated at capacity of 5 MVA. It is operated on two voltage levels of 4.16 kV, 0.48 kV with the help of transformer (XFM-1) connected between the nodes 633 and 634 [26]. Proposed test system interfaced with wind and solar power plants is illustrated in Fig. 1. The line data with interconnection used in the proposed grid are described in the Table 1. The data related to load and capacitors are described in the Tables 2 and 3 respectively. Load models are star-connected and constant P and Q type. All the lines used in the proposed grid are three phase overhead lines. The proposed test system is integrated to the utility grid with the help of substation transformer. The 1MW solar PV plant is connected to the node 680 through transformer XSPV and 5 km long overhead transmission line. The 1.5 MW doubly fed induction generator based wind power plants are integrated to the node 675 (WG-1) and 646 (WG-2) through transformer XWG. The DC to DC boost converter and DC to AC inverter are used in the test system to incorporate the solar PV system to the test system.

The details of transformers used in the test grid are provided in Table 4. The switch between nodes 671 and 692 of the test system is modelled using a three pole circuit breaker (CB). Line segments are considered with length equal to that used in original test network. Solar PV data and wind generator data reported in [27]-[29] has been utilized for this study.

- Details of Lines Used in the Test Grid

Node A	Node B	Length(ft.)	Configuration
632	645	500	601
632	633	500	601
633	634	0	XFM-1
645	646	300	601
650	632	2000	601
684	652	800	601
632	671	2000	601
671	684	300	601
671	680	1000	601
671	692	0	Switch
684	611	300	601

692	675	500	601

- Details of Loads Used in the Test Grid

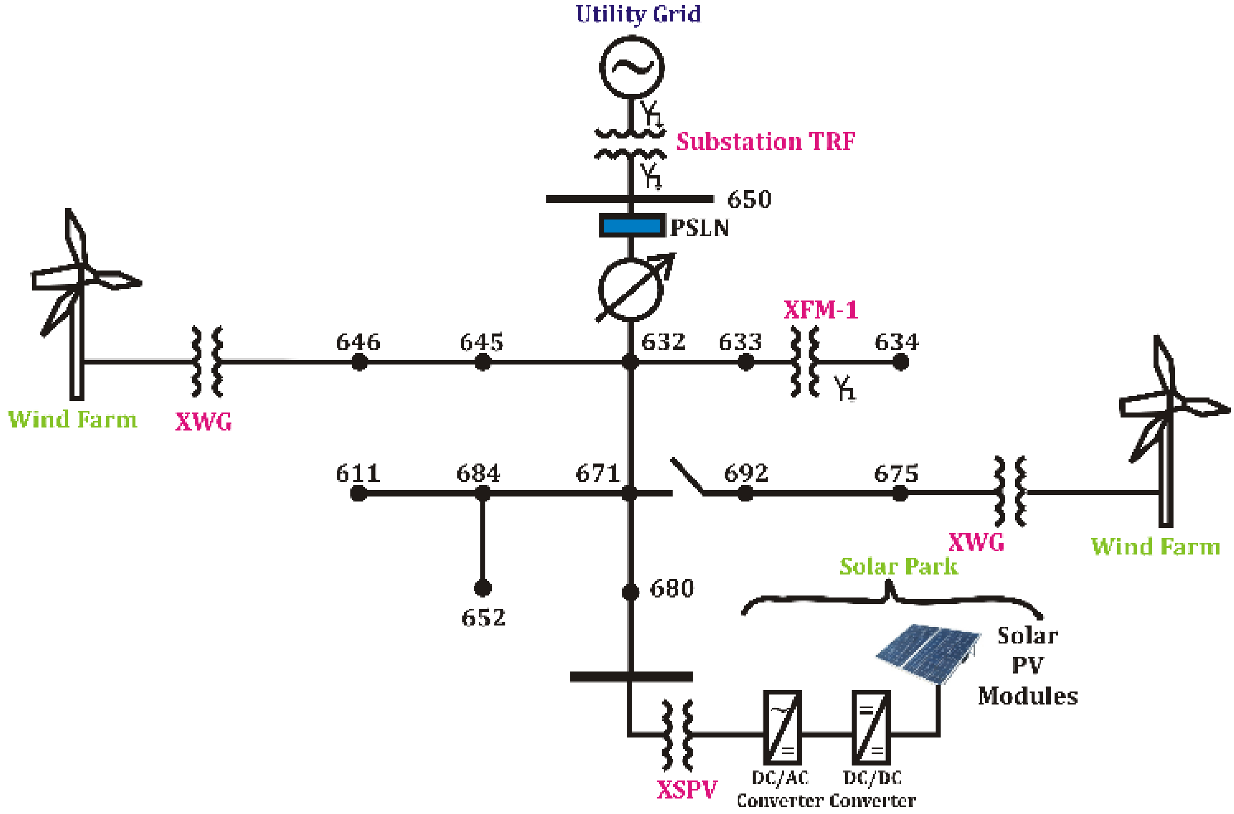
Node	Load Quantity (kW)	Load Quantity (kVAr)
634	400	290
645	170	125
646	230	132
652	128	86
671	1155	660
675	843	462
692	170	151
611	170	80

- Details of Capacitors Used in Test Grid

Node	Ph-A (kVAr)
675	600
611	100

- Details of Transformers Used in the Test Grid

Transformer	kVA	kV-high	kV-low	R – %	X – %
Substation:	5,000	115 – D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2
XSPV	500	4.16 Gr. Y	0.260- Gr. Y	1.1	2
XWG	5000	4.16 Gr. Y	0.575- Gr. Y	1.1	2

- Test system with RE generation.
- 

3. Proposed Fault Detection Algorithm

The algorithm used for detection of the faults and based on the DWT and RBDT is detailed below. The feeder between the nodes 632 and 671 has been used to simulate the various types of the faults. The following are main steps utilized in detection of faults:-

- Simulate the various types of faults at middle of the feeder connected in between nodes 632 and 671 of IEEE-13 bus test network modeled as test grid and incorporating wind and solar PV systems.
- Capture current waveforms on the node 650 of test grid.
- Process the signals of the current by application of the DWT with db4 as mother wavelet.
- Obtain the proposed fault index with the help of following sequence/operations on the detail and approximation coefficients. The fault index proposed is represented by FI.

A= CD1.*CD1

B= CD1.*CD1

FI=A.*B

- Compute threshold magnitude of FI to differentiate the faulty and healthy phases as well as different

  types of the faults.

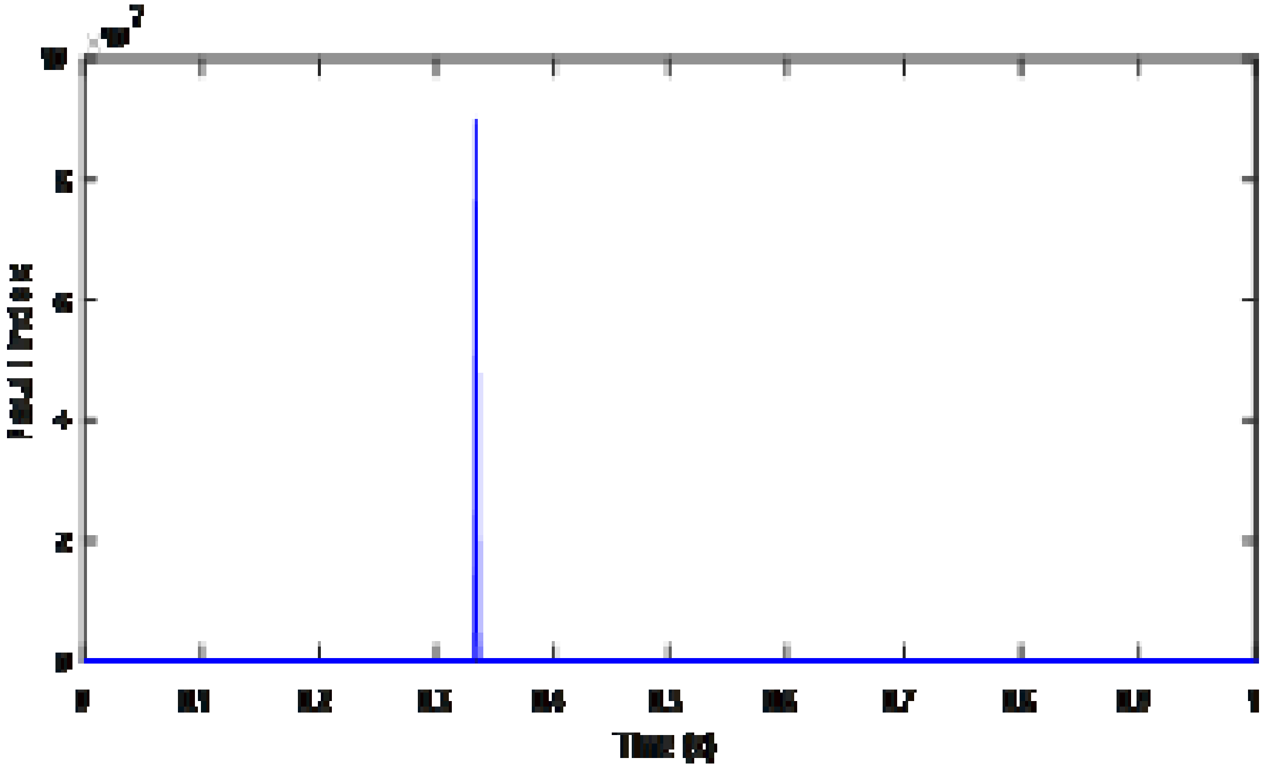
- This process is repeated for all types of the faults which are studied in this paper.

4. Simulation Results

Results of simulation pertaining to detection of faults in test grid where generation from both the wind and solar power is available and their discussion are described in this section. Investigated faults include LG, LL, LLG and LLG faults.

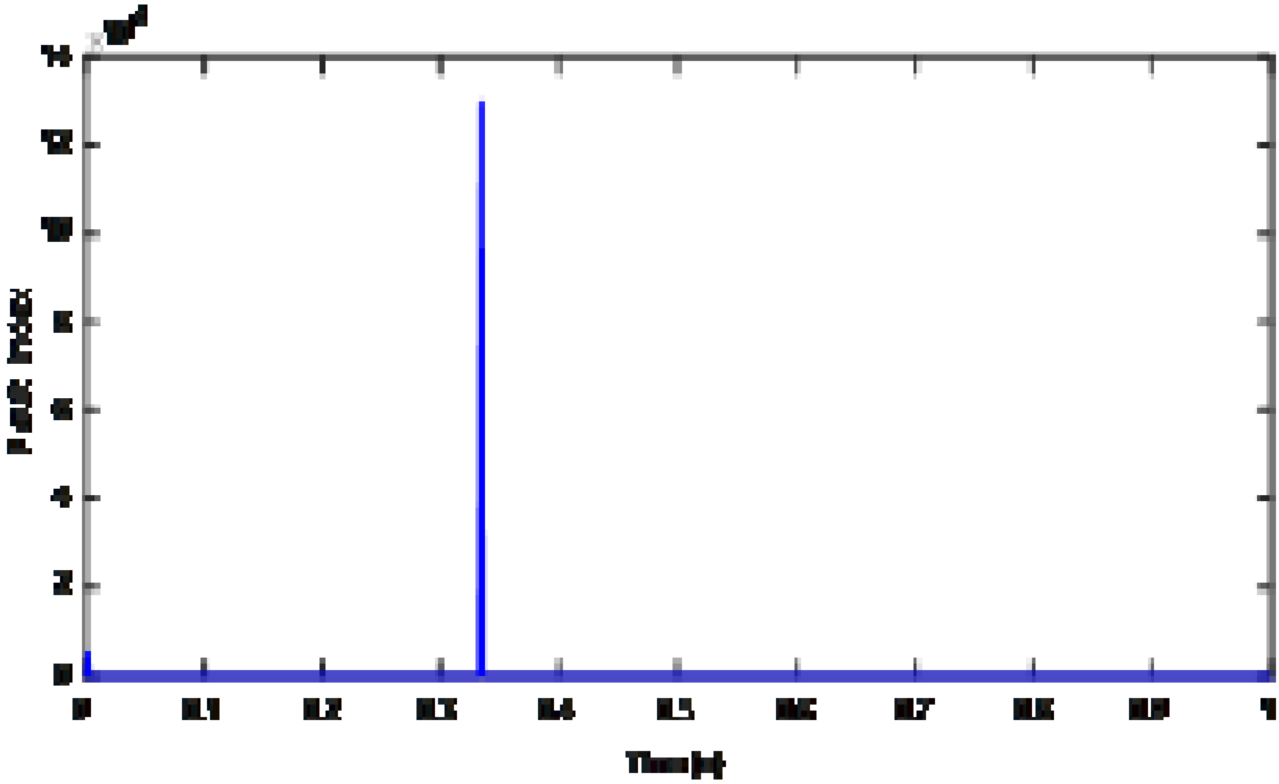
- **Line to Ground Fault**

A fault of LG type is performed on phase-A at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-A recorded on bus 632 of the test system has been processed using DWT with the help of db4 mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 2. This can be inferred from Fig. 2 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to 9×10^{7} during the events of LG fault indicating occurrence of the fault in the test grid. A threshold value equal to 5×10^{7} has been selected for discrimination of the LG fault from the other faults as well as the faulty phase from the healthy phases during the event of LG fault. The values of proposed fault index higher than 1×10^{6} indicates the presence of the fault in the test grid network.



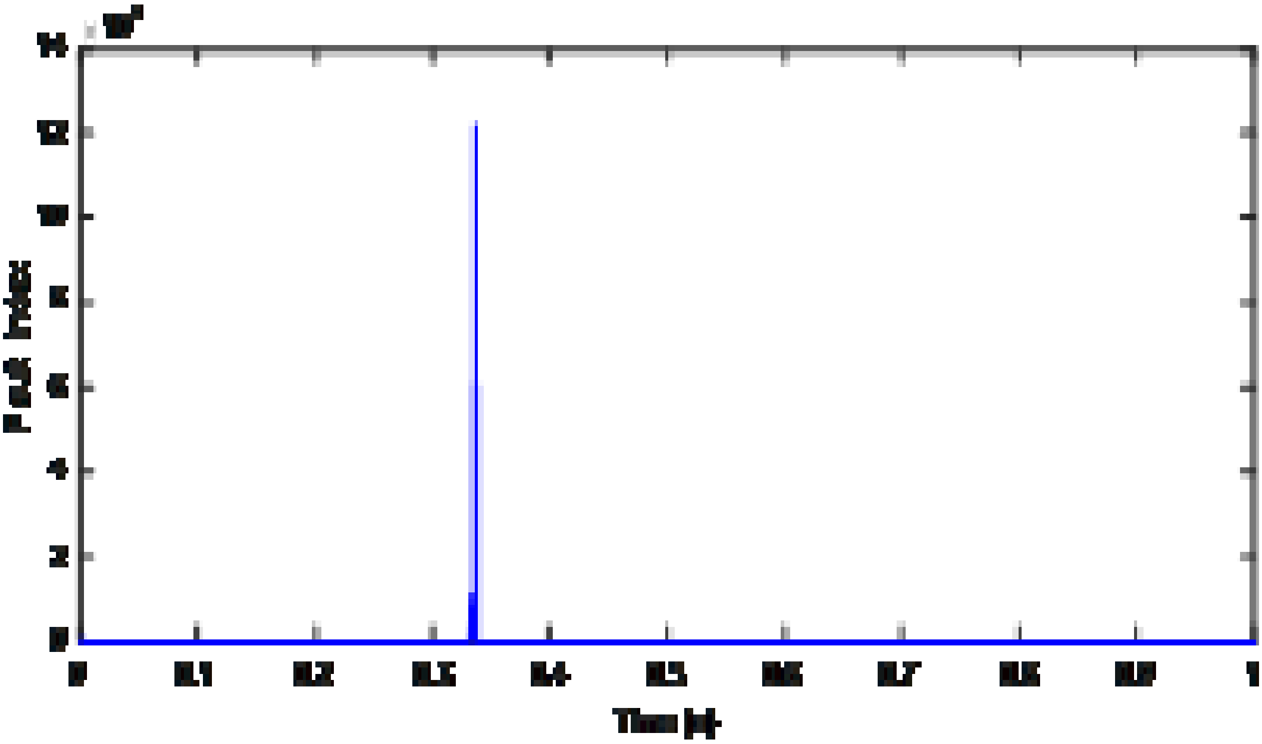
- FI for current in phase-A during LG fault on phase-A.

The line to ground (LG) fault is created on the phase-A at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-B recorded on bus 632 of the test system has been processed using DWT using db4 as mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 3. This is inferred from Fig. 3 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these magnitudes are high equal to $13×10^4$ but less than the threshold value of $1×10^6$ indicating the healthy phase during the event of LG fault.



- FI for current in phase-B during LG fault on phase-A.

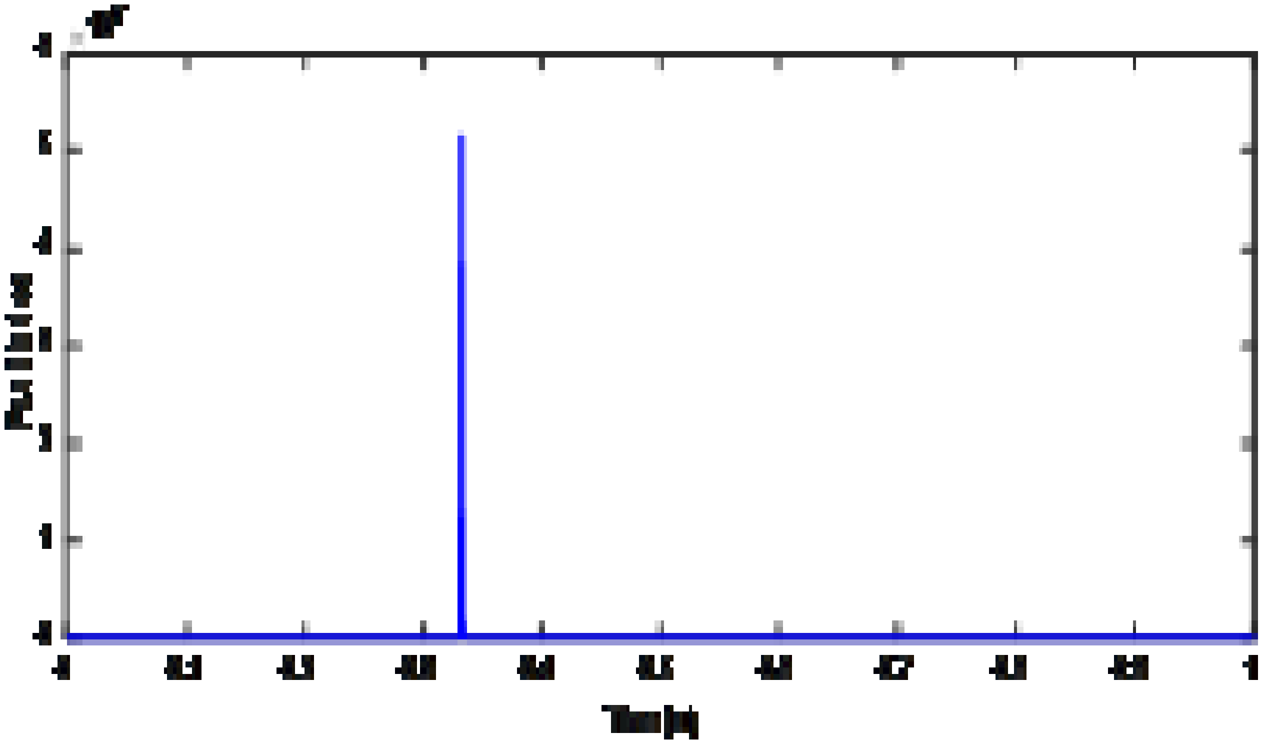
The line to ground (LG) fault is created on the phase-A at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-C recorded on bus 632 of the test system has been processed using DWT using db4 as mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 4. This can be inferred from Fig. 4 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to 12×10^4 but less than the threshold value of 1×10^6 indicating the healthy phase during the event of LG fault.



- FI for current in phase-C during LG fault on phase-A.

    - **Double Line Fault**

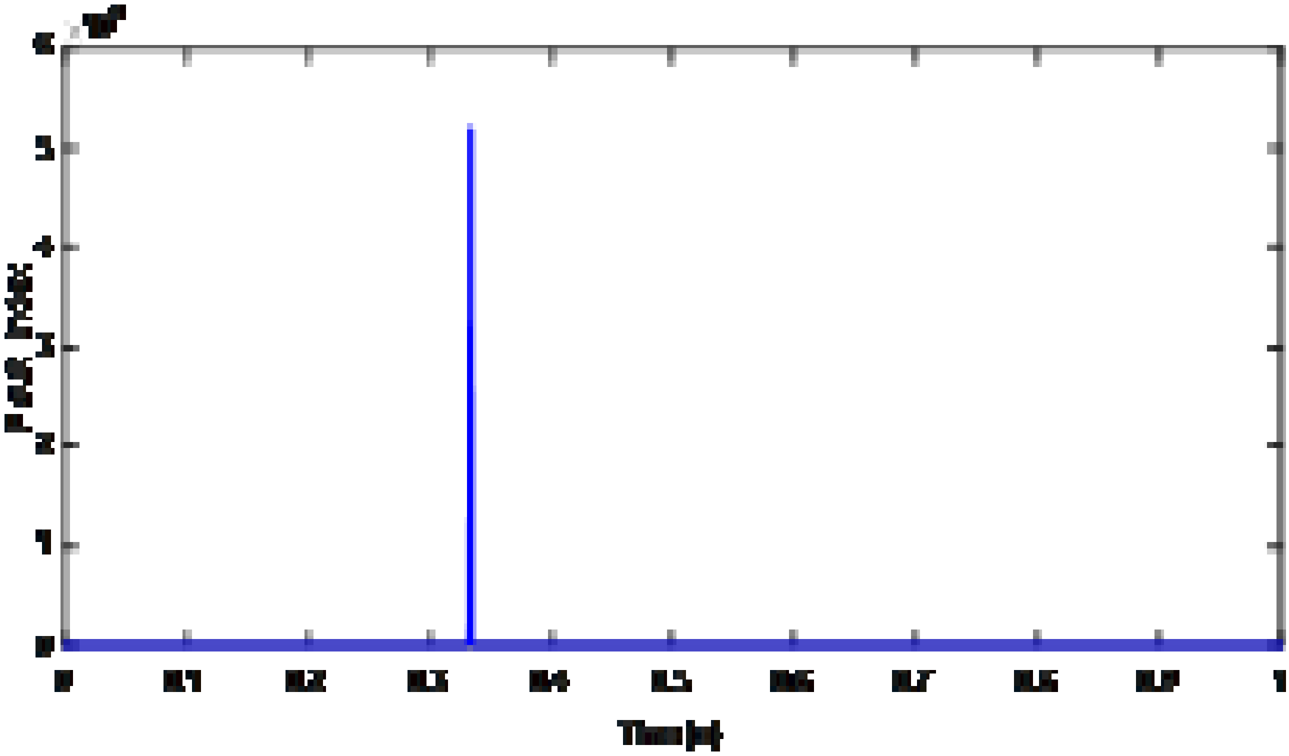
The double line (LL) fault is created by short circuiting the phases-A&B at middle of the line connected between the nodes 632 and 671 of the test system in simultaneous presence of the wind and solar PV power generation. The current of phase-A recorded on bus 632 of test system has been processed using DWT using db4 mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 5. This can be evaluated from Fig. 5 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to the 5.2×10^{7} during the events of LL fault indicating the occurrence of the fault in the test grid. A threshold value equal to 4×10^{6} has been selected for discrimination of the LL fault from the other faults as well as the faulty phases from the healthy phase during the event of LL fault. The values of proposed fault index higher than 4×10^{6} indicates the presence of the LL fault in the test grid network.



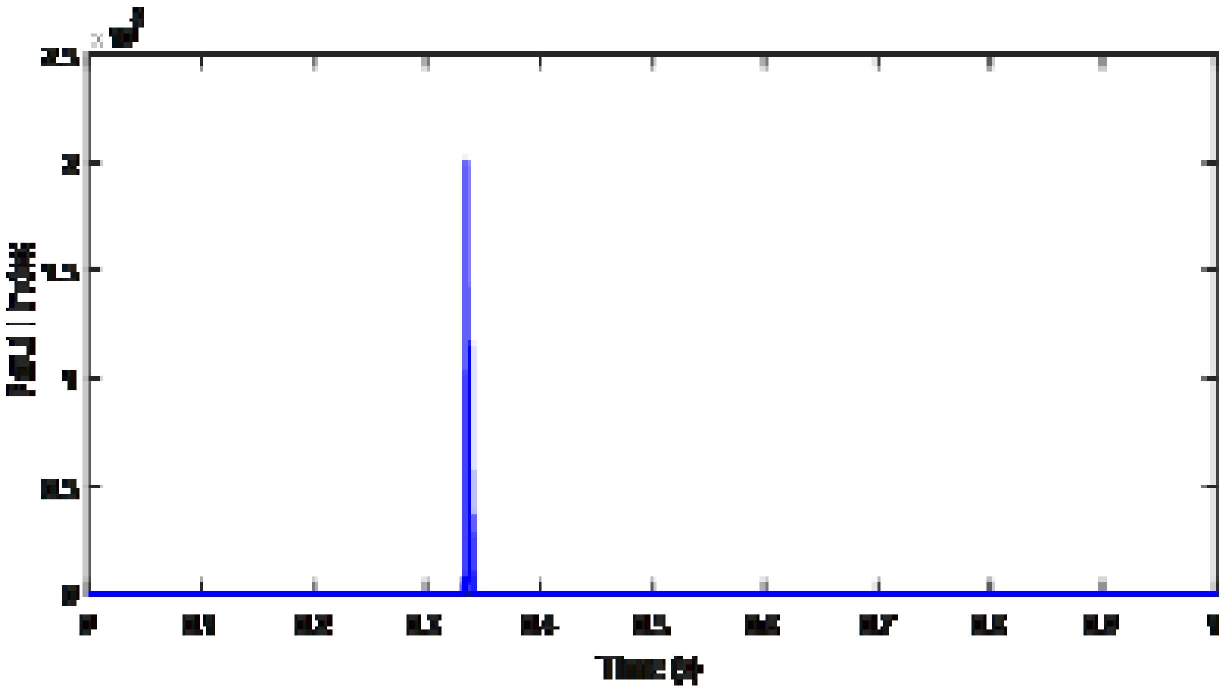
- FI for current in phase-A during LL fault on phases-A&B.

The double line (LL) fault is created by short circuiting the phases-A&B at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-B recorded on bus 632 of the test system has been processed using DWT using db4 mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 6. This is evaluated from Fig. 6 that magnitudes of the proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are higher compared to 4×10^6 indicating the faulty phase during the event of LL fault.

The double line (LL) fault is created by short circuiting the phases-A & B at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-C recorded on bus 632 of the test system has been processed using DWT with db4 mother wavelet for four levels of decomposition. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 7. This is inferred from Fig. 7 that magnitudes of the proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to 2×10^6 but less than the threshold value of 4×10^6 indicating the healthy phase during the event of LL fault.



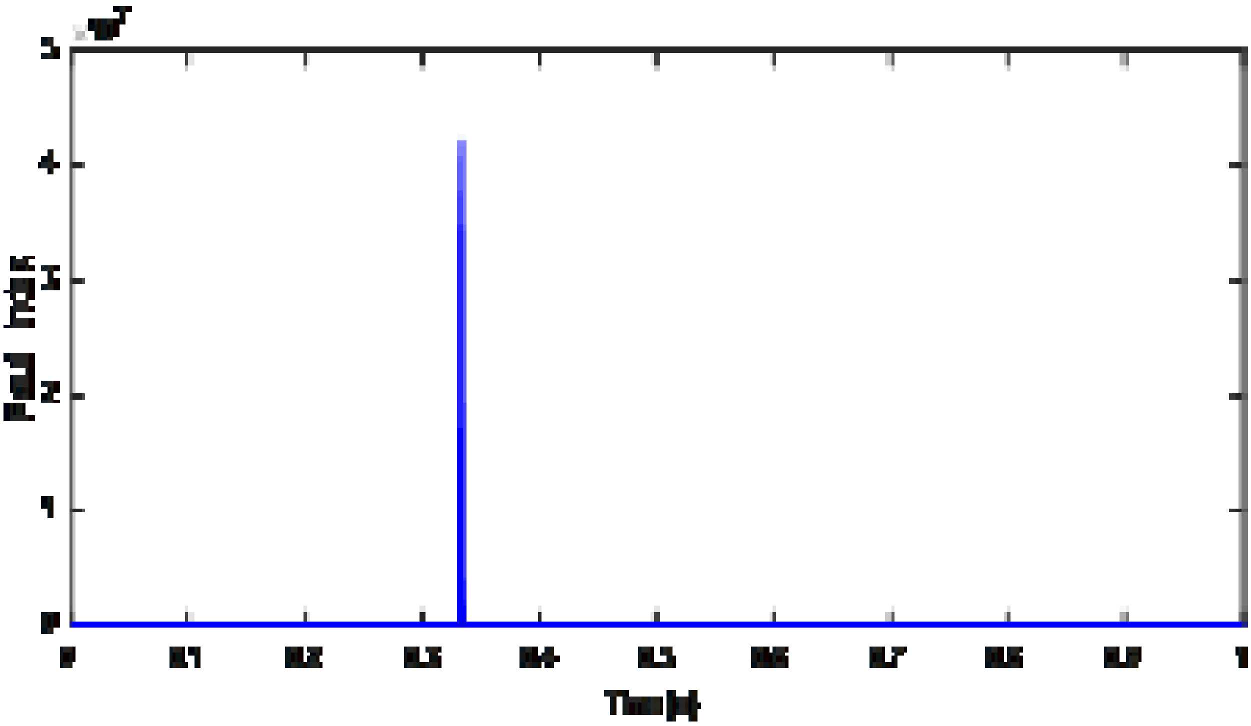
- FI for current in phase-B during LL fault on phases-A&B.

- 

- FI for current in phase-C during LL fault on phases-A&B.

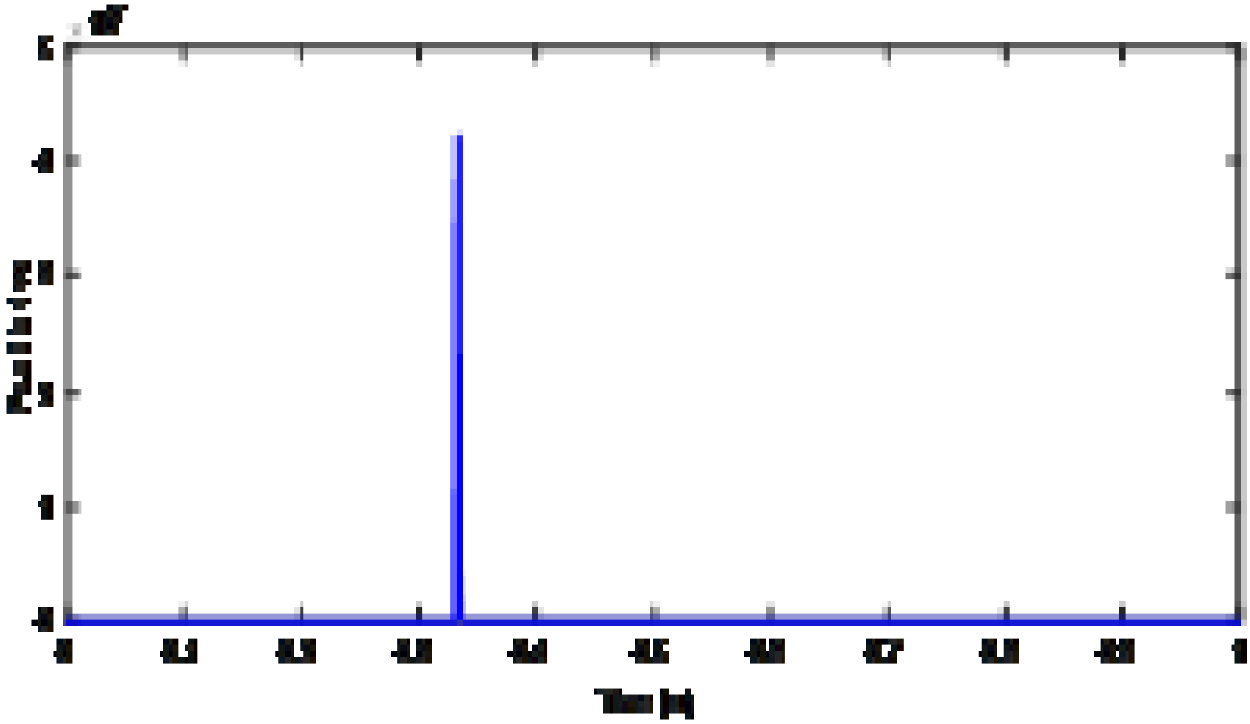
  - **LLG Fault Event**

The LLG fault event is performed by grounding phases-A&B on same moment at middle of the line connected between the nodes 632 and 671 of the test system in simultaneous presence of the wind and solar PV power generation. The current of phase-A recorded on bus 632 of the test system has been processed using DWT using db4 mother wavelet for four levels of decomposition. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 8. This is evaluated from Fig. 8 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to the 4.2×10^{7} during the events of LLG fault indicating the occurrence of the fault in the test grid. A threshold value equal to 3×10^{7} has been selected for discrimination of the LLG fault from the other faults as well as the faulty phases from the healthy phase during the event of LLG fault. The values of proposed fault index higher than 3×10^{7} indicates the presence of the LLG fault in the test grid network.



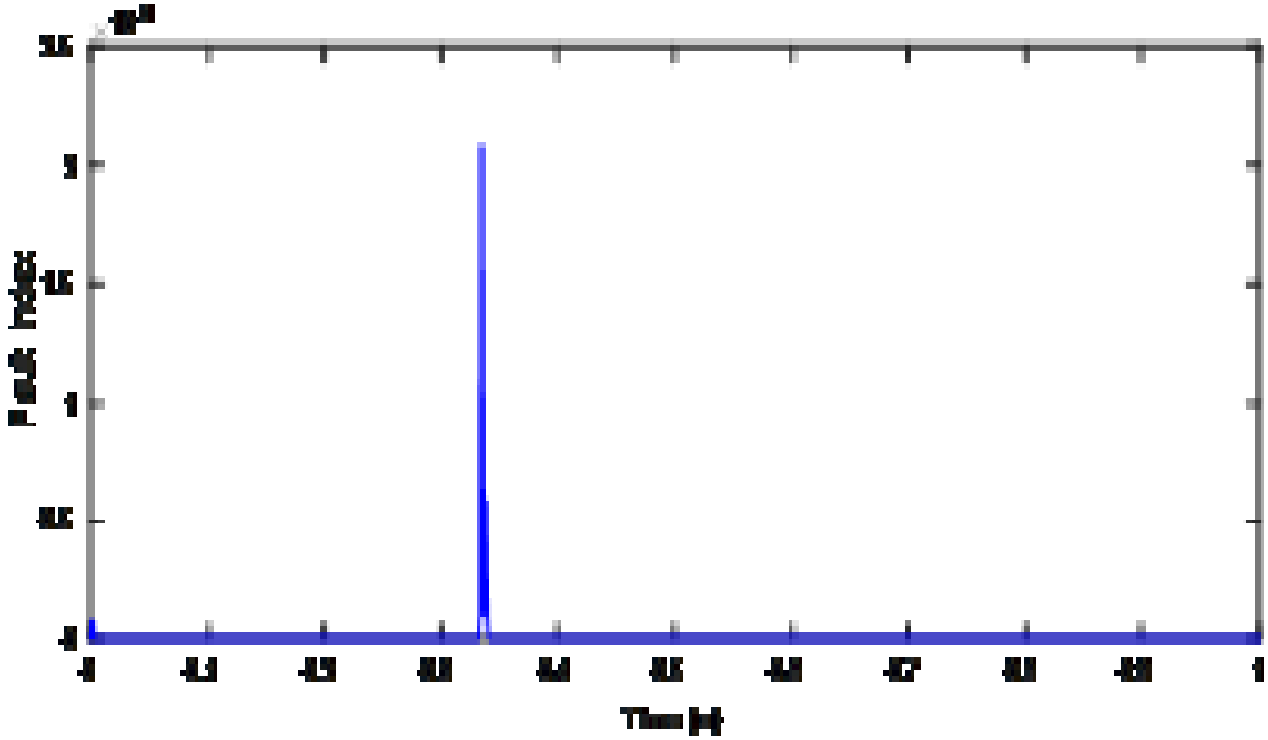
- FI for current in phase-A during LLG fault event on phases-A&B.

The LLG fault is created by short circuiting the phases-A&B at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-B recorded on bus 632 of the test system has been processed using DWT with db4 mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 9. This is evaluated from Fig. 9 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are higher compared to 4×10^{6} indicating the faulty phase during scenario of LLG fault.



- FI for current in phase-B during LLG fault event on phases-A&B.

The LLG fault is created by short circuiting the phases-A & B at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-C recorded on bus 632 of the test system has been processed by the use of DWT with db4 mother wavelet for four decomposition levels. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 10. This is evaluated from Fig. 10 that the values of the proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to 2.2×10^{5} but less than the threshold value of 4×10^{6} indicating the healthy phase during scenario of LLG fault.



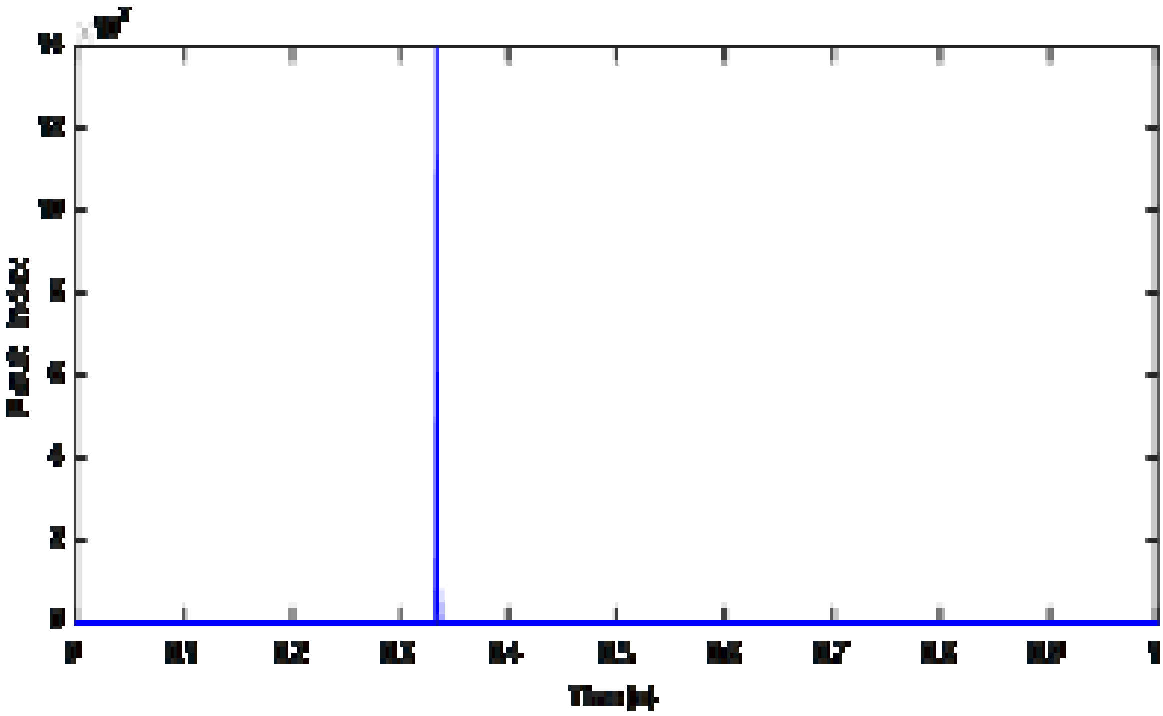
- FI for current in phase-C during LLG fault event on phases-A&B.

    - **LLLG Fault Event**

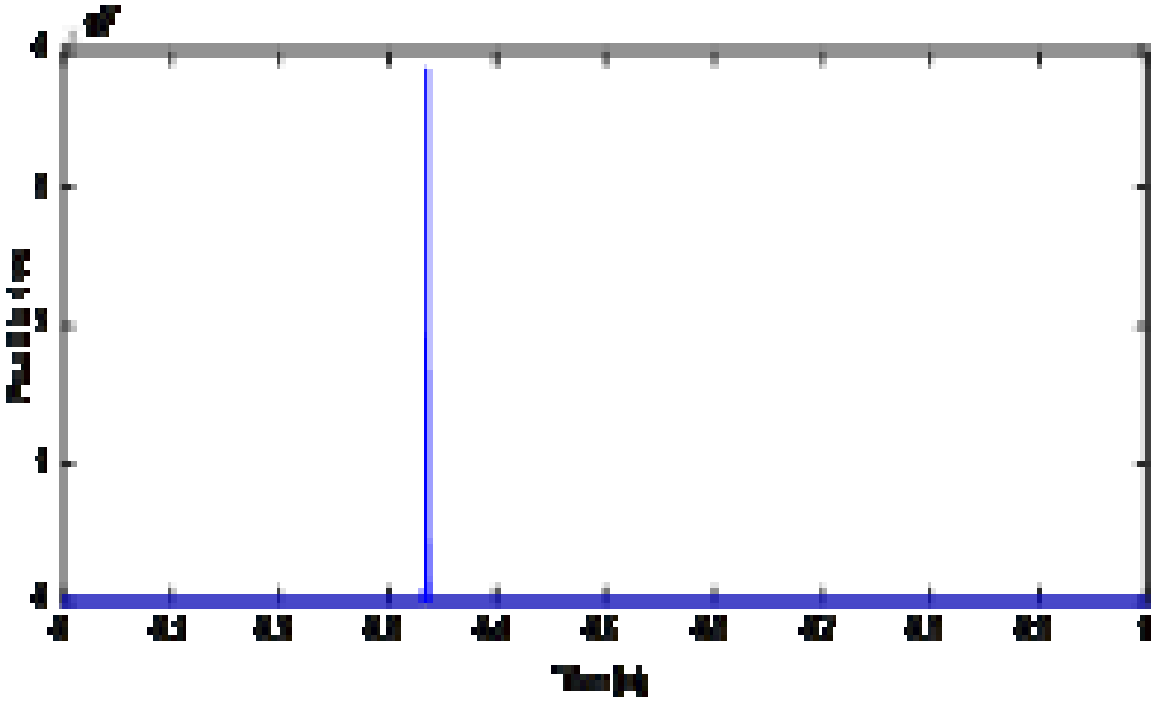
The LLLG fault is created by simultaneous grounding of all the three phases at middle of the line connected between the nodes 632 and 671 of the test system in simultaneous presence of the wind and solar PV power generation. The current of phase-A recorded on bus 632 of the test system has been processed by application of DWT using db4 mother wavelet for four levels of decomposition. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 11. This is evaluated from Fig. 11 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are high and equal to the 14×10^7 during the events of LLLG fault indicating the occurrence of the fault in the smart grid. A threshold value equal to 12×10^7 has been selected for discrimination of the LLLG fault from the other faults. The values of proposed fault index and higher than 12×10^7 indicate the presence of the LLLG fault in the test grid network.

The three-phase fault involving ground (LLLG) fault is created by short circuiting all the three phases at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-B recorded on bus 632 of the test system has been processed using DWT with db4 mother wavelet for four levels of decomposition. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 12. This is evaluated from Fig. 12 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are higher compared to 3×10^7 indicating the faulty phase during scenario of LLLG fault.

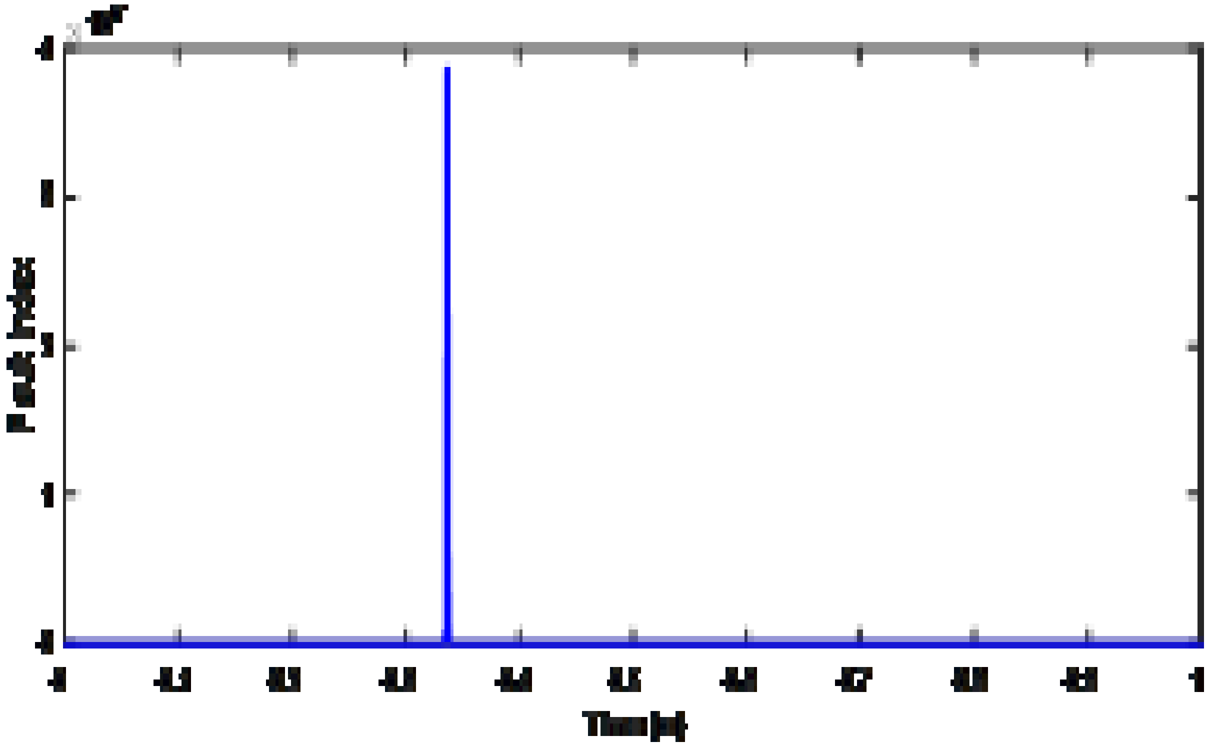
Type of Fault	Phase-A	Phase-B	Phase-C	Threshold based for phase-A
LG	9.00×10^{7}	1.30×10^{5}	1.30×10^{5}	7.00×10^{7}
LL	5.00×10^{7}	5.00×10^{7}	2.00×10^{6}	4.50×10^{7}
LLG	4.00×10^{7}	4.00×10^{7}	2.00×10^{5}	1.00×10^{7}
LLLG	$1.40\ x10^{8}$	4.00×10^{7}	4.00×10^{7}	1.00×10^{8}

- 

- FI for current in phase-A for LLLG fault event

- 
- FI for current in phase-B during LLLG fault.

The three-phase fault involving ground (LLLG) fault is created by short circuiting all the three phases at middle of the line connected between the nodes 632 and 671 of the test system in the simultaneous presence of the wind and solar PV power generation. The current of phase-B recorded on bus 632 of the test system has been processed by application of DWT using db4 as mother wavelet for four levels of decomposition. Proposed fault index is calculated from the detailed coefficient at first level of decomposition and provided in Fig. 13. This is inferred from Fig. 13 that magnitudes of proposed fault index are zero in both the pre-fault and post fault conditions. However, these values are higher compared to 3×10^{7} indicating the faulty phase during scenario of LLLG fault.



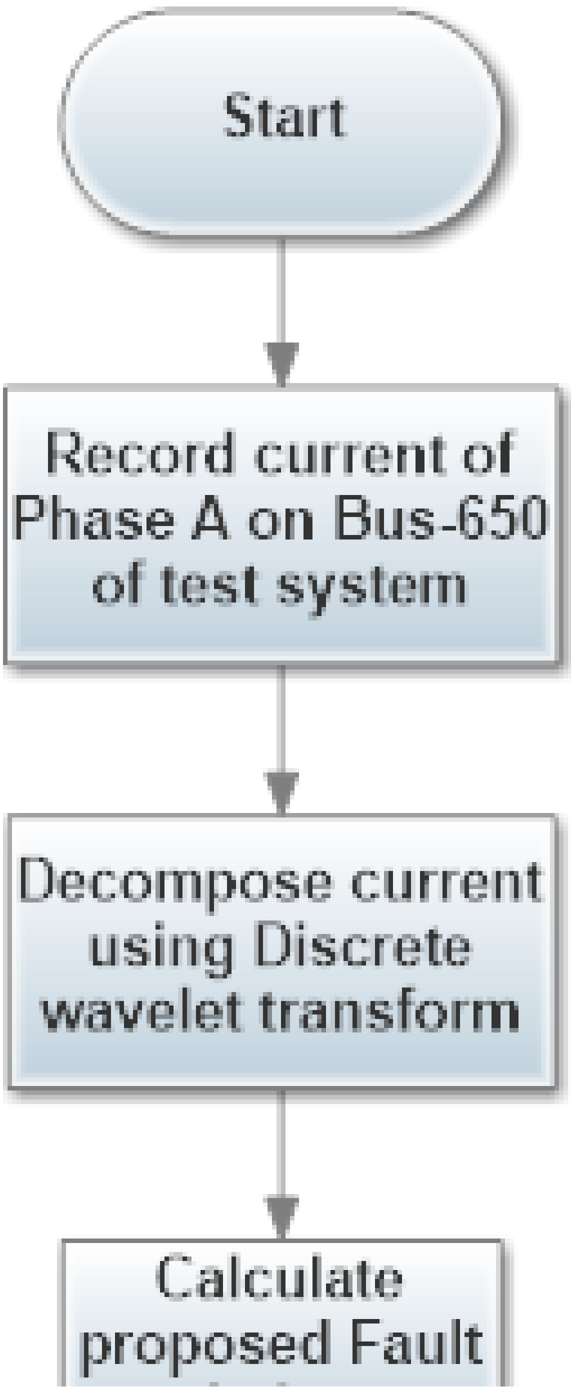
- FI for current in phase-C during LLLG fault.

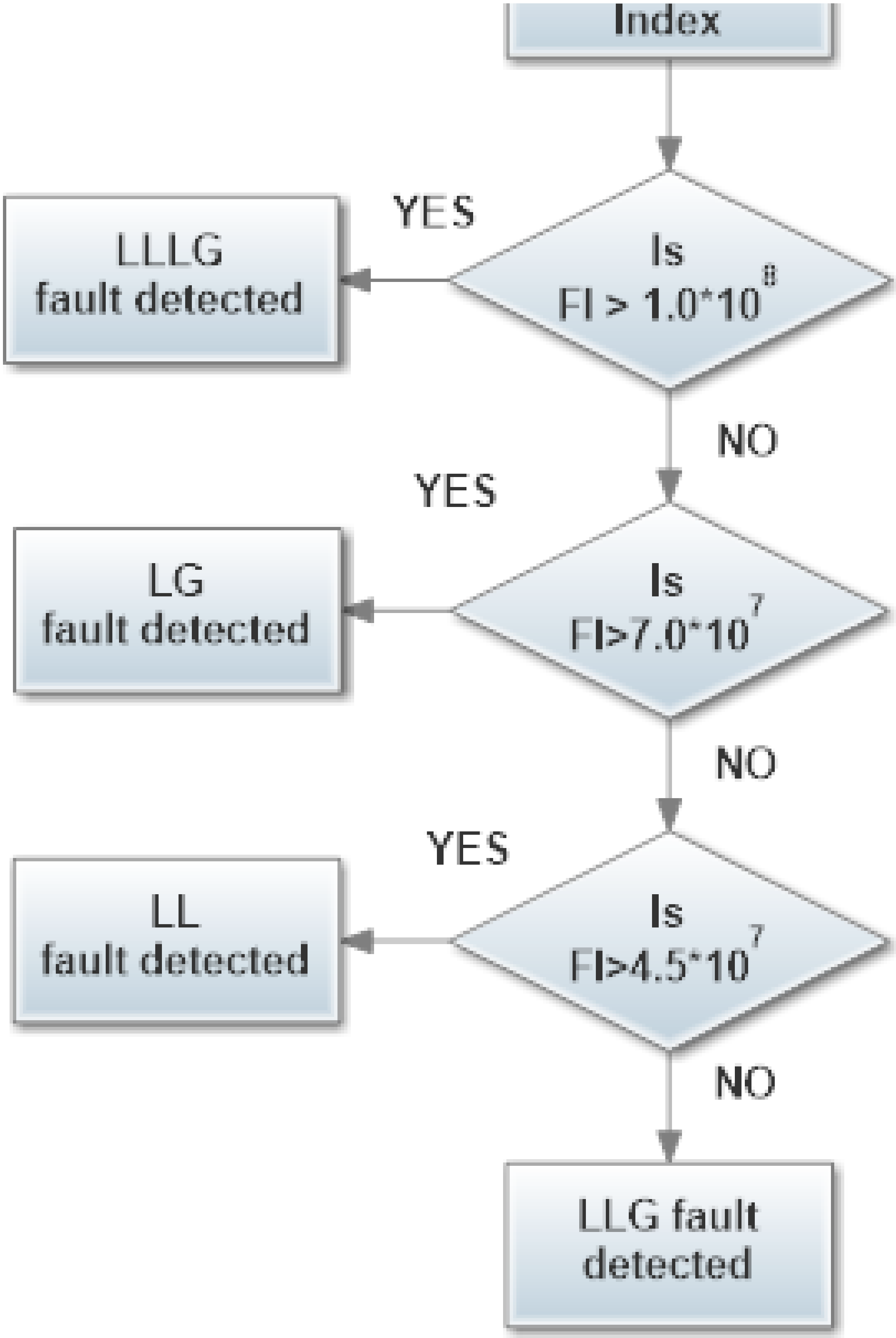
  - **Classification of Faults in the Hybrid Smart Grid**

The peak values of the fault indices for all the three phases during the events of different nature of faults like LG, LL, LLG and LLLG in the test grid in the presence of both solar PV power generation and wind energy conversion system have been provided in the Table 5. The values of proposed thresholds to identify and to discriminate of different types of faults have also been presented in this Table 5. The values provided in the Table 5 are taken as input to RBDT for classifying the faults. The threshold values provided in the Table 5 are taken as references for design of the decision rules used for the classification purpose. The flow chart used by the RBDT for classifying different types of faults in the test grid in the presence of both solar PV power and wind power generations is sown in Fig. 14.

- Peak Magnitudes of Fault Indices and Threshold Magnitudes in the Test Power System

Type of Fault	Phase-A	Phase-B	Phase-C	Threshold based for phase-A
LG	9.00×10^{7}	1.30×10^{5}	1.30×10^{5}	7.00×10^{7}
LL	5.00×10^{7}	5.00×10^{7}	2.00×10^{6}	4.50×10^{7}
LLG	4.00×10^{7}	4.00×10^{7}	2.00×10^{5}	1.00×10^{7}
LLLG	1.40×10^{8}	4.00×10^{7}	4.00×10^{7}	1.00×10^{8}





- Flow chart used for classification of the faults using rule based decision tree.

6. Performance Comparison

Performance of DWT and RBDT based algorithm designed in this paper is compared with the algorithm reported in [5]. It is established that the algorithm reported in [5] can only be applied for the recognition of fault events with solar energy. The algorithm is not tested for the hybrid power systems. However, the algorithm introduced in this paper can be applied for identification of the faults in the presence of both the wind and solar power generation. Hence, proposed method can be used for designing the protection schemes in the present day hybrid power systems.

7. Conclusions

A current based fault detection method to design protection scheme for the hybrid power system in the presence of both wind and solar power generation is introduced in this paper. It is concluded that the proposed algorithm detects the faults in the hybrid power system using the current signals. Algorithm effectively recognized the faulty events such as LG, LL, LLG and LLLG faults. Performance of technique is established to be better compared to method reported in literature with different features.

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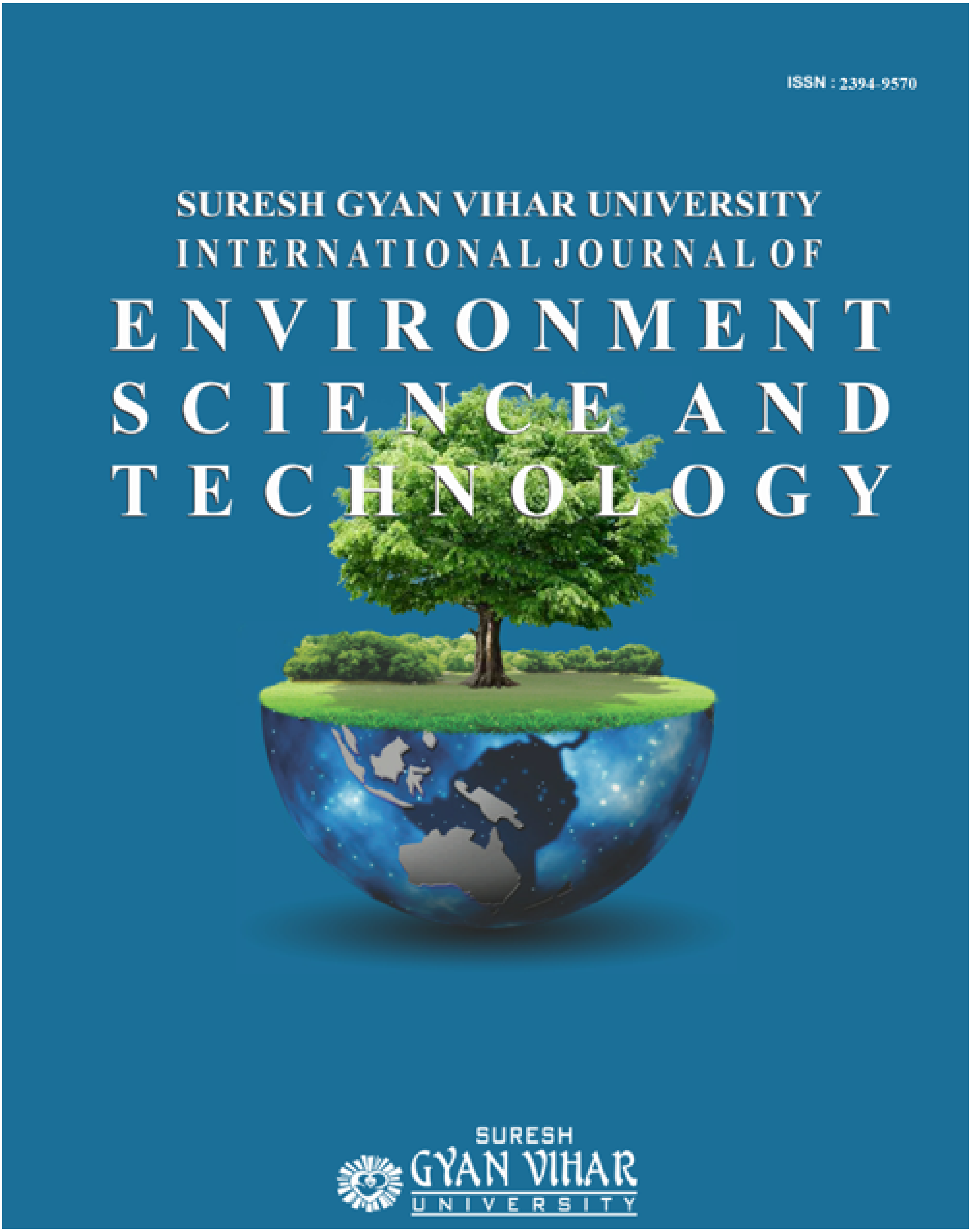

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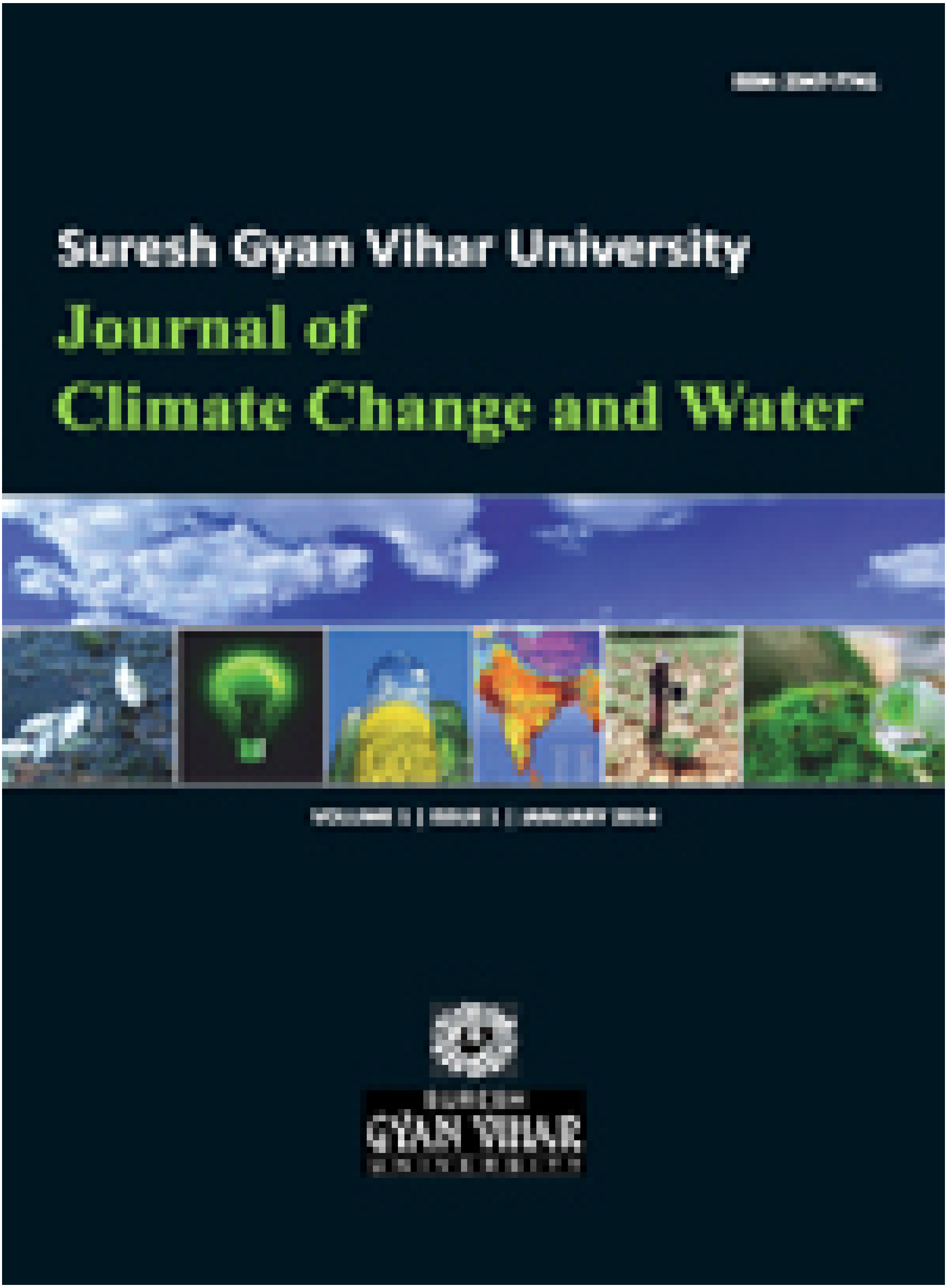

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