Incipient fault detection in active-distribution networks based on Time-varying Kalman Filter

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Abstract

Renewable energy resources (RER's) are increasing near load centers day by day. However, due to very-short fault-time interval, the Incipient Faults detection is the most challenging problem in such active-distribution networks. In this research paper, a dual fault detection index (DFDI) based on the Time-Varying Kalman filter (TVKF) has been proposed. The DFDI comprises the TVKF dependent estimation error index (EEI) and the Harmonic index (HI). In the first step, the TVKF is applied to the current signal of each phase separately, to estimate non-fundamental harmonic content. In addition, the TVKF-based harmonic content is utilized to calculate the EEI and HI of each phase separately. However, the OR operation of both the estimation error index and Harmonic index is utilized for the incipient fault detection in active distribution networks. If the DFDI of any individual phase is more than a constant threshold value relatively, the associated phase is regarded as faulty. The suggested method is simulated on MATLAB/Simulink software package. Results show that the suggested method detects incipient faults in less than 5 mili-seconds in active-distribution networks in worst cases.

Keywords: *Active-distribution networks; Incipient Fault detection; Renewable energy resources; Time-varying Kalman Filter.*

1. Introduction

In the past few years, the energy demand of consumers has been increased, due to which integration of renewable energy resources in power systems is widely spread. Therefore, it's transforming the conventional power distribution networks into active distribution networks [1]. Active distribution networks composed of distributed generators (DGs) which include photovoltaics, wind turbines, fuel cells, etc, that will lead to bidirectional power flows and some other issues. However, incipient faults detection is a dominant problem linked with such active distribution networks [2].

The incipient faults may occur due to moisture, lightning, switching a device, and demand change, etc. Furthermore, they are very short-duration faults that can persist for about 2 seconds or less, with a smaller magnitude. However, the conventional fault detection strategies (CFDS) were based on an overcurrent methodology. In consequence, it was difficult for the CFDS to detect such kinds of low magnitudes/short duration faults promptly [3].

In the recent past, many incipient fault detection strategies were proposed for the reason that conventional schemes are not good enough to detect such faults rapidly. In ref.[4], Yahyaei et al. suggested a novel technique for incipient fault identification that performed residual estimation. Proposed scheme used Lyapunov exponent and correlation functions for this purpose. A Universal Correntropy filtering technique was presented in [5], for incipient fault identification. A modified technique was presented in ref. [6] that used Kullback-Leibler branching criteria for incipient fault detection. Similarly, Paula et al. put forward a new approach in ref. [7] based on qualitative trend analysis (QTA) & Naïve Baye's Classifier for various incipient fault estimations in transmission lines.

A very simple approach of incipient fault events diagnosis was suggested by Bowen et al. & Zhou et al. based on detrending and resampling of signals from transducers [8]. Another modified technique which is the mixture of canonical variate analysis, variance analysis & KPCA to identify real-time incipient faults was established in [9]. Furthermore, an approach was proposed by Izadi et al. based on metering of synchronous wave shapes using waveform measurement units (WMUs) for detecting short-duration faults in distribution systems [10]. Also, a new and simple scheme for locating incipient events was suggested in [11] based on Electromagnetic Time Reversal.

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Many techniques were presented from last recent years but still there exist some limitations that cause inefficiency & inaccuracy in detecting such faults that are smaller in magnitude and appear for a smaller duration of time. In the case of recent intelligent machine learning techniques, a large amount of data is required for testing & training that will lead to a high computational burden. Similarly, more time is required for the processing of data in previous techniques. So, there is a need for a better development & evolution of technology that can overcome previous work limitations to a great extent.

This paper proposed a state-of-the-art methodology that is a dual fault-detection criteria-based strategy that uses a Time-Varying Kalman Filter (TVKF). Two indices have been used named as Estimation Error Index (EEI) & Harmonic index. In the first stage, the time-varying Kalman filter is practiced on a current signal coming from the current transformer (CT) & harmonic components are acquired. Then TVKF is used to compute EEI & HI for each phase individually. After that, OR-operation is implemented on both indices, so that if any index crossed the threshold value, an incipient fault event is detected. This technique is more efficient as two indices are used, so a vast variety for fault identification is catered. The proposed method is implemented on MATLAB/SIMULINK and results are used for the technique's performance estimation. The main benefaction of paper is:

- A time-varying Kalman filter is used that consists of dual detection criteria to provide a wide range for incipient fault detection.
- The proposed technique is simple and easy to implement.
- The time-varying Kalman filter can deal with noisy signals also [12].
- The technique has a less computational burden and it can detect faults faster than other similar techniques.

The paper is further categorized as follows: Section 2. presented the mathematical modeling of the proposed method. The suggested incipient fault detection strategy is presented in Section 3. Section 4 elaborates on simulation results. At last, the paper was concluded in Section 5.

2. Mathematical modeling

2.1. Time-varying Kalman filter

Time-Varying Kalman Filter is a generic sort of time-dependent algorithm [13]. As the TVKF provides filtering in the time domain that will lead to reducing the problem of handling high dimensionality in state-space vectors because TVKF is specifically used for State Estimation. There is a huge mathematical modelling of TVKF which is beyond the scope of this paper. In past schemes many different filters were used for incipient fault detection, such as a simple Kalman filter that deals only linear data so, the state-space conversion is required. Apart from this, the TVKF deals with non-linear data efficiently, so there is no need for conversion. Moreover, the TVKF can detect incipient faults more accurately and faster than other techniques. As incipient faults occur in a system for a very short duration of time, TVKF can detect these faults faster using the dual index criterion. Also, there is no need for testing and training of data like previous techniques that will cause complexity in estimation. TVKF can deal with such systems that are not perfect means it can handle noisy signals/ non-linear signals that provide an accurate and better estimation of results. A complete algorithm of the Time-Varying Kalman Filter is depicted in Fig. 1. While implementing TVKF, the first step is the estimation of the initial value. Then, TVKF gain is computed, and the estimated value is updated using the measured value.

2.2. Three Phase Balanced Active Distribution Networks (ADN) model

The balanced 3-ϕ system has voltage and current magnitude on all three phases separated by 120°. In addition, a non-sinusoidal three-phase balanced system is the summation of fundamental and non-fundamental components. However, in the proposed scheme only current signal is utilized for incipient-faults detection therefore only current models are represented as follows:

$$i_a(t) = A_1 Sin\left(\omega_f(t).t + \theta_1\right) + A_2 Sin\left(2\omega_f(t).t + \theta_2\right) + A_3 Sin\left(3\omega_f(t).t + \theta_3\right) + \cdots \quad (1)$$

$$i_b(t) = A_1 Sin\left(\omega_f(t).t - {}^{2\pi}/_{3} + \theta_1\right) + A_2 Sin\left(2\omega_f(t).t + {}^{2\pi}/_{3} + \theta_2\right) + A_3 Sin\left(3\omega_f(t).t + \theta_3\right) + \cdots \quad (2)$$

$$i_c(t) = A_1 Sin\left(\omega_f(t).t + {}^{2\pi}/_{3} + \theta_1\right) + A_2 Sin\left(2\omega_f(t).t - {}^{2\pi}/_{3} + \theta_2\right) + A_3 Sin\left(3\omega_f(t).t + \theta_3\right) + \cdots \quad (3)$$

Generally, every non-fundamental component having a sequence of order n, for all n ε N is considered as a balanced 3ϕ network with magnitude A_n & frequency $\omega_n = n\omega_f$, whereas ω_f is fundamental frequency & θ is represented as phase angle [12]. The 3ϕ non-fundamental current signal's state-space estimation is as follows:

$$\begin{aligned} \dot{Y}_n &= By_n + c\omega_n \\ I_n &= Ky_n + U_n \end{aligned} \tag{4}$$

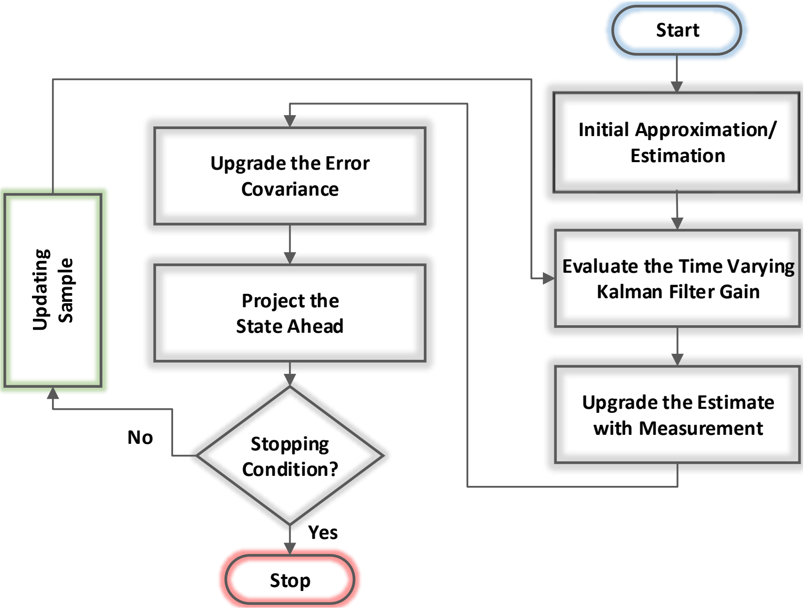

Fig. 1: Time Varying Kalman Filter (TVKF) Algorithm flow chart

However, y_n network condition will be:

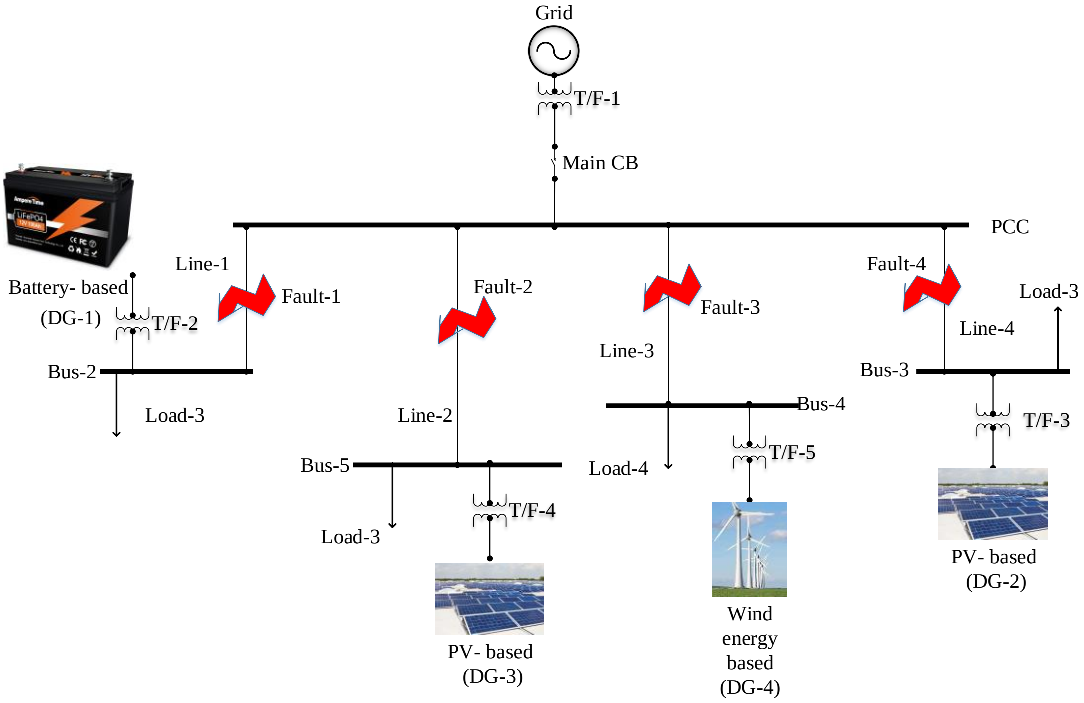

Fig. 2: Active distribution network (ADN) test system

$$\dot{Y}_n = [i_n \quad i_{n-1}]^{-1}, c = [1 \quad 0]^i, K = [1 \quad 0]^T \; \& \; B = \begin{bmatrix} 2cos\omega & -1 \\ 1 & 0 \end{bmatrix}$$

2.3. Thresholds setting

Two threshold constant values are chosen Th-1 and Th-2 for corresponding indexes EEI and HI respectively. The Th-1 is chosen to be 0.1, whereas Th-2 is chosen as 0.5. If the value of the EEI and the HI of any phase is greater than the corresponding threshold values during abnormal conditions the relative phase is deemed to be faulty. All the incipient faults that are generated at different locations, at different scenarios, were timely detected using these threshold values.

2.4. ADN Test system

The active distribution system has been implemented in MATLAB/Simulink software to examine the proficiency of the devised technique. Whereas, this test system was modeled by slight modification in IEC standard test system. However, the proposed strategy has been also tested on IEEE-9. Bus system. The single-line diagram of the active distribution network (ADN) test system is presented in Fig. 2. The test system consists of six buses and 4 DGs whereas, three of them are inverter-based DG and one of them is synchronous-based DG. More specifically, 1 wind-based DG, 2 solar-based DGs, and 1 battery storage system. Four incipient faults F1 to F4 are generated at different locations of different lines for the validation of the proposed scheme.

2.5. Proposed detection strategy

The Strategy proposed in this research paper entails several steps such as current signal acquisition, TVKF based state estimating, and fault detection logic. Each step is depicted in Fig 3**Fig**, however, a detailed explanation of each step was discussed in the following sub-sections.

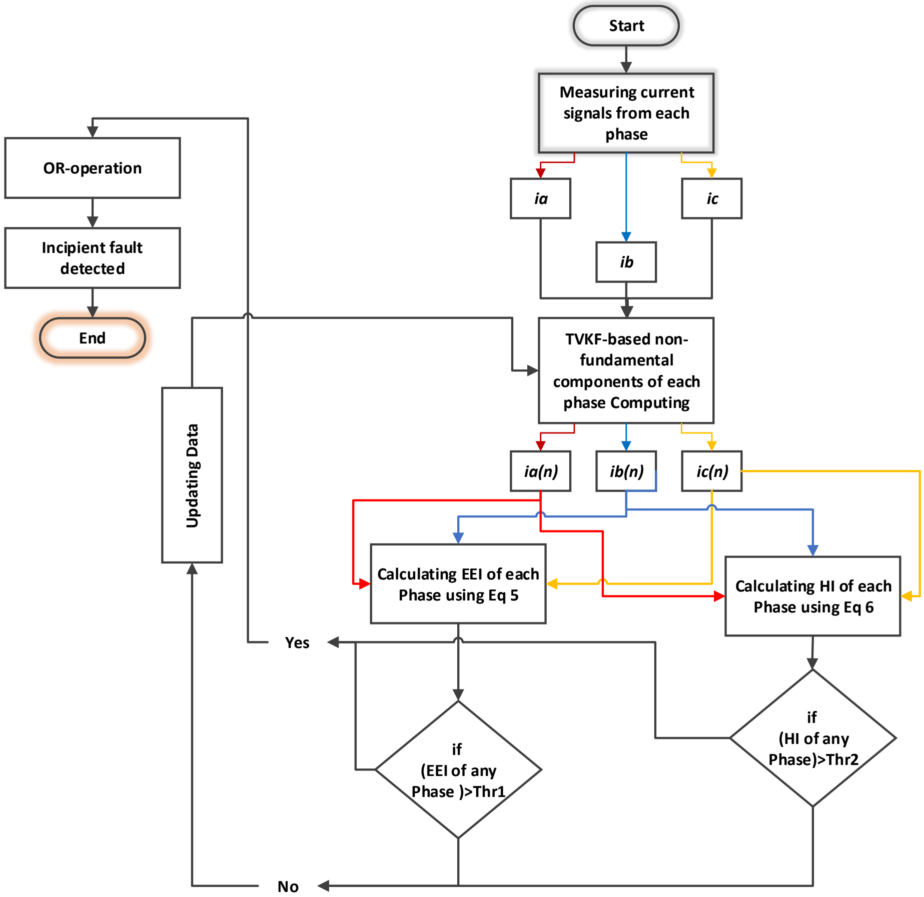

Fig. 3. Proposed incipient-faults detection strategy work-flow diagram.

2.6. Current-Signal Acquisition

The first step of data acquisition measures the current signal from the current transformer and preprocesses it to remove noise. As the data is analog so, analog to digital converter is used for conversion. The converter used is 12-bits with having a sampling rate of about 3600 Hz so it can sample the signal according to this frequency. After gaining a digital signal, the higher-order harmonic components are present in them. To remove these components a finely tuned Bessel Filter which is a low pass filter having a cut-off frequency f_c of about 1.6 kHz is used. The output of the low pass filter is then applied to the Time-varying Kalman filter for further procedure.

2.7. State Estimating Using TVKF

Exact state estimation and feature extraction of non-fundamental are important in any fault detection scheme to avoid false tripping and blinding issues. Therefore, in the second stage, the discrete current signal which is obtained in the previous stage used as input of TVKF for feature extraction and the State estimation purpose. Therefore, the TVKF is practiced on each phase separately for harmonic content estimation of the current signals. Whereas, the estimated non-fundamental current signals are further used for fault identification in the third stage using proposed DFDI criteria.

2.8. Fault Detection Logic

Fault detection criteria majorly consist of two indices that are used for incipient fault identification in active distribution networks. OR-operation is used for decision making, if any of the indexes crosses the predetermined threshold value, the fault condition will be detected. These two indices are EEI &. HI.

2.8.1. Estimation Error Index (EEI)

*T*he Estimation error-index is a difference signal that is obtained by subtracting the filtered current signal from the estimated fundamental current signal and it can be represented in mathematical form as follows:

$$\mathrm{EEI_a} = \mathrm{I_{fa}} - \mathrm{i_{na}} \tag{5}$$

Whereas

$\mathrm{I_{fa}}$ is a filtered current signal of phase “a”
$\mathrm{i_{na}}$ is estimated fundamental current signal.
However, the remaining phases of EEI can also be obtained in the same manner as in Eq. (5).

2.8.2. Harmonic Index (HI)

One more index is also provided for the incipient fault identification, which is a challenge in active distribution networks during the low level of fault currents and short duration. However, this index is a harmonic index which is more sensitive to such kind of situation furthermore, the mathematical model of HI can be represented as follows:

$$HI_a = \frac{\sqrt{\sum_{n=3,5,..}^{\infty} I_{n-rms}^2}}{I_1} \tag{6}$$

Similarly, the remaining phases HI can be computed using the above formula in Eq.(6).

3. Results and discussions

The test system is simulated in MATLAB/SIMULINK and different scenarios are considered to create incipient-fault events. However, few cases are presented here for the validation of the proposed scheme.
As shown in Fig. 4 the fault-1, which is a double-line to ground fault that occurs at t=0.15s on phases A and C. As it is clear from the figure, the incipient fault can be detected efficiently in milliseconds. The proposed scheme detected the fault speedily and more accurately due to the TVKF having this ability. Fault terminates at t=0.2s. However, the double line to ground fault occurs for a short duration of time of about t=0.05s and the incipient fault duration is 2sec or less. So, TVKF easily detects this fault using dual index criteria. As depicted from the figure, the EEI crossed the threshold

lately, but the HI index crossed the Th-2 timely. Furthermore, the OR-operation of both these indexes output given a logic 1 which means the fault is detected.

A single line to a ground fault is the most occurring fault in the power system. So, it must be detected as faster as possible. So, in Fig.**Error! Reference source not found.** 5, a single-phase incipient fault takes place at t=0.2s and terminates at t=0.25s, which means fault occurs for about t-0.05s. From Fig. 5 the EEI and the HI both indices crossed their values as the fault occurred which shows that the TVKF technique work more efficiently and detects a fault in milliseconds. Therefore, the technique reduces the tripping and blinding issues in the power system that are more frequently happening.

Fault 3 happens in the test system which is a three-phase to ground fault as displayed in Fig. 6. The three-phase fault is the rarest in the system, but it is most dangerous. Therefore, a 3-phase incipient fault is simulated at t=0.25s. From the figure only is cleared only one index which is the HI index crossed the threshold-2 and detects the fault. Whereas the EEI index did not cross the threshold value. But, OR operation on both these outputs will result in the output logic of 1 that will lead to fault identification. TVKF detects this fault using dual index criteria. As it is clear from results that dual criterion provides the benefit of accurate detection that if any of the indexes cannot deal with the situation, another index can predict the condition and detect the fault in a smaller time interval.

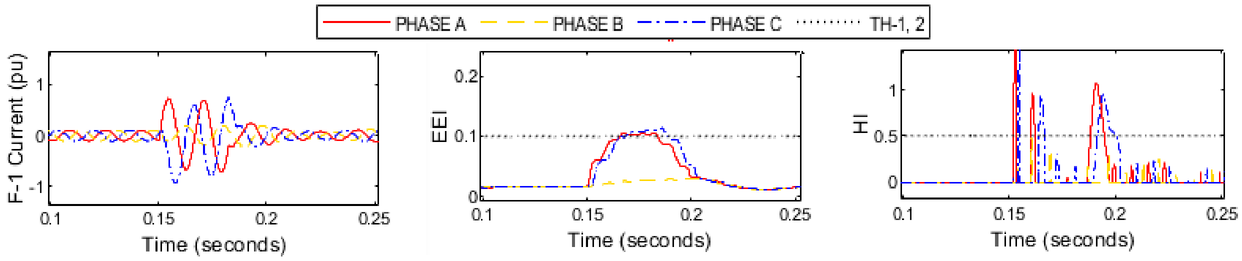

Fig. 4: Double-line to ground (AC-g) incipient fault

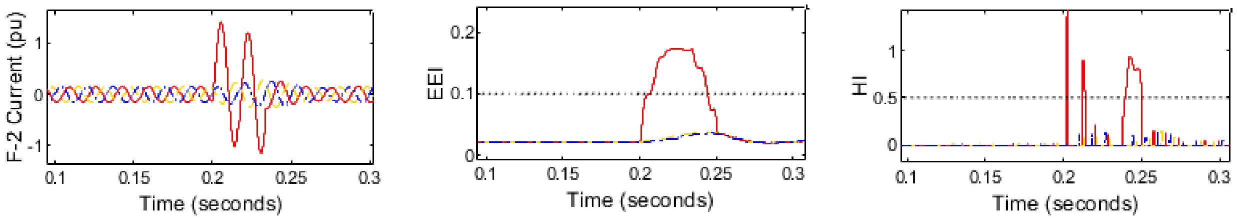

Fig. 5: Single-line to ground (A-g) incipient fault

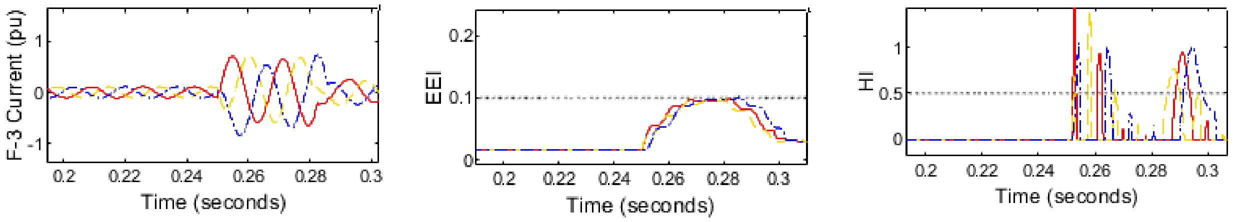

Fig. 6: 3-phase (ABC-g) incipient fault

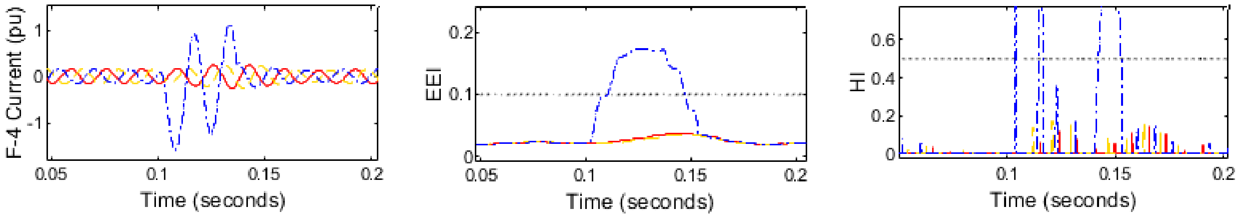

Fig. 7. Single-phase (C-g) incipient fault

Similarly, to F-1 the Fig. 7 throws light on another situation created by the single line to ground fault on phase. Simulation results in the figure show that the technique efficiently detects the fault. The fault occurs at t=0.1s and ends at t=0.15s.

4. Conclusion

The Incipient Faults detection is the most difficult issue related to active-distribution networks. This paper proposed a dual fault detection index (DFDI) established from the Time-Varying Kalman filter (TVKF). The DFDI contains the estimation error index (EEI) and Harmonic index (HI). Initially, TVKF was applied to the current signal of all phases separately, for the non-fundamental harmonic components estimation. Secondly, the TVKF-based harmonic content is used to compute the EEI and HI for each phase individually. At last, the detection decision is generated by the OR-ing of both the EEI and HI in active distribution networks. If the DFDI of any phase is greater than a pre-specified threshold value, the corresponding phase is considered to be faulty. The proposed scheme is simulated on MATLAB/Simulink software. Results show that the proposed scheme detects incipient faults in less than 5 mili-seconds in active-distribution networks in worst cases.

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