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An Improved Cumulative Sum-Based Fault Detector for Power Network Protection

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ABSTRACT

An improved cumulative sum (ICUSUM)-based technique for fault detection has been proposed in this paper. A fault detection algorithm has been presented using only one filtered signal to detect a fault, unlike the two complementary signals used earlier in the cumulative sum-based method, in order to compute detector index. The fault detection techniques so far suggested in the literature are sensitive to uncertainties and change in system condition, yielding inaccurate output. The relative performances of different algorithms have been tested in the presence of noise, harmonics, spike, and high-resistance fault. The test results obtained using the present method reveal better performance over other detection algorithms. The proposed detector is robust against any distortion in the current samples. A system has been considered for simulation under the MATLAB®/Simulink™ environment.

***Index Terms*—**Cumulative sum (CUSUM), digital relaying, distance protection, discrete wavelet transform (DWT), fault detection, transmission line protection.

I. INTRODUCTION

In a power system, the role of a relay is to prevent component damage and keep the system stable when a fault occurs. An effective relaying principle involves current magnitude as an indicator of fault. In windy conditions, transmission line phases may swing and touch, and the dielectric strength of air between them in monsoon may reduce, resulting in a flashover, which leads to a line–line fault. The most common fault in overhead lines is the line–ground fault, which occurs due to failure of line insulators in lightning storms, or due to broken conductors, and many other factors. Literature suggests that in statistics of overhead line fault occurrence, the line-to-ground faults have 80–90% occurrence, followed by line–line fault, line–line–ground, and triple-line faults. The system's performance is affected by these kinds of faults [1].

Normally, the trip decision of a relay depends upon the fundamental component of current or voltage waveforms. In the literature, various methods have been proposed for fault detection in a transmission line. The steady-state voltage and current waveforms distort the onset of a fault in the transmission line. This change is utilized for development of digital relaying algorithms. Two simple conventional techniques have been suggested for fault detection [2,3]. One of the methods involves comparison of a recent sample with a previous sample of the same cycle, and the other is based upon comparing a recent sample with a sample from the previous cycle. The accuracy of conventional methods is affected due to signal with noise, harmonics, frequency deviation, and other uncertainties.

Recent relaying algorithms employ discrete Fourier transform (DFT), recursive least square, and Kalman filter to extract phasors of current and voltage signals [4,5]. Wavelet transform has been applied for fault detection using samples of voltage and current signals [6,7]. Adaptive filters are used for fault detection by statistical approach [8,9]. An adaptive moving sum approach has been considered for fault detection in a transmission line [10]. In pre-fault conditions, the sum of one cycle of sinusoidal current signal at fundamental frequency is zero. The moving sum index will be non-zero with inception of a fault. An index value exceeding a threshold value confirms the occurrence of a fault. The concepts of superimposed component-based fault detection in the presence of power swing and directional detection have been suggested [11]. An adaptive

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superimposed component-based fault detector has been proposed [12], in which adaptive windows render the technique insensitive to change in frequency.

Algorithms based on the statistical approach using cumulative sum (CUSUM) have been developed to detect and isolate faults [13]. An adaptive CUSUM algorithm is presented to detect false data in a smart grid, using a real-time sensor [14]. A CUSUM-based algorithm has been reported in case of detecting a fault in high voltage transmission line [15]. Another CUSUM-based method has been developed to track high-resistance faults in transmission lines [16].The performance of the CUSUM-based fault detector is satisfactory so far as accuracy and reliability are concerned. The CUSUM-based technique uses a two-sided current signal for fault detection in a single phase and requires six signals for a three-phase system. The consistency of a CUSUM-based fault detector is oscillatory and the index value is found to be low.

The contribution of this study is an efficient yet simple fault detection technique based on the CUMSUM approach of current signal samples. The proposed approach is immune to disturbances and other uncertainties, thanks to the one-cycle DFT-filtered signal. When the fault occurs, the CUMSUM approach produces a high non-oscillating index value. Unlike the two-sided CUMSUM-based fault detector, the suggested method uses only one current signal, which saves microprocessor memory. This extra memory can be used for one-cycle DFT and other digital relaying computations. The proposed fault detector uses only one signal per phase and three signals of a three-phase system. The suggested new version offers all features of the CUSUM method and also eliminates the limitation of low oscillatory index value. The proposed method has been compared with CUSUM and other methods to study effectiveness of the algorithm. The performance of the ICUSUM method is found to be comparatively better than other fault detection techniques.

II. FAULT DETECTION TECHNIQUES

The voltage and current signal get distorted when a fault occurs, and the distortion involves change in magnitude, frequency, and phase of the signal. Many researchers have developed fault detection algorithms utilizing the features of a distorted fault signal. An index is computed using the attributes of a sinusoidal current/voltage signal and a fault is registered if the index exceeds a threshold value. A fault detection algorithm should be able to detect the fault within a few milliseconds. The relay then activates the main algorithm to classify and locate the fault. Normally, current samples are employed for fault detection since distortion in the current signal is prominent. Several fault detection algorithms discussed below have been developed using the properties of the current signal.

Methodology: Fault current signals in various conditions are synthesized from MATLAB/Simulink two-terminal models. The signals are then processed through different fault detector algorithms. The index values of the fault detector are used for comparative assessment.

A. Sample-to-Sample Comparison Method

A straightforward technique for fault identification is based on calculating the difference between the latest sample and previous sample. A routine process continuously checks this difference with a threshold value. A fault is detected when difference becomes greater than the threshold value. The equation can be written as:

$$m_k = |i_k - i_{k-1}| \tag{1}$$

A fault is indicated when

$$m_k > a, Y_1 = 1 \text{ else } Y_1 = 0 \quad Y_1 = 1 \text{ else } Y_1 = 0 \tag{2}$$

where k is sampling instant, i_k is phase current instantaneous sample value, a is threshold value, and Y_1 is detector output.

B. Cycle-to-Cycle Comparison Method

The periodicity of the sinusoidal signal helps in fault detection using cycle-to-cycle comparison. In this method, the present sample is compared with the value obtained one cycle earlier. The two samples considered at the same instance corresponding to consecutive cycles remain the same during pre-fault conditions. The two values only differ upon occurrence of a fault and the significant change is registered by the fault detector. The equation can be written as:

$$n_k = |i_k - i_{k-N+1}| \tag{3}$$

A fault is indicated when

$$n_k > b, Y_2 = 1 \text{ else } Y_2 = 0 \tag{4}$$

where N is window length, i_k is phase current, instantaneous sample value b is threshold value, and Y_2 is detector output.

C. Phasor-to-Phasor Comparison Method

Another fault detection method has been proposed involving comparison of phasors [9]. The technique employs first and second derivatives of the input signal to compute the phasor at any instant. The current phasor magnitude at the k^{th} instant is compared with that of $(k-3)^{th}$. The difference exceeding a threshold value indicates occurrence of a fault. The technique can be expressed as:

$$(\hat{I}_p(k))^2 = \left(\frac{i''(k)}{w^2}\right)^2 - \left(\frac{i'(k)}{w}\right)^2 \tag{5}$$

where i' and i'' are the first and second derivatives of the current signal. A fault is indicated when

$$o(k) > c, Y_3 = 1 \text{ else } Y_3 = 0 \tag{6}$$

where

$$o(k) = \hat{I}_p(k) - \hat{I}_p(k-3) \tag{7}$$

and c is a threshold value and Y_3 is detector output.

D. Moving Sum-Based Approach

The sum of sampled values during a normal condition over a cycle is nearly zero for a sinusoidal current signal. An adaptive moving window is considered for fault detection using the characteristics of a current signal. For implementing the moving sum-based approach in real time, the following procedure is adopted. The digital relay processor will store one cycle post-current data samples at each instant. The moving sum function in the associated relaying embedded system will calculate the sum of the samples in the current window. The index value moving sum fault detector is the sum of data of one cycle. The corresponding register will change its value from

0 to 1 if the moving sum fault detector index exceeds the threshold, and the fault will be identified. The window length is decided according to signal frequency at that particular instant and the moving sum is computed over one cycle of window length. The value of the moving sum index is zero during normal conditions and changes significantly if the window contains post-fault current samples. The moving sum index can be expressed as:

$$p_k = \sum_{j=k-N-1}^{k} i(j) \tag{8}$$

A fault is indicated when

$$p_k > d, Y_4 = 1 \text{ else } Y_4 = 0 \quad Y_4 = 1 \text{ else } Y_4 = 0 \tag{9}$$

where d is the threshold value, j is a recent sample, and Y_4 is detector output.

E. Superimposed Component-Based Approach

The fault current contains steady-state current along with a superimposed transient component. The superimposed component-based approach can be suitably applied for fault detection where the fault is initiated corresponding to a single event and no other simultaneous event occurs. The superposition of pre-fault and fault-generated quantities result in the faulted network state. The superimposed component is zero under normal conditions, and the value increases with the occurrence of a fault. The equation for the superimposed component can be expressed as:

$$q_k = \sum_{j=k}^{k+N} \left| i(h) \right| - \sum_{j=k}^{k+N} \left| i(h-N) \right| \tag{10}$$

where j is the sample number variable and k is a recent sample.

A fault is indicated when

$$q_k > e, Y_5 = 1 \text{ else } Y_5 = 0 \tag{11}$$

where e is the threshold value and Y_5 is detector output.

F. Conventional Cumulative Sum-Based Approach

The CUSUM method is applied to identify unexpected deviations of state variables indicating abnormal system behavior in many processes. A two-sided CUSUM-based algorithm has been proposed earlier for fault detection [15]. The CUSUM algorithm uses the phase current samples and prepares two complementary signals, as

$$x(1) = i_k \tag{12}$$

$$x(2) = -i_k \tag{13}$$

The two-sided CUSUM indices can be expressed as

$$r_k(1) = \max\left[\left\{ r_{k-1}(1) + x_k(1) - \nu \right\}, 0\right] \tag{14}$$

$$r_k(2) = \max\left[\left\{ r_{k-1}(2) + x_k(2) - \nu \right\}, 0\right] \tag{15}$$

where r_k represents the detector index for two-sided signal and ν is a drift parameter which provides a low-pass filtering effect. A fault is indicated when

$$r_k(1) > f \text{ or } r_k(2) > f, Y_6 = 1 \text{ else } Y_6 = 0, Y_6 = 1 \text{ else } Y_6 = 0 \tag{16}$$

where f is threshold value and Y_6 is detector output.

G. Wavelet-Based Approach

The transient voltage and current signals contain a high-frequency component upon the inception of a fault. The energy of these high-frequency signals is used for detection of the fault [8]. The wavelet coefficient energy is computed, in which a moving window of half cycle passes through the current wavelet coefficients. Wavelet coefficient energy is nearly zero under normal operating conditions, and increases when a fault occurs. The choice of the mother wavelet function is critical to the analyses' effectiveness. It has settings that allow you to change the wavelet form's attributes based on the features of the signal being analyzed.

$$s_k = \sum_{j=k-N_h+1}^{k} \left[d_w(k) \right]^2 \tag{17}$$

Where j is the sample number, k is a recent sample, N_h is half-cycle window length, and d_w is detailed coefficients. A fault is indicated when

$$s_k > g, \; Y_7 = 1 \text{ else } Y_7 = 0 \tag{18}$$

where g is the threshold value and Y_7 is the detector output.

H. Proposed Fault Detector

The conventional CUSUM-based fault detector has certain limitations. The CUSUM employs two-sided complementary signals leading to complex hardware, involving an increment in cost. It is noteworthy to mention that the CUSUM method yields a low index value, resulting in a low threshold setting. This makes the detector prone to noise and other uncertainties.

An ideal fault detector index has zero value during pre-fault condition and attains high value after inception of fault. The detector has to respond to all types of faults and should remain unaffected by any change in system condition. An improved CUMSUM-based algorithm has been proposed in this paper to eliminate the limitations of the conventional CUSUM method. In the proposed method, only one signal is considered to detect a fault, instead of two complementary signals used earlier in the CUSUM-based method [15]. The absolute sum of the current signal is used to detect the fault in both the positive and the negative halves, resulting in a high non-oscillating index value. One cycle DFT in the proposed technique will only allow the fundamental component to pass and therefore make the technique immune to sensor noises present in the current signal. The current signal is processed through a DFT-based filter to eliminate noise and other uncertainties present in the current signal. A sinusoidal current signal can be expressed as:

$$i_k = I_m \cos(\psi\kappa + \phi) \tag{19}$$

where I_m is the amplitude of the current signal, k is the sample number, φ is the phase angle in radians, and $\psi = 2\pi/N'$.

DFT of the sinusoidal current signal corresponding to fundamental frequency is

$$I_1 = \frac{2}{N}\sum_{k=0}^{N-1} i_k e^{-j\frac{2\Pi}{N}k} \tag{20}$$

where I_1 is the phasor estimated in terms of peak, and can also be represented as:

$$I_1 = I_m e^{j\phi} \tag{21}$$

The fundamental signal can be obtained by using phasor values at each instant, as:

$$\hat{i}_k = [I_m e^{j\phi}] e^{j\omega_0 kTs} \tag{22}$$

The one-sided ICUSUM can be expressed as:

$$u_k = \max\left[\left\{|\hat{i}_{k-1}| + |\hat{i}_k| - \nu\right\}, 0\right] \tag{23}$$

where u_k represents the detector index and ν is drift parameter which provides a low-pass filtering effect.

A fault is indicated when

$$u_k > h, Y_8 = 1 \text{ else } Y_8 = 0 \tag{24}$$

where h is the threshold value and Y_8 is the detector output.

The fault detection algorithms discussed in the above sections are mainly employed in digital relaying schemes. It is expected that the relay microprocessor will compute the index value in a few milliseconds. If only one current signal is processed instead of two complementary signals, then the computation time will be less and the extra saved memory can be used for other parallel computations.

III. TEST RESULTS

The proposed detector is tested using synthesized and simulated signals. A comparative assessment has been made with the various other fault detectors discussed earlier. An acceptable condition for a fault detector is that it continuously maintains an index value higher than the threshold value after inception of the fault. An ideal fault detector should have non-zero oscillatory response and a high index value for accurate detection of the fault. The detector output (Y) after inception of a fault varies between 0 and 1 for an oscillating index value, resulting in an unstable state. The detector output should be zero, with no fault, and upon occurrence of a fault, it should be 1. A detector should not respond to uncertainties present in the current signal, as it may behave erroneously under no fault conditions, making the fault detector unreliable.

It is also necessary to select a proper threshold value for a fault detector. A lower threshold value may generate a false alarm, since the signal may contain noise, harmonics, and other uncertainties. A high threshold value increases detection time and may even fail to detect high impedance fault. The optimum threshold value is decided based on many factors such as the magnitude of fault current, low frequency noise, DC offset, inter harmonics, frequency deviation, sampling rate, and load variation.

The comparative results are shown in the following sections. The effect of noise, harmonics, spike, high resistance, and compensation have been considered in the test result.

A. Fault at a Nominal Frequency of 50 Hz

A synthesized 50 Hz sinusoidal signal with fault at 0.5 seconds is considered. The detection algorithms discussed earlier are applied to test the effectiveness of each. The processed current signal and respective fault detector index values are shown in Fig. 1 and 2. It is revealed from the results that the earlier methods of fault detection suffer from either low oscillating index value or non-zero value before fault. The proposed method has been found to contain a non-oscillatory high index value and maintain zero value before fault.

B. Signal with Harmonics

A steady-state current signal containing 75% third harmonics, 50% fifth harmonics, and 25% seventh harmonics is considered. The current signal is processed using different detection algorithms and the results are plotted in Fig. 3 and 4. It can be observed that the proposed method is not affected by the presence of harmonics, unlike the other methods.

C. Signal with Noise

A current signal contaminated with random white Gaussian noise (SNR 30 dB) is considered for testing different detection algorithms. The performance of each fault-detector algorithm is shown in Fig. 5 and 6. It is concluded that indices derived by other methods except the one proposed are significantly affected by noise.

D. Signal Containing Spike

A current signal may contain a spike due to several factors. The effect of a spike in a current signal on a fault detector is studied. A current signal having a spike at 0.56 seconds is processed through different fault detector algorithms. The results are plotted in Fig. 7 and 8. It is found that the CUSUM and ICUSUM methods remain unaffected in the presence of spike, as compared to other methods.

E. High Resistance Fault

A 400 kV, 50 Hz transmission system has been considered, as shown in Fig. 9. Simulink model details are provided in Appendix-1. The performance of different fault detectors has been studied in case of faults with high resistance. A single line-to-ground fault with 60 Ω fault resistance has been simulated, and the results are shown in Fig. 10 and 11. The results reveals that the index of the proposed method is higher than all other methods, with a slower rate of rise.

F. Fault in a Series-Compensated Line

A metal oxide varistor with air gap arrangement introduces nonlinearity in a series-compensated line, resulting in distortion of the current signal when a fault occurs. The effect of a series-compensated line on fault detectors is analyzed. A transmission line having 30% series compensation at the midpoint is considered, as shown in Fig. 12. The series-compensated line with an "ag" type fault near the midpoint is used to test fault detector algorithms and the responses are shown in Fig. 13 and 14. It is observed that the proposed method yields non-oscillating output.

IV. DISCUSSION

The setting of the drift parameter value becomes simple since it should be the peak value of the current signal. The proposed method has an edge over other fault detection techniques as the method yields a high index value due to cumulative sum of post-fault

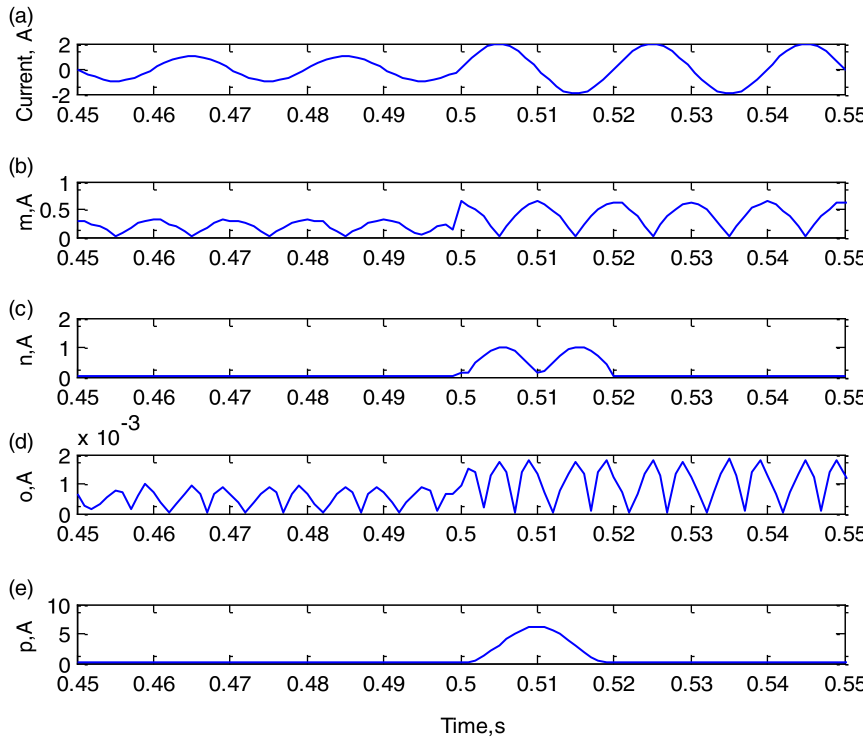

Fig. 1. (a) Current signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

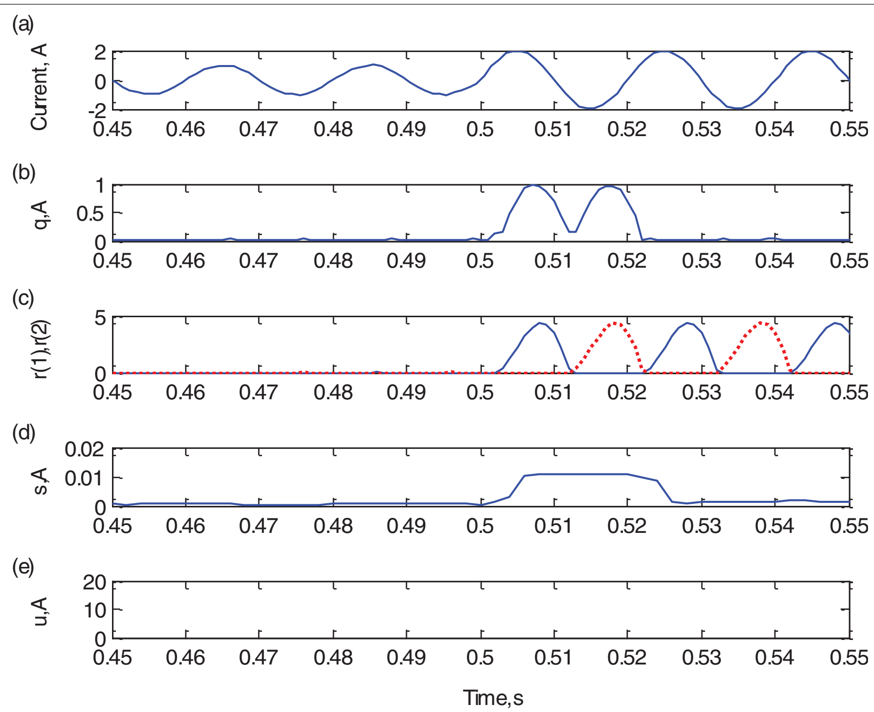

Fig. 2. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), _ _ _ r (2)). (d) DWT. (e) Proposed.

absolute current samples. A tabular form has been presented in Tables I and II, to study the relative performance of different methods. The fault detector responses to modulated signal containing harmonics, noise, and spike have been studied with no fault, and the results are shown in Table I. An ideal fault detector should be insensitive in the presence of uncertainties. It is observed from Table I that the proposed algorithm is unaffected in the presence of uncertainties as compared with other detector algorithms. The methods have

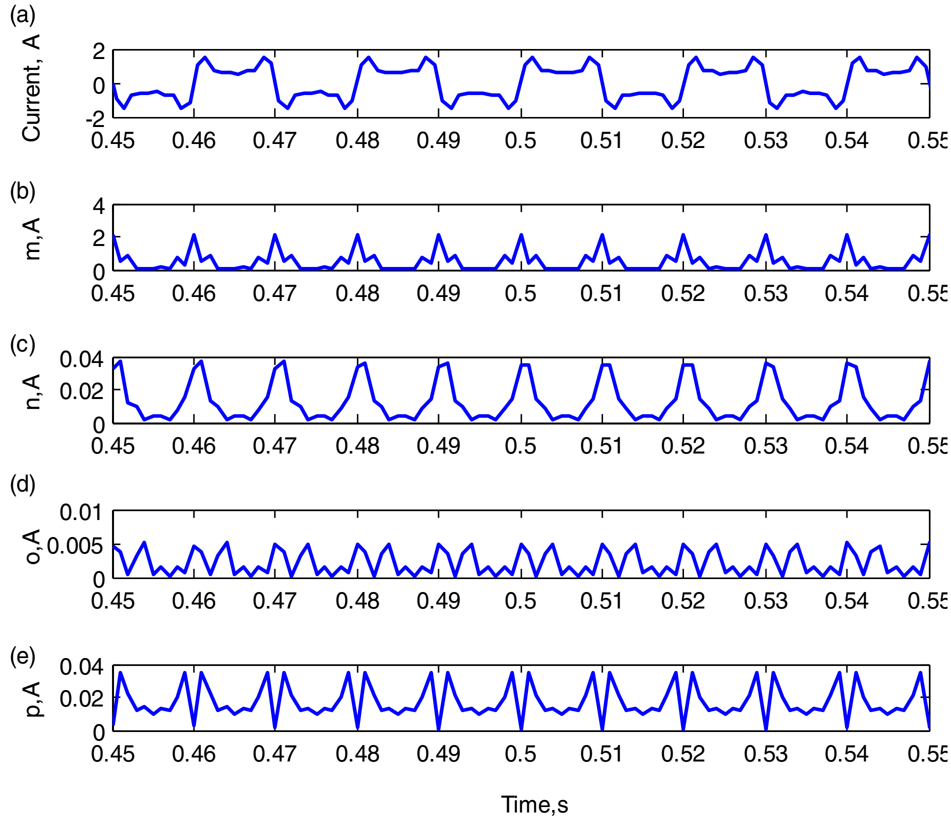

Fig. 3. (a) Current Signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

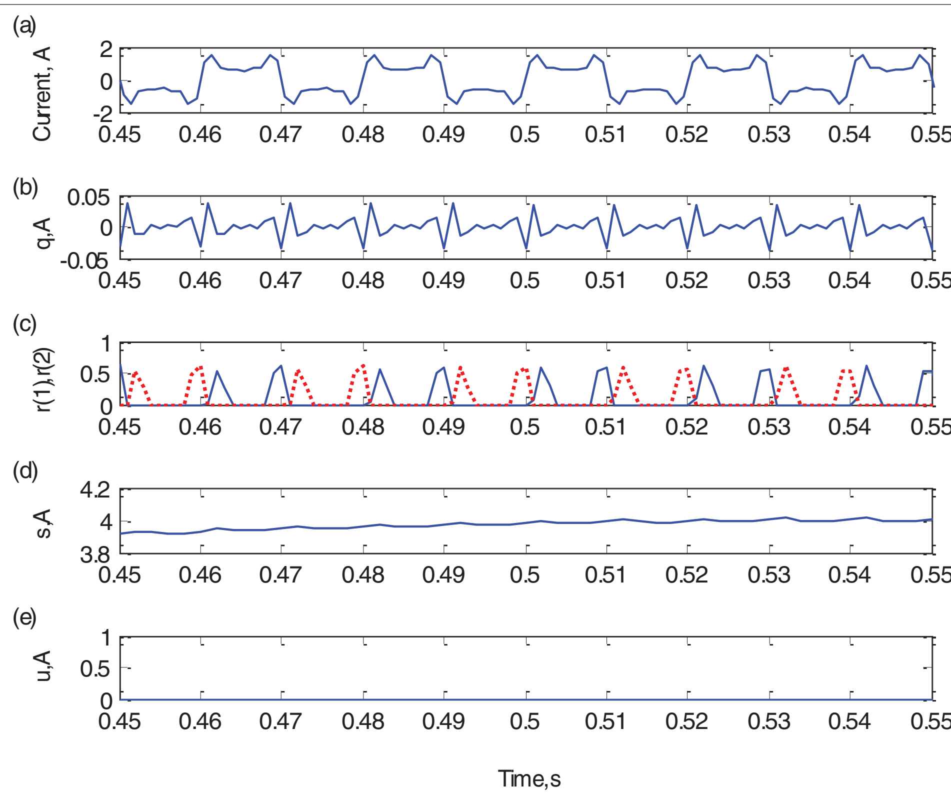

Fig. 4. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), _ _ _ r (2)). (d) DWT. (e) Proposed.

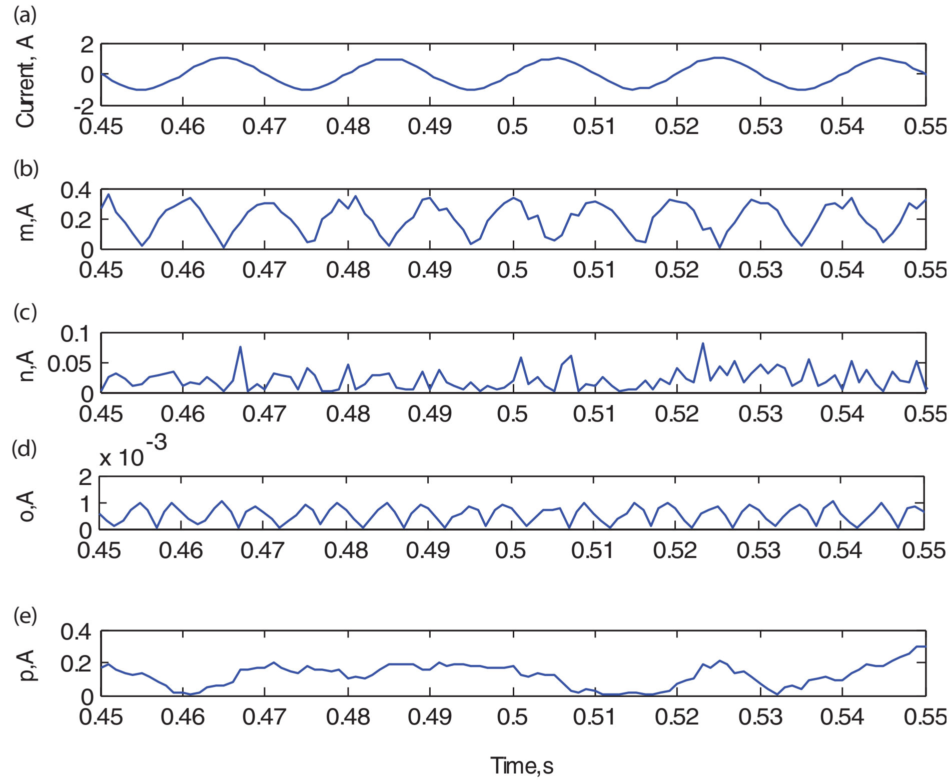

Fig. 5. (a) Current Signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

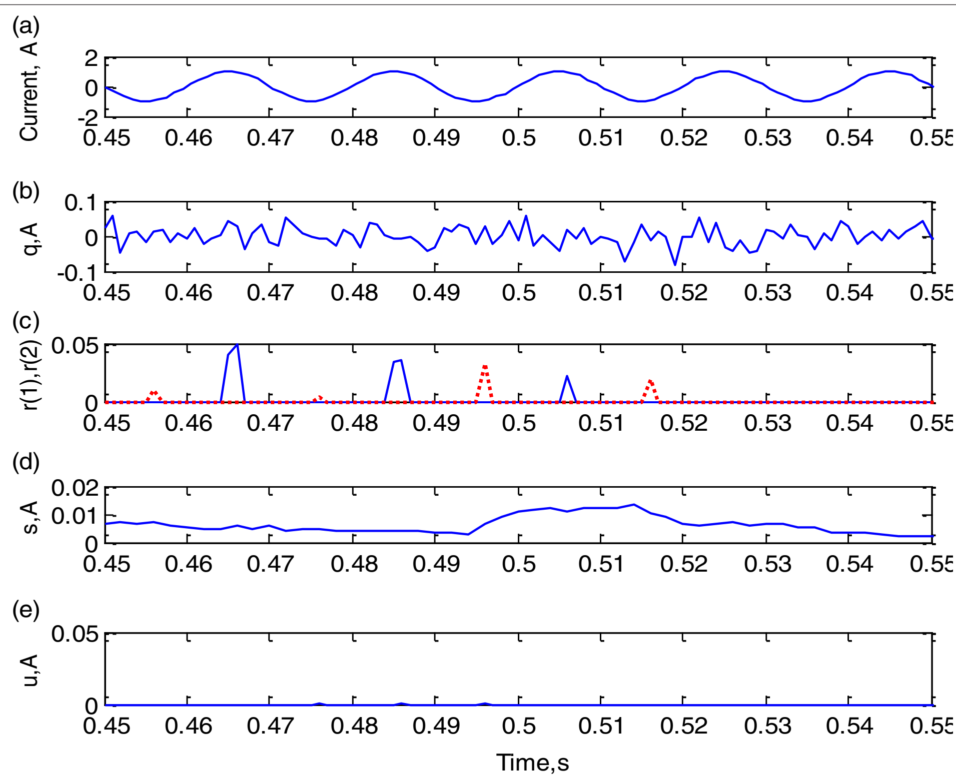

Fig. 6. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), ____ r (2)). (d) DWT. (e) Proposed.

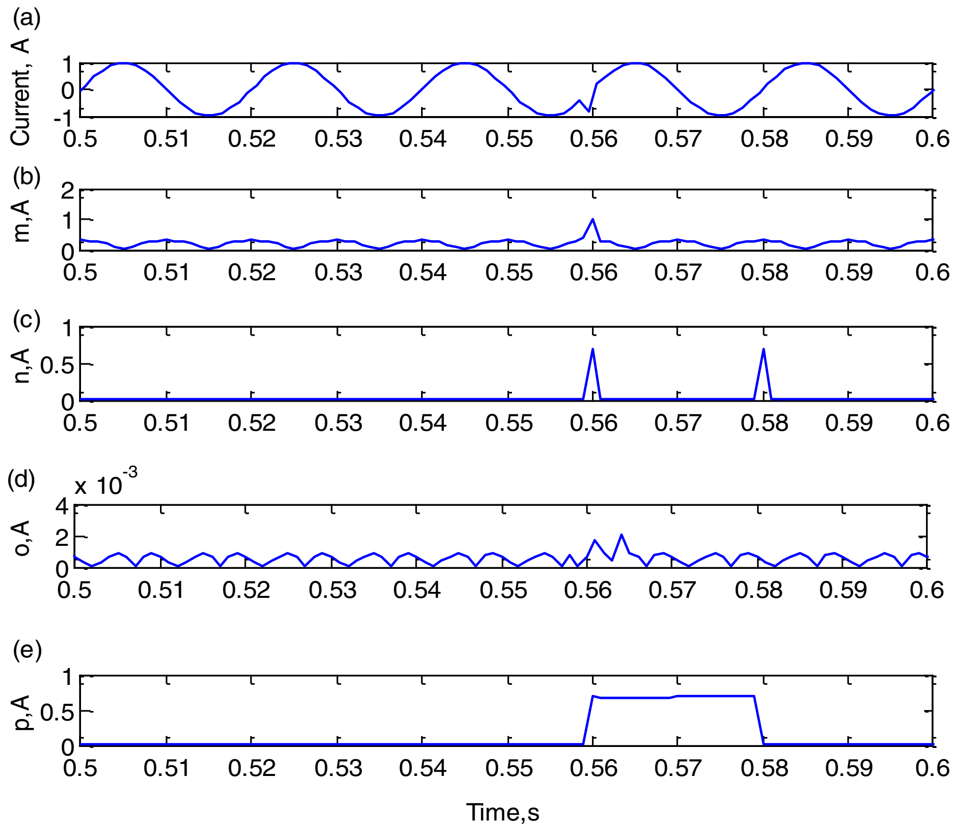

Fig. 7. (a) Current Signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

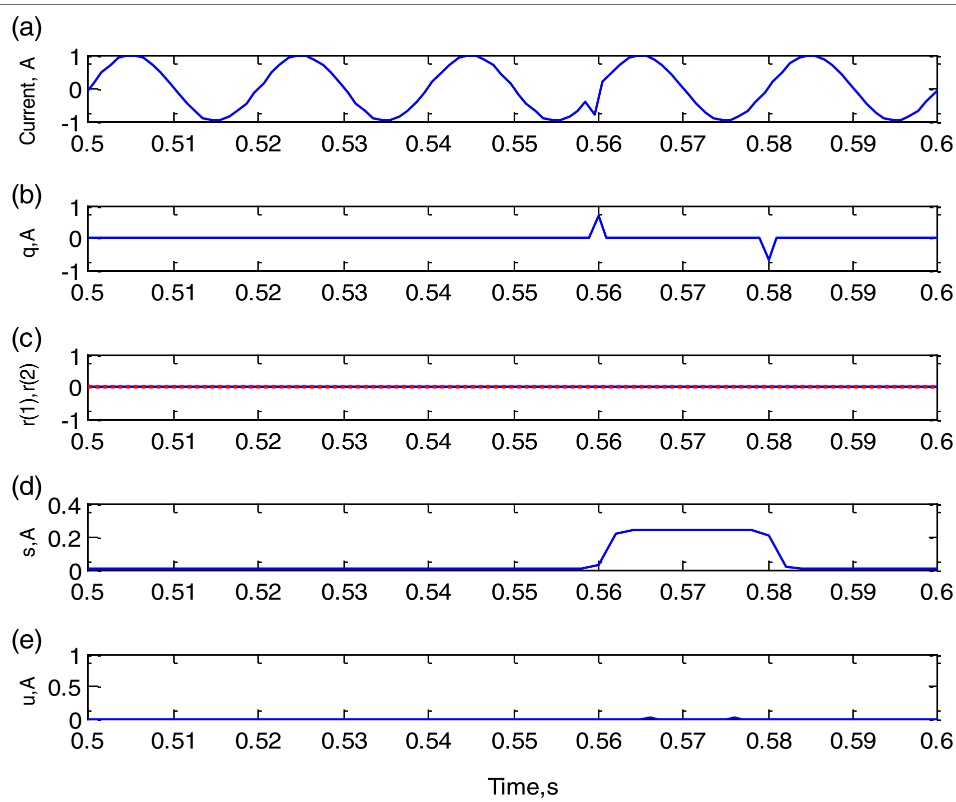

Fig. 8. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), ...r (2)). (d) DWT. (e) Proposed.

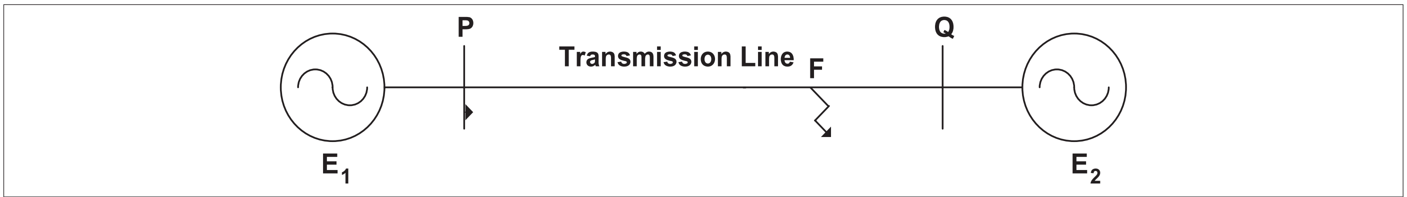

Fig. 9. A 400 kV power system.

been ranked in the first column of Table I, according to their overall performances.

The novelty of the proposed work is an efficient fault detector having non-oscillating and high index value during and after the occurrence of any fault in the transmission line. It is a fault-detection technique based on the cumulative sum of current samples that is simple yet effective. In comparison to the various fault detectors mentioned in this article, the proposed approach is least influenced by uncertainties. The gap in this area of work is that most of the available fault-detecting techniques are affected by noises and other uncertainties. The proposed fault detector is the least affected among them. The weakness of this proposed method is the selection of optimal threshold. This is the main challenge to implement any fault detection method, including the proposed method.

The behaviors of fault detectors with fault in different cases are shown in Table II. The pre-fault and post-fault output of the fault detector should be zero and non-zero respectively. Some detector indices show non-zero value before fault whereas some indices either falls back to zero after one cycle or oscillate after the fault, with a low index value. It is expected from an efficient fault detector that its indices in pre-fault condition should be zero, so that it will not trigger any false alarm. However, as any fault occurs, the indices must be non-zero and should the threshold cross the threshold in a minimum time possible, which will result in initiation of the fault clearing process. Zero or oscillating index value during fault and after the fault is not desirable as it is not indicative of the occurrence of a fault. A non-zero value in pre-fault conditions is also not desirable as the indices should reflect a fault occurrence.

The fault detector having pre-fault non-zero indices requires a high threshold value, resulting in increase in detection time. A fault detector having zero indices within one fault cycle is unwanted, as the detector output changes from one to zero in few milliseconds. A fault detector having an index value with high rate of increase is desirable. The fault detector should have consistency in relation to non-oscillating index with a constant output.

Many restrictions, such as noise, harmonics, frequency variation, sampling rate, and many other factors, might influence the threshold

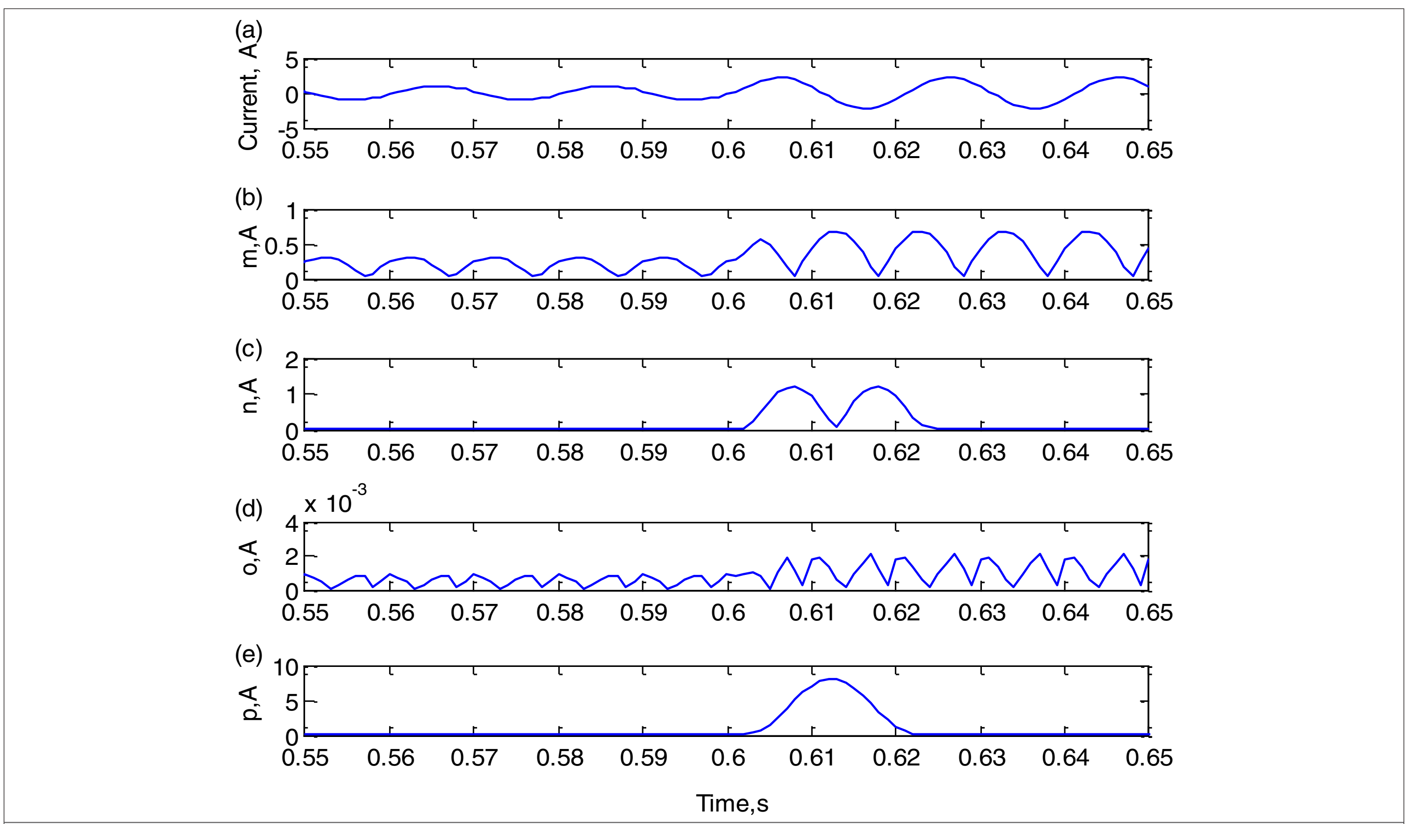

Fig. 10. (a) Current Signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

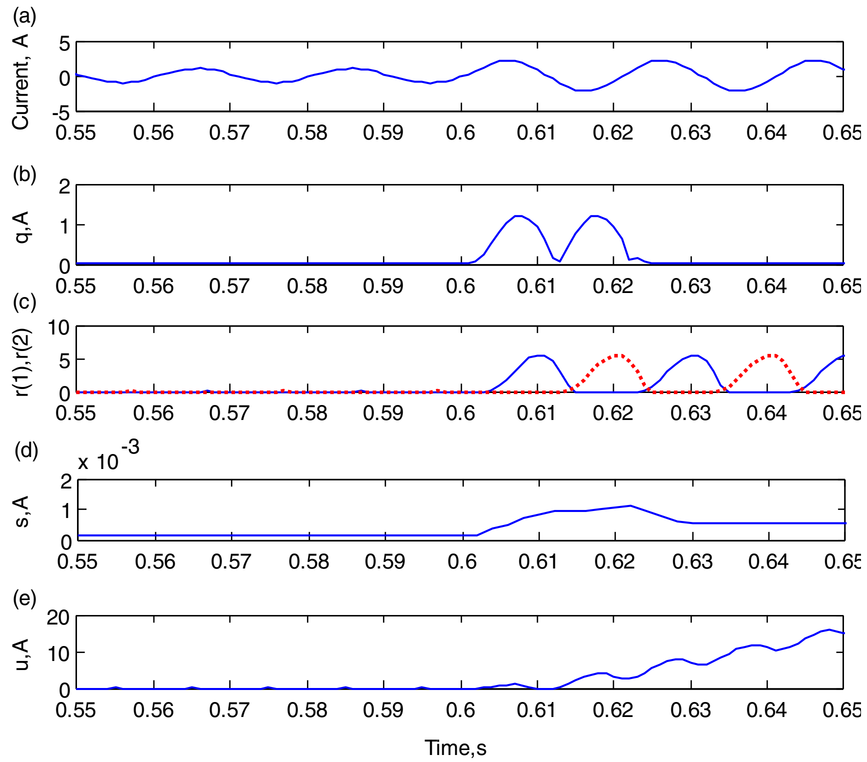

Fig. 11. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), ____ r (2)). (d) DWT. (e) Proposed.

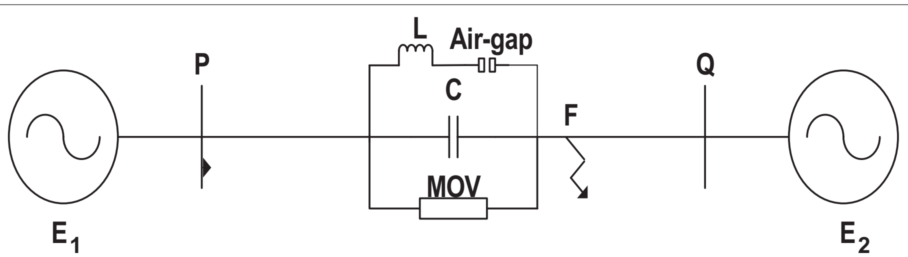

Fig. 12. A series-compensated transmission line.

value. Even if all of the detectors have the same optimal threshold value, the proposed technique will still outperform the others. An appropriate threshold, on the other hand, will increase the individual performance of all detectors, including the one proposed. For all strategies, choosing the best threshold is crucial. Harmonics, noises, and the existence of a spike in the current signal are found to have the least impact on the proposed techniques. These uncertainties will have an impact on the threshold value for other techniques, including the suggested method. As a result, we believe that no alternative strategy mentioned in this study will produce a better outcome than the proposed technique.

A fault detector's performance with various uncertainties such as noise, harmonics, and spikes is independent of any threshold setting. In the absence of a fault, an ideal fault detector should maintain a zero index value. When there is a defect component in the current signal, the effect of the threshold value on the performance of different methods becomes more noticeable. At the individual level, selecting a threshold value in all detectors will undoubtedly increase the performance of all approaches. However, in a comparative analysis, if all techniques are given the same optimal threshold, the suggested technique's high non-zero indices during fault make it more efficient than other methods.

V. CONCLUSION

In this paper, a highly efficient fault detection technique is presented for power system relaying applications. An improved cumulative sum-based algorithm has been proposed using only one filtered signal to detect a fault, unlike two complementary signals used in earlier cumulative sum based methods. The relative performances of detector algorithms have been tested in the presence of noise, harmonics, spike, and high fault resistance. The proposed algorithm provides a better result when compared with other the fault detectors discussed. It is found that the proposed method has a non-oscillating high index value and is unaffected by uncertainties present in the current signal.

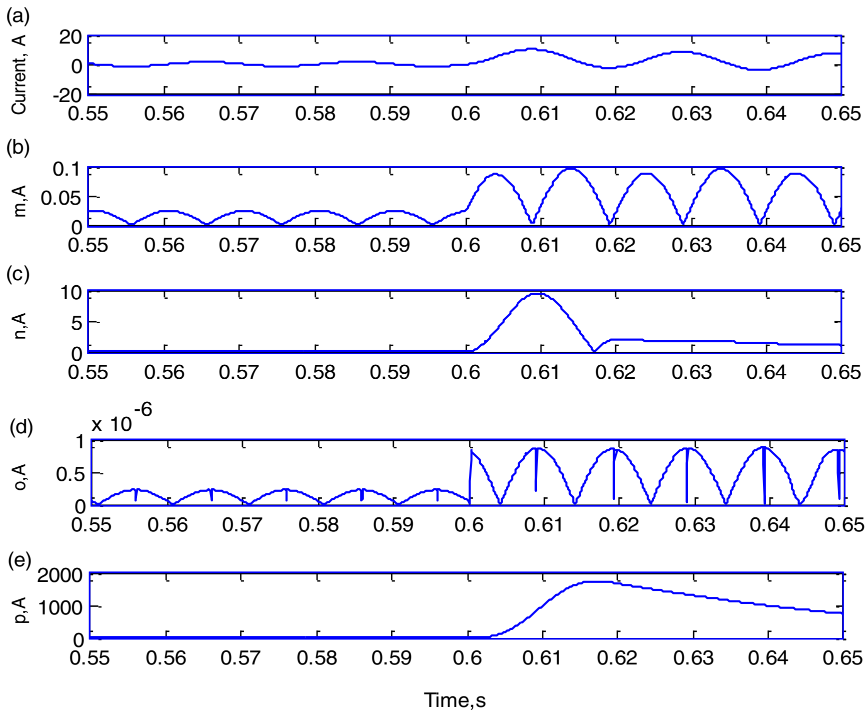

Fig. 13. (a) Current Signal. (b) Sample-to-sample. (c) Cycle-to-cycle. (d) Phasor Method. (e) Moving sum.

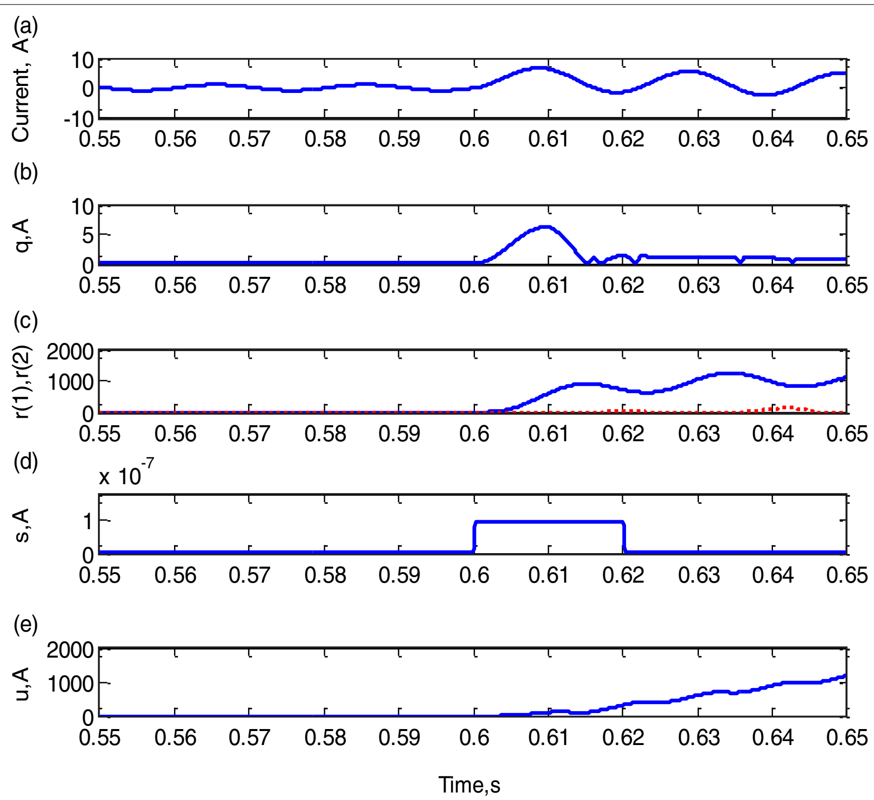

Fig. 14. (a) Current Signal. (b) Superimposed. (c) CUSUM (____ r (1), ____ r (2)). (d) DWT. (e) Proposed.

TABLE I. PERFORMANCE OF FAULT DETECTOR WITH DIFFERENT MODULATED SIGNALS

Performance Ranking	Fault Detector	Harmonics	Noise	Spike
1	ICUSUM	Not affected	Not affected	Not affected
2	CUSUM	Affected	Affected	Not affected
3	Sample-to-sample Cycle-to-Cycle Phasor Method	Affected	Affected	Slightly affected
4	Moving SumWavelet Transform	Affected	Affected	Affected

TABLE II. FAULT DETECTOR INDICES BEHAVIOR WITH FAULT IN DIFFERENT CASES

Fault Detector	Normal Fault (Indices behavior)	High Resistance Fault (Indices behavior)	Series-Compensated Line (Indices behavior)
Sample-to-sample	Before: non-zero After: non-zero Max: low Consistency: oscillating	Before: non-zero After: non-zero Max: low Consistency: oscillating	Before: non-zero After: non-zero Max: low Consistency: oscillating
Cycle-to-cycle	Before: non-zero After: zero Max: low Consistency: oscillating	Before: non-zero After: zero Max: low Consistency: oscillating	Before: non-zero After: zero Max: high Consistency: good
Phasor Method	Before: non-zero After: non-zero Max: very low Consistency: oscillating	Before: non-zero After: non-zero Max: very low Consistency: oscillating	Before: non-zero After: non-zero Max: very low Consistency: oscillating
Moving Sum	Before: zero After: zero Max: high Consistency: oscillating	Before: zero After: zero Max: high Consistency: oscillating	Before: zero After: non-zero Max: very high Consistency: good
Superimposed	Before: zero After: zero Max: low Consistency: oscillating	Before: zero After: zero Max: low Consistency: oscillating	Before: zero After: non-zero Max: low Consistency: oscillating
CUSUM	Before: zero After: non-zero Max: low Consistency: oscillating	Before: zero After: non-zero Max: low Consistency: oscillating	Before: zero After: non-zero Max: very high Consistency: good
Wavelet Transform	Before: zero After: zero Max: low Consistency: oscillating	Before: zero After: zero Max: low Consistency: good	Before: zero After: zero Max: low Consistency: oscillating
ICUSUM	Before: zero After: non-zero Max: very high Consistency: good	Before: zero After: non-zero Max: high Consistency: good	Before: zero After: non-zero Max: very high Consistency: good

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APPENDIX I

The system information is given for a power system operating at 50 Hz. For all instances, the negative sequence impedance is equal to the positive sequence impedance.

I. Source voltages:
- Source 1: $E_1 = 400$ KV
- Source 2: $E_2 = 400\angle\delta$ KV, where δ is the power angle.

II. Source impedance : (Source 1)
- Positive sequence impedance = $1.74 + j19.92\ \Omega$
- Zero sequence impedance = $2.6100 + j29.8858\ \Omega$

III. Source impedance : (Source 2)
- Positive sequence impedance = $0.87 + j9.96\ \Omega$
- Zero sequence impedance = $1.3050 + j14.9400\ \Omega$

IV. Transmission line parameters (per km)
- Positive sequence impedance = $0.0256 + j0.3670\ \Omega$
- Zero sequence impedance = $0.1362 + j1.1096\ \Omega$

V. Sampling time: 1 ms.

VI. Line length: 128 km.