Assessment of Integral Based Fault Detection Methods for Power System Relaying

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Abstract

In this paper, cumulative sum and moving sum based fault detection algorithms are presented for a power system relaying application. Simplicity and accuracy are the two attractive features for both of the methods. The methods are tested in a simple test system. When compared with conventional methods, it is found that integral based fault detection methods are more effective than the conventional ones. CUSUM method is not affected in the presence of noise, system frequency deviation and the other uncertainties. The moving sum method has a small detector output for the same conditions. But since the index value is high for this method, it can be accepted as negligible.

1. Introduction

Fast and accurate fault detection is essential in power system relaying. Voltage and current waveforms as well as travelling waves are used for decision purpose of fault detection. Waveforms deviate from the normal sinusoid during the fault. Deviations are required to be checked continuously so as to recognize a fault case properly. There are several methods used for that purpose and two of the simplest ones are: 1) sample-to-sample comparison methods (SSCM) and 2) cycle-to-cycle comparison methods (CCCM) [1]-[3]. However, these methods are affected when system frequency deviates from the nominal value and by the presence of noise in the signal [4], [5]. A statistical approach for fault detection has been presented in [6] where adaptive forms of filters are employed. Other more sophisticated techniques are also available using the phasor estimation algorithms [7]–[10]. It is to be noted that conventional phasor estimation techniques based on discrete Fourier transform, recursive least square or Kalman filtering are not suitable for fault detection in relaying as the processing takes more than half a cycle of the fundamental period. Further, these methods are also sensitive to frequency deviation, harmonics, etc.

Optimal threshold selection is an important factor for fault detection. Because, a lower threshold value may cause numerous false fault alarms when there is noise in the signal and some kind of other uncertainties in the system. Besides that, in the presence of a higher threshold value, the detection may be late and it takes long time for the detection when a faulty condition appears. So in order to avoid that kind of a conflict, an optimal threshold selection must be considered.

In power systems, threshold selection depends on various factors such as magnitude of fault current, the sampling rate, the presence of noise, DC offset, inter harmonics and deviation in power frequency. All of these factors affect the performance of the detection methods, so they must be selected properly to get better results

In this paper, a cumulative sum (CUSUM) and moving sum (MSM) based fault detection algorithms are presented for the power system relaying applications. The methods are tested in a simple power system and compared to the conventional methods, effectiveness of the algorithms is found to be better than conventional ones.

2. Conventional fault detection methods

Two simple methods are considered as sample to sample and cycle to cycle. These methods use either voltage or current signals. They are outlined below.

2.1. Sample to sample comparison method

One of the simplest methods for fault detection of a power system is to compute the difference of present sample with previous sample and check whether the value is greater than a threshold value to register a fault. This is based on the principle that the sample difference is expected to be fixed during normal condition while it will be significantly high at the fault condition. Thus;

$$d_k = \left| s_k - s_{k-1} \right| \qquad (1)$$

$$\text{if} \quad d_k > h \quad O_1 = 1 \quad \text{else} \quad O_1 = 0 \qquad (2)$$

Where s_k represents the sample value of the signal at the k_{th} instant, d_k is the index value of SSCM, h is a threshold, O_1 is the detector output. Figure 1 illustrates the sample to sample method.

2.2. Cycle to cycle comparison method

The method is based on the comparison of present value with the corresponding value of the sample in the previous cycle. The difference is expected to be zero during normal condition. With a fault in the system, it would be a significant difference between the two samples. This is clearly depicted in figure 1.

If this difference remains greater than a threshold value for three consecutive samples, the detector registers a fault. Mathematically;

$$c_k = \left| s_k - s_{k-N+1} \right| \qquad (3)$$

$$\text{if} \quad c_k > h \quad O_2 = 1 \quad \text{else} \quad O_2 = 0 \qquad (4)$$

Where N is the window size of one period, c_k is the index value of CCCM, h is a threshold, O_2 is the detector output.
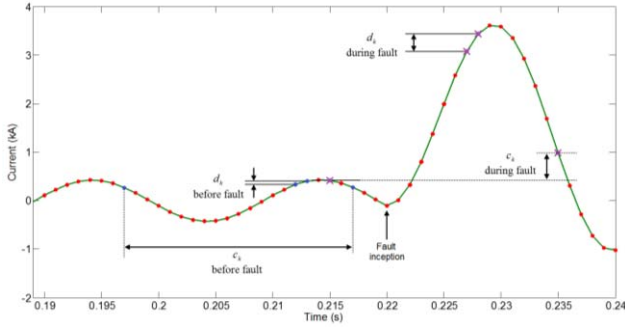
Fig.1. Sample to sample and cycle to cycle comparison

3. Integral approaches for fault detection

The conventional fault detection algorithms use differential principle and are affected by the deviation of system frequency from nominal or in the presence of noise or spike in the signal. To overcome this, an integral approach, which is a cumulative sum-based (CUSUM) or moving sum-based method, is applied.

The two integral approaches presented in this section are immune to conditions like noise and spike in the signal and the deviation of system frequency from nominal. The selection of h is also important for accurate detection which is decided by influencing factors, such as noise and other uncertainties [3],[4].

3.1. Moving sum method

During normal power system operation, owing to the symmetrical and sinusoidal nature of the current or voltage signals, the sum of sampled values taken over one cycle is very close to zero. In case of faults, however, when the signal changes abruptly and the observed window contains fundamental components of two different values besides decaying DC, the one cycle sum substantially deviates from zero. This principle is applied for fault detection where a one-cycle moving window that computes the sum of discrete values of current has been used [3]. Mathematically,

$$i_{sum}(k) = \sum_{l=k-N+1}^{k} i(l) \qquad (5)$$

$$if \quad |i_{sum}| > h \quad O_3 = 1 \text{ else } O_3 = 0 \qquad (6)$$

Where N is the window size of one period, h is a threshold for current, O_3 is the detector output.

3.2. A cumulative sum method

The CUSUM is widely used for industrial process control systems where the deviation of parameters is tracked to indicate any abnormal condition.

This technique uses the current sample (s_k) of any phase and derives complementary signal as

$$s_k(1) = s_k \qquad (7)$$

$$s_k(2) = -s_k \qquad (8)$$

Using the aforementioned two signals, two sided CUSUM test [10] is expressed as

$$g_k(1) = \max(g_{k-1}(1) + s_k(1) - v, 0) \qquad (9)$$

$$g_k(2) = \max(g_{k-1}(2) + s_k(2) - v, 0) \qquad (10)$$

Where $g_k(1)$ and $g_k(2)$ represent the fault occurrence at positive and negative half cycles, v is a drift parameter in it.

A fault is registered if

$$g_k(1) > h \quad \text{or} \quad g_k(2) > h \qquad (11)$$

Where h is an arbitrary constant and which should be ideally zero.

The value of v should to be set at the peak value of the relay setting current [11]-[13]. When any $s_k > v$, the corresponding g_k starts growing. As observed from (7) and (8), the value increases by a factor of the difference between s_k and v. With further current samples available, the cumulative sum process of the above relations provides an easy way to make a decision for fault using (9). The max-operation in the aforementioned relations provides a positive or zero value for the g_k.( ). This two-sided approach is advantageous from the speed aspect.

In the case of a power system fault, either of the two g_k's will be higher than a threshold value for three consecutive samples and a fault can be registered. After each fault detection, $g_k(1)$ and $g_k(2)$ are reset to zero.

4. Assessment of algorithms

In this section, four selected fault detection methods are studied and compared with each other from different standpoints which affect the operational performances. The outputs of the fault detectors are examined for some common and special cases. They are tested for existence of faults, with and without high fault resistance, load change, frequency drift and noise in the power signal. The outputs of detectors are plotted and evaluated in such terms of correctness, clarity and remarkability.
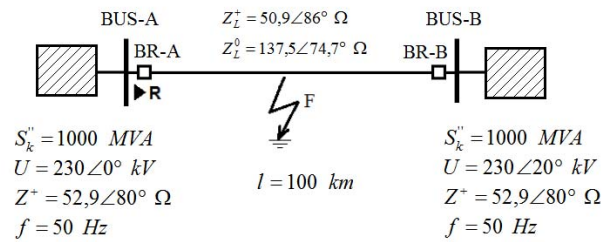
4.1. Fault case

Fig. 2. Test power system

The performances of aforementioned four algorithms are studied when there is a three phase short circuit fault in a power system for both low fault resistance and high fault resistance cases. For this purpose, a 230 kV, 50 Hz test system, shown in Figure 2, is simulated in PSCAD and the data are processed in MATLAB.

Two networks are connected via a 100 km transmission line. Phase angle difference between two sources is set as 20º. To

demonstrate the potential of the approaches, a symmetrical three phase fault condition is analyzed. The fault is created at the middle of the transmission line at t=220 ms with the duration of 115ms. Current of phase-1 at bus-A is measured, and the data are used for computation of the indices. The sampling frequency is 1 kHz (20 samples per cycle).

4.1.1. Three phase fault with low fault resistance

For a low fault resistance case (as expected in normal conditions), 0.001 Ω fault resistance is simulated. The outputs of the four fault detection methods are shown in Figure 3-6.
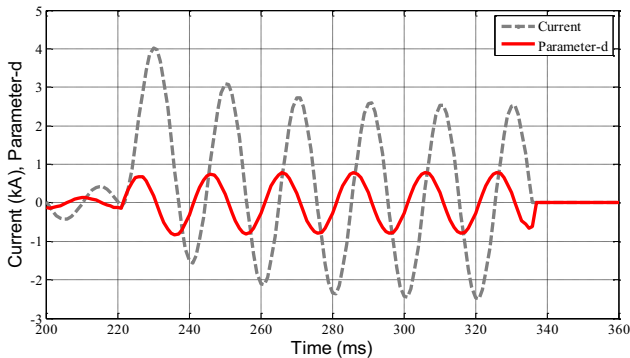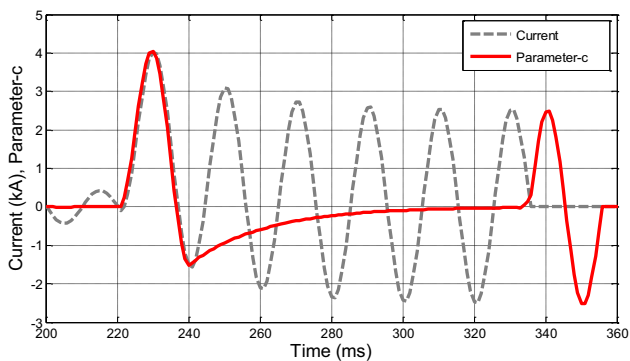

Fig. 3. Fault detection index for SSCM

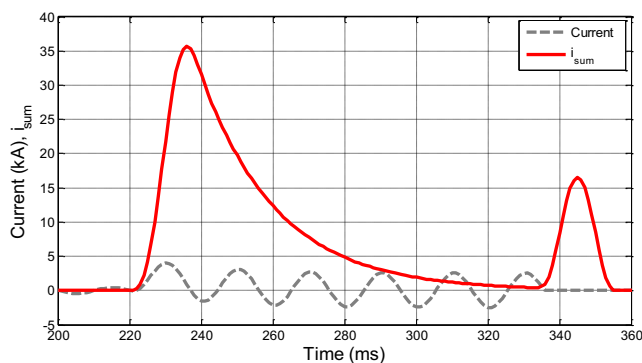
Fig. 4. Fault detection index for CCCM

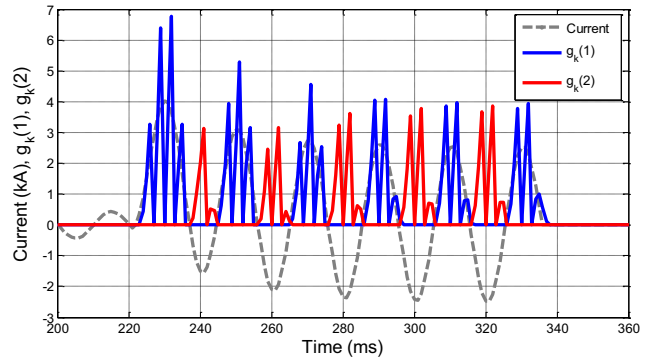

Fig. 5. Fault detection index for MSM

Fig. 6. Fault detection indices for CUSUM

The detector is expected to decide within a few milliseconds, so the first few sampling periods are important when evaluating the speed of an algorithm. The performance of four algorithms are close to each other in this manner. All of them give quick response after the fault is incepted.

When the power system is in a normal condition, output of a fault detector must be zero or any negligible value. In addition to this, any detector must give smooth and meaningful outputs during fault. In this context, it is observed that outputs of different types of detectors have different characteristics.

First of all, for a sample-to-sample comparison approach, the index d significantly deviates from the value which is computed during normal condition. Secondly, for the cycle-to-cycle approach, index c increases from zero and gives nonzero values for a period of more than half a cycle. It can be said that conventional fault detectors have low capability when the outputs (the c and d parameters) of the methods are observed for a fault case. However, when integral approaches are used, the situation for detector outputs is better. For the moving sum method, the parameter i_{sum} increases and a nonzero value is obtained. The detector output, O_3, gets a nonzero value and when it exceeds a pre-defined threshold, it gives a fault declaration correctly. Similarly, for cumulative sum method, the signal changes in the positive half, the $g_k(1)$ value increases and a significant nonzero value is obtained at once. The other parameter $g_k(2)$ starts growing when the signal reaches the negative region. It is an advantageous result. The structure of the detector is much better than the conventional methods. The integral approaches give more accurate and sensitive results than the conventional methods.

4.1.2. Three phase fault with high fault resistance

Power system faults with high fault resistance are cases worth to be studied, because some protection units may not detect the fault when the fault resistance exceeds some amount. The same test system is simulated for a 50 Ω fault resistor in order to investigate the effect of this case. The outputs of the detectors are shown in Figure 7.

As can be seen from the figure, the output is not affected significantly when sample-to-sample comparison method is used. But the output is more significant for cycle-to-cycle method. For moving sum method, the detection seems to be successful although the output value gets lower compared with the former low fault resistance case. The cumulative sum (CUSUM) method is also successful for fault detection. Similarly, the output is also lower compared with the low fault

resistance case. It is clearly seen that the sample-to-sample method has a significantly low performance for fault detection when the fault resistance is high. However, since the output values of the remaining methods are lower, they have higher performance and the results are sufficient for them in this condition.
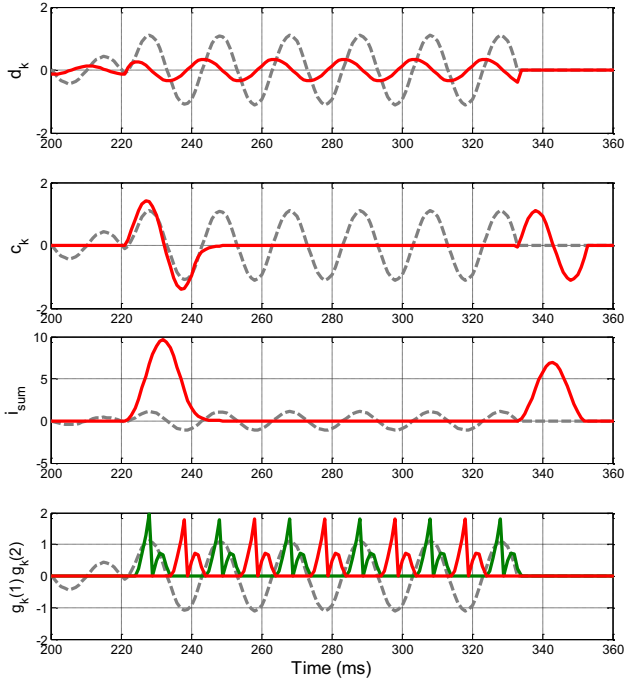

Fig. 7. Outputs of fault detectors 50Ω fault resistor

4.2. Load Change

The power system is underwent a high current situation when there is a short-circuit fault. By the way, if there is a similar but a smaller increase in current, caused by a serious loading, protection relay may also operate. For simulating that kind of a loading case, phase angle of the grid connected to bus-B is changed from 20° to 30° at t=220 ms corresponding to a load change. The performance of the methods are compared with each other. The results as the outputs of the detectors are shown in Figure 8.

It is observed that, the output of the fault detector is affected from the load change for all of the methods applied. However, the change is small and there is no tripping action for any of them. In fact, the decision here is related to the parameter set within the protection relay and the parameter determines the sensitivity of operation. In CUSUM method for instance, the upper limit of the protection relay is set to 0.4444 kA having a 10% tolerance for current increase, since the peak value of the signal is approximately 0.4 kA in normal operation. For this setting, there is no fault identification for CUSUM method (or any other method), because the load change created here is not out of the tolerance for protection algorithms.
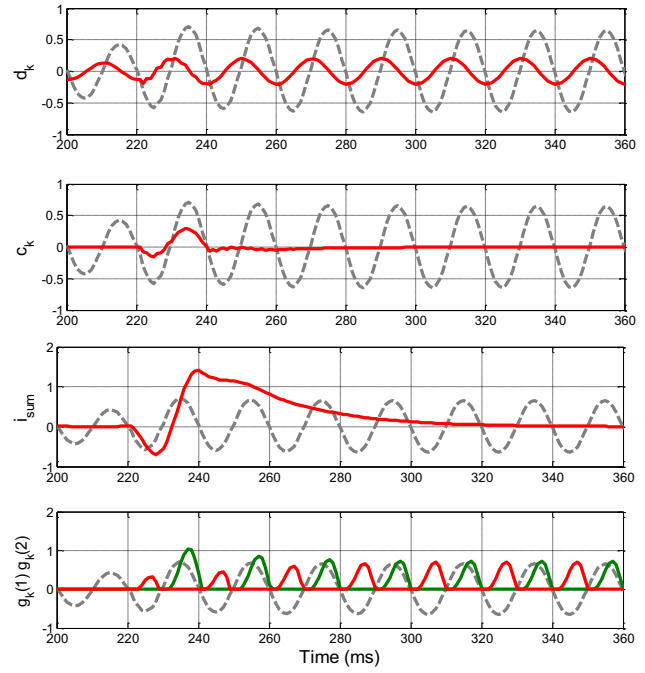

Fig. 8. Outputs of fault detectors in the case of load change

4.3. Drifted frequency

The frequency drift is also a potential problem in fault detection applications. In order to test the performance of the detection methods, a pure 50 Hz sine wave is created in MATLAB and it is changed to 49 Hz at t=0.08 s. The outputs of the detectors are shown in Figure 9.
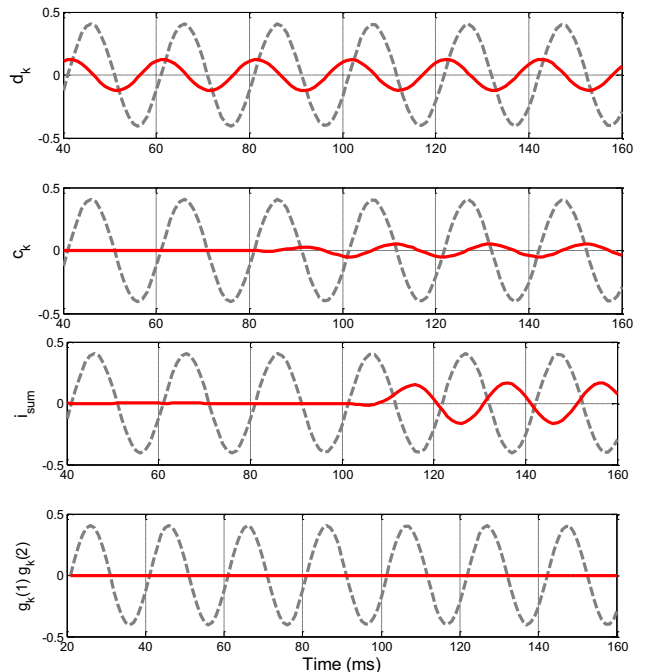

Fig. 9. Outputs of fault detectors in the case of drifted frequency

As can be seen from the figure, the CUSUM method and the sample-to-sample method have a high performance since there is no effect for both of them in a frequency drift condition. By the way, for the cycle-to-cycle comparison method the output has a small deviation, though it is a negligible change and it doesn't lead to a fault alarm. The similar effect is valid for moving sum method, it also has a small deviation and it also doesn't cause a tripping action.

4.4. Noisy signal

The performance of fault detectors are also worth to be investigated for a noisy signal condition. For testing the performances of fault detectors, a Normal (Gaussian) distributed signal is added to a pure 50 Hz sine wave created in MATLAB so as to obtain a noisy signal and then the outputs of detectors are observed. The results are all shown in Figure 10.
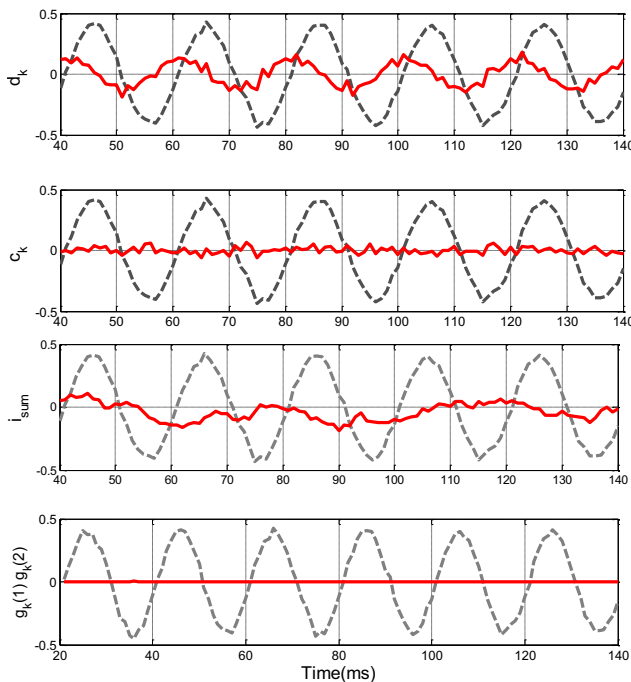

Fig. 10. Outputs of fault detectors in the noisy signal.

The best detection performance is obtained with CUSUM since there is no output effect as the others have. However, the others have only some parasitic outputs and the tripping operation is not affected from these negligible changes. The performance of the four methods can be considered as successful and sufficient for noisy conditions.

5. Conclusion

In this paper, integral based moving sum and cumulative sum algorithms are assessed as fault detection methods for a power system relaying application. The methods are compared both with each other and with the conventional methods. It can be concluded that the integral based methods are simple, computationally efficient and have rather high performance.

Performance comparison is made in terms of correctness, clarity and remarkability and tested for power system events like low/high resistance short circuit faults, load changes and signal deviations like frequency drift and noise. Performance of the integral based methods is found to be better than the conventional ones', alongside the cumulative sum (CUSUM) method is found to be the best for all of the cases investigated. The cycle-to-cycle method is found to be sufficiently successful although the output of the detector for this method is affected by different factors for various conditions. The sample-to-sample method is found to be disadvantageous a bit, since it gives low detection outputs in short circuit fault cases.

As a result, the integral based methods, especially the CUSUM method, are successful for fault detection and they can also be tried for other applications such as faulty phase identification, fault classification and power-quality problem detection in future work.

6. References

[1] A. G. Phadke and J. S. Thorp, "Computer Relaying for Power Systems", Wiley, New York 1988.

[2] A. K. Pradhan, A. Routray, S. Pati, and D. K. Pradhan, "Wavelet-fuzzy combined approach for fault classification of a series compensated transmission line", *IEEE Trans. Power Del.*, vol. 19, no. 4, pp.1612–1618, Oct. 2004.

[3] A. K. Pradhan, A. Routray, and S. Mohanty, A moving sum approach for fault detection of power systems, *Elect. Power Components Syst.*, vol. 34, pp. 385–399, 2006.

[4] S. Mohanty, A. K. Pradhan, A. Routray, "A cumulative sum-based fault detector for power system relaying application", IEEE Trans. Power Delivery , vol. 23, no.1, Jan 2008.

[5] M. S. Sachdev and M. Nagpal, "A recursive least square algorithm for power system relaying and measurement applications," *IEEE Trans. Power Del.,* vol. 6, no. 3, pp. 1008–1015, Jul. 1991.

[6] D. M. Gilbert and I. F. Morrison, "A statistical method for the detection of power system faults," *Elect. Power Energy Syst.*, vol. 19, pp.269–275, 1997

[7] J. Barros and J. M. Drake, "Real-time fault detection and classification in power systems using microprocessors," *Proc. Inst. Elect. Eng., Gen. Transm. Distrib.*, vol. 141, no. 4, pp. 315–322, 1994.

[8] F. N. Chowdhury, J. P. Christensen, and J. L. Aravena, "Power system fault detection and state estimation using Kalman filter with hypothesis testing," *IEEE Trans. Power Del.,* vol. 6, no. 3, pp. 1025–1030, Jul.1991.

[9] C.-S. Chen, C.-W. Liu, "Application of combined adaptive fourier filtering technique and fault detector to fast distance protection", *IEEE Trans. Power Del.,* vol. 21, no 2 pp 619-626, April 2006.

[10] F. Gustafsson, "Adaptive Filtering and Change Detection", Wiley, New York 2000.

[11] M. R. Noori, S. M. Shahrtash, and S. Jamali, "Security assessment for a cumulative sum-based fault detector in transmission lines," *EEEIC Conf.*, Rome, Italy, 2011

[12] M. R. Noori and S. M. Shahrtash, "Adaptive cumulative sum-based fault detector for transmission lines", *6th PSPC Conference*, Tehran, Jan. 2012.

[13] M. R. Noori and S. M. Shahrtash, "Combined Fault Detector and Faulted Phase Selector for Transmission Lines Based on Adaptive Cumulative Sum Method", *IEEE Trans. Power Del.*, vol. 28, no. 3, July 2013.