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A highly efficient relay triggering circuit for fault detection during Power swings

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Abstract: This paper introduces a discrete wavelet transform based on simple and fast acting algorithm with multi-resolution analysis to sense all types of faults in presence of power swings using current signal analyzation. The algorithm confirms very quick and efficient detection of various fault types in the first signal decomposition level of signal. The novelty of proposed algorithm lies in use of special type of Battle-Lemarie mother wavelet having an advantage of perfect symmetry ensuring decomposition into B-Spline or same order polynomials capturing excellent speed and time-frequency localization of signal. The algorithm is evaluated for different fault parameters such as fault resistance, fault distance and time of initiation of faults considering EHV double circuit transmission line network and IEEE 9 bus system developed in MATLAB environment. The proposed algorithm can detect all types of faults consistently within a minimum time of 0.001 sec.

Keywords: Digital relay, discrete wavelet transform, multi resolution analysis, power swing, Battle-Lemarie wavelet

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1. Introduction

Power swings are the outcome of large amount of changes in system load or presence of any type of fault in neighboring circuit of a power system network. If the load change outside the line is insignificant, then there is a stable power swing and the system itself regains stability because of speed governing control mechanism and automatic voltage regulatory system.

In case of stable swings also, temporary rise in load angle 'δ' between the two generating stations connecting the transmission line increases the tie line current and subsequently drop in line voltage. This will reduce impedance seen by the distance relay and if it enters any of the trip zones, then the relay will consider it as a fault and mis-operates.

Chatterjee and Roy (2019) use voltage and current based synchro phasor measurement and formulating fault index based on change in voltage, current and power from one end of line. If the index is higher than the set value, then the fault is identified. The algorithm is capable of sensing faults in presence of power swing for series compensated line as well as in presence of renewable integration. The effect of asymmetrical power swings on distance relaying is studied by Hashemi and Sanaye-Pasand (2018) by employing two different methods, first one including rate change of zero sequence current and other one having phase voltage, phase current with phase angle between them. Pang and Kezunovic (2010) used high frequency components present in forward and backward travelling waves of voltage and current signal induced due to fault. Lotfifard et al. (2009) worked with Prony method based on current signal to sense symmetrical faults in presence of power swings. Wavelet transform based current and/or voltage signal decomposition for fault detection in presence of power swings is reported by Brahma (2007), Alsyoufi and Hajjar (2019), Hajjar (2013) with other applications of wavelet transform presented in Zheng-You et al. (2006), Bousaleh et al. (2009), Williams and Amaratunga (1994) and Zhu et al. (1997). Other studies reported a differential power-based approach using auto regression technique by Venkatesh and Swarup (2012) and frequency components of three phase active power by Rao and Pradhan (2012) and Mahamedi and Zhu (2012) for fault identification during power swings.

From the literature survey, it is seen that voltage and current and/or power are used to set the detection threshold value for fault and power swing and thus algorithm complexity increases. Also, there is a limited coverage of fault resistance value for testing algorithm fitness. Hence, this paper proposes a simple and fast-acting single variable current signal-based sensing of faults and power swings by implementing a special type of Battle-Lemarie mother wavelet.

2. Materials and methods

Detection of abrupt system transients is one of the important applications of wavelet transform, other including removal of noise and compression of large amount of data. Wavelet-based signal processing technique is an effective tool for power system transient analysis and power system relaying by Pang and Kezunovic, (2010). The applications of wavelet transform in power system have been reported for fault detection, fault classification, power system disturbance modelling and identification by Zheng-You et al. (2006) and power quality analysis by Bousaleh et al. (2009).

The frequency of transient voltage and current signals is much higher than the nominal frequency during fault condition as compared to power swing condition. Hence, the wavelet details coefficients covering the frequency of the fault transients will have significant energy only when a fault occurs in the system. This fact is utilized in this paper to implement discrete wavelet transform of current signal and calculate spectral energy of current signal to detect faults during power swings. The novelty of proposed work lies in the fact that there is no need of getting various wavelet decomposition levels, but the required results are obtained only in the first decomposition level of current signal with minimum detection time. Two different energy threshold values are utilized for power swing and fault, respectively. The multi resolution analysis allows for signal decomposition with separation of signal into different components having different resolution.

2.1. Discrete wavelet transform

Mathematical transformation like discrete wavelet transforms is applied to power system transients to get required information which cannot be obtained from the time domain nonstationary raw signals. The signal decomposition in DWT is conducted by passing a signal through series of high pass filter and low pass filters for analysis of high pass and low pass frequencies of signal, respectively.

The fault current signals have extremely high frequency components for short durations and low frequency components for long duration which is well taken care by an approach known as multi resolution analysis implemented along with the DWT in this study. The method represents a function at various required levels of resolution (Alsyoufi & Hajjar, 2019). If the signal is sampled by a sampling frequency of (fs), the signal information captured by cD1 will be within the band [fs/4–fs/2], cD2 will capture the information within the band [fs/8–fs/ 4], and cA2 will retain the rest of the information of the original signal within the band [0–fs/8].

The discrete wavelet transforms of function $f(x)$ is given by Eq. 1.

$$f(x) = \frac{1}{M} \sum_K W_\varphi (j_0, K)\, \varphi_{j_0,K} (x) + \frac{1}{M} \sum_{j=j_0}^{\infty} \sum_K W_\Psi (j, K)\, \Psi_{j,K} (x) \quad (1)$$

First and second term indicate approximation and detail coefficients respectively and j_0 is the arbitrary starting scale.

The discrete wavelet transforms of function $f(x, y)$ of size M*N is given by Eq. 2 as below.

$$W_\varphi(j_0, m, n) = \frac{1}{\sqrt{MN}} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y)\, \varphi_{j_0,m,n} (x,y) \quad (2)$$

$$W_\Psi(j, m, n) = \frac{1}{\sqrt{MN}} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x,y)\, \Psi^{i}_{j,m,n} (x,y) \quad (3)$$

$$\varphi_{j,m,n}(x, y) = 2^{\frac{j}{2}}\, \varphi\, (2^j x - m, 2^j y - n) \quad (4)$$

2.2. Battle-Lemarie mother wavelet

In the present study, piecewise linear spline wavelet from Battle-Lemarie family which forms a class of orthonormal wavelets is used as a mother wavelet for current signal decomposition. This mother wavelet has the advantage of simplicity and short support as compared to Daubechies mother wavelet (Alsyoufi & Hajjar, 2019). The high pass and low pass filters for the chosen piece wise linear spline mother wavelet are summarized in Eqs. 5 and 6 as per (Alsyoufi & Hajjar, 2019).

$$g[n] = \frac{1}{4}\, \delta\, [n+1] + \frac{1}{2}\, \delta\, [n] + \frac{1}{4}\, \delta\, [n-1] \quad (5)$$

$$h[n] = -\frac{1}{4}\, \delta\, [n+1] + \frac{1}{2}\, \delta\, [n] - \frac{1}{4}\, \delta\, [n-1] \quad (6)$$

2.3. Detection methodology

The spectral energy of any signal means the distribution of signal energy in terms of required frequency range. The developed algorithm calculates spectral energy of the first details coefficient d_1 of the current signal to sense fault and power swing, respectively. The wavelet spectral energy calculation is performed using Eq. 7 as stated below with reference to method put forward by Brahma (2007), Alsyoufi and Hajjar (2019), and Hajjar (2013).

$$E = \sum_{i=1}^{N} [d(i)^2] \quad (7)$$

Here, 'N' is the total number of samples for the selected window and 'd_i' is the i[th] detail coefficient. The threshold value is decided using calculated energy level. The percentage change in spectral energy appears during a transient period which decides whether there is a power swing or fault by calculating threshold value based on Eq. 8.

$$\Delta E_n = \frac{E_n - E_{n-1}}{E_{n-1}} \times 100 \quad (8)$$

The decision triggers the concerned relay to sense the abnormal condition and circuit breaker to open circuit after power swing or fault occurrence. The change in energy of first detail coefficient of current signal is used as power swing as well as fault indicator.

Thus, criteria for 'swing' and 'fault' detection are stated in terms of set threshold value as follows.
If $\Delta E_1 \geq Th1$; then power swing is detected
If $\Delta E_1 \geq Th2$; then fault is detected

2.4. Working of main algorithm

The detailed flowchart of the proposed main algorithm is depicted in Fig. 1 consisting of 10 kHz sampling frequency. When fault occurs, the sudden rise in energy E_1 of details coefficient d_1 at the instant of occurrence of fault triggers the algorithm output as a 'Fault.' Unlikely, the wavelet energy variation during power swing condition is gradual. The details of the energy graph are depicted in Fig. 2.

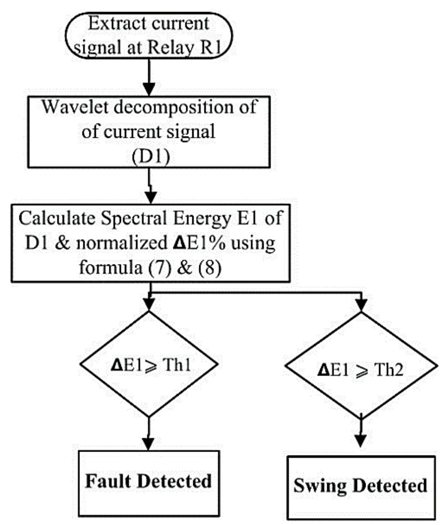


Figure 1. Flowchart for main algorithm.

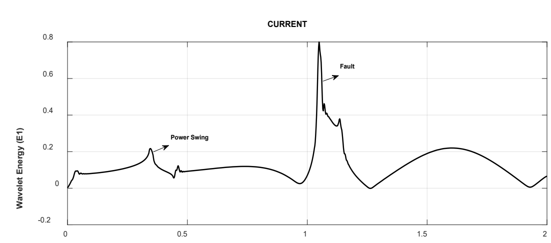


Figure 2. Battle-Lemarie mother wavelet energy graph during fault and power swing.

3. Simulation results

The simulation results are presented considering two different cases: double circuit transmission line network and WSCC 3 machine 9 bus system.

3.1. Results in case of 400 kV double circuit parallel transmission line network

The power system under study consists of 400kV double circuit transmission line network consisting of a synchronous generator and an infinite bus which is used extensively in earlier literature for studying effect of power swing on distance relay operation of EHV transmission line protection scheme (Lotfifard et al., 2009).

The total length of both the lines is 280 km each and upper Line 1 consists of two equal sections of 140 km length. The details of system are given by Brahma (2007) and system is shown in Fig. 3. The line is assumed to be protected using Mho distance relays R_1, R_2, R_3, R_4, R_5, and R_6 placed at both ends of each line section. The current signal is monitored and captured at relay R_1 and all the fault lengths are w.r.t. location of this relay the details of various lengths considered are mentioned in next section.

A three-phase fault is created in the middle of Line 2 to generate power swing in Line 1. Several types of faults are created in zone1, zone2 and zone3 with variation in fault resistance in multiples of ten. The summary of simulated cases in MATLAB software is stated in Table 1. From space constraint point of view, only results for few cases are presented elaborating detection of faults in zone1, zone2 and zone3 respectively at different times of initiation through Fig. 4, Fig. 5, and Fig. 6 respectively presented below.

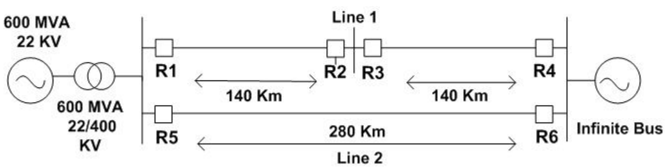
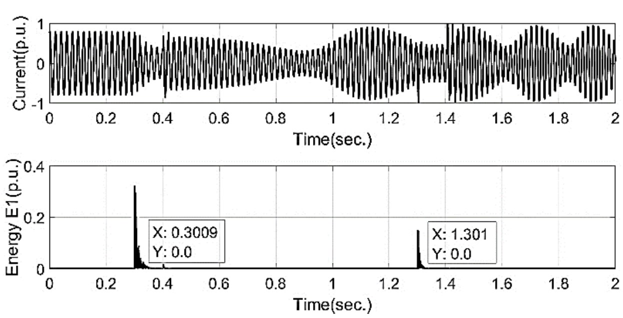
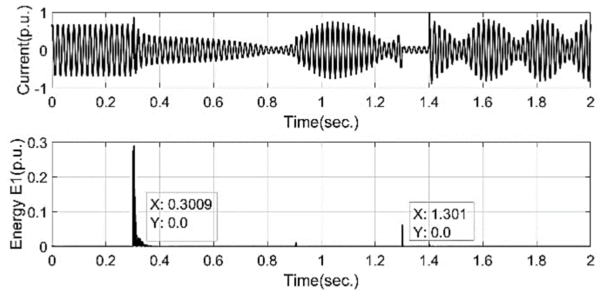


Figure 3. System under study.

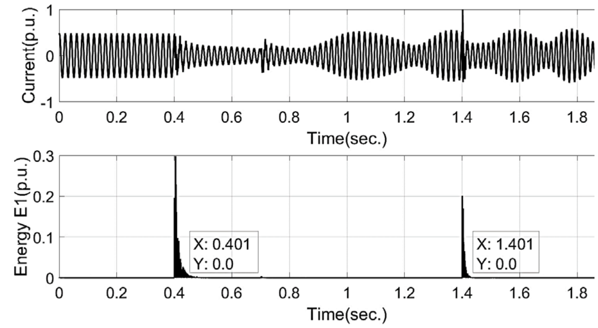


(a)

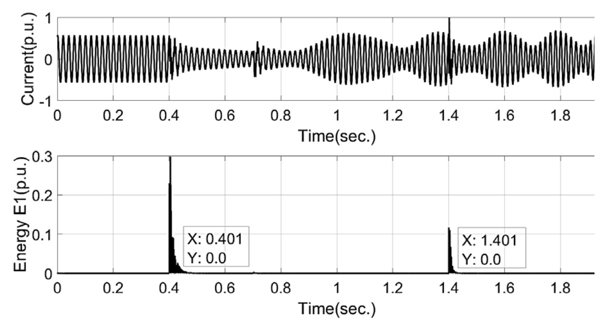


(b)

Figure 4. Fault detection in Zone1
(a) LLL fault (b) LG fault.

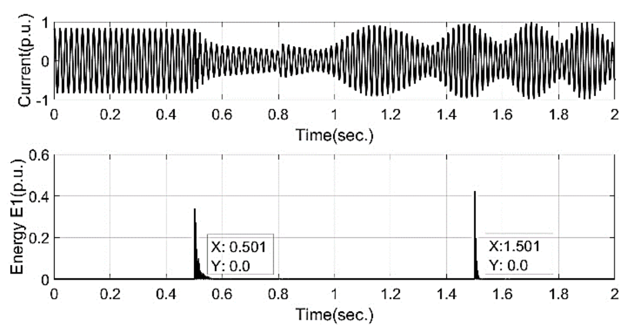


(a)

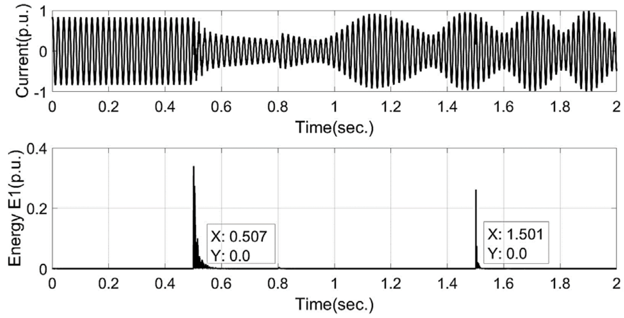


(b)

Figure 5. Fault detection in Zone2 (a) LLL fault (b) LG fault.



(a)



(b)

Figure 6. Fault detection in Zone3 (a) LLL fault (b) LG fault.

3.2. Results in case of multi-machine 9 bus system

To evaluate the fast-acting proposed algorithm for multi-machine system, a WSCC 3 machine, 9 bus system is considered as shown in Fig.7. The line under consideration is Line 7-8 connecting Bus 7 to Bus 8 and to generate a power swing in this line, a three-phase fault is created in neighboring Line 5-7 connecting Bus 5 to Bus 7.

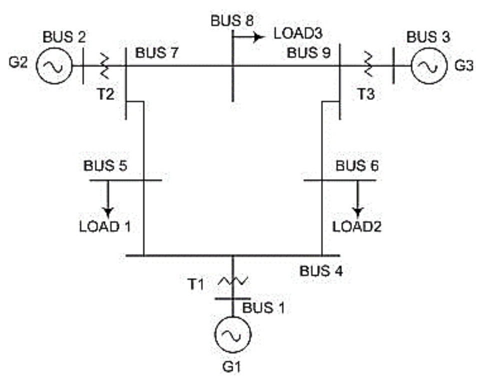


Figure 7. WSCC 3 machine 9 bus system under study.

For generation of power swings, three different timings of 0.3 sec., 0.4 sec. and 0.5 sec. and for fault inception, 1.3 sec., 1.4 sec. and 1.5 sec. are considered as shown in Fig. 8, Fig. 9 and Fig. 10. Also, fault location is chosen considering all three protection zones. The system parameters are referred from (Chatterjee & Roy, 2019). From the simulation finding, it is observed that the proposed algorithm is successfully able to detect power swing and all types of faults within a brief span of 0.001 sec.

3.3. Choice of appropriate sampling rate

For any signal processing method, one of the crucial signal processing parameters includes sampling frequency which is 10 kHz decided by the Shannon sampling theorem in this work. This sampling rate should be related to processor capability and data transmission speed of digital relay for practical implementation and hence should be carefully chosen.

In earlier literature by Venkatesh and Swarup (2012), a total of 16, 24, 32 and 64 samples per cycle of the fundamental frequency (50 Hz) are considered to investigate the impact of varied sampling rates on digital relay operating time. Interestingly, investigations show that operating time does not decrease (improve) with increase in sampling rate. Hence higher sampling rate may be avoided and chosen value should be as close as possible with actual digital relay sampling rate which is 10KHz.

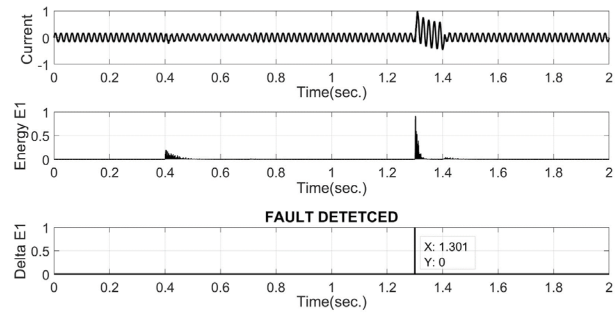


Figure 8. Detection of LLL fault in Zone1 (swing at 0.3 sec. and fault at 1.3 sec).

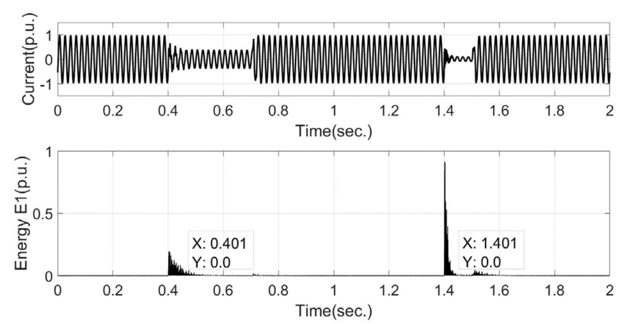


Figure 9. Detection of LLL fault in Zone2 (swing at 0.4 sec. and fault at 1.4 sec).

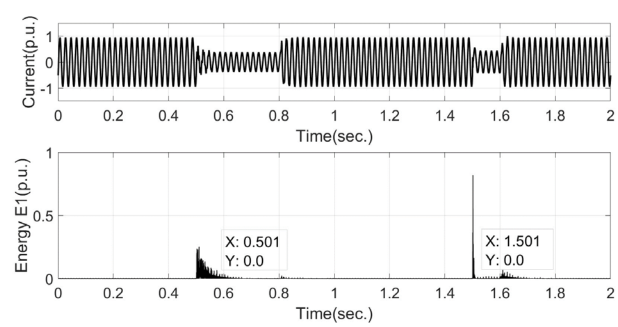


Figure 10. Detection of LLL fault in Zone3 (swing at 0.5 sec. and fault at 1.5 sec).

The simulation results are presented in Table 1 clearly depict power swing detection timing in each case which is also equal to 0.001 sec. If the fault occurs in Zone1, the energy generation is higher and is least for Zone3 fault location due to considerable impedance value between relay point and fault location. The case is critical for the case of Zone3 fault with maximum fault resistance involved.

Such a scenario is also detected clearly and with minimum detection time using proposed algorithm. This proves the robustness of the proposed algorithm in all extreme situations as well.

Table 1. Simulated cases for 400kV parallel transmission line network.

SN	Fault distance (km)	Fault type	Fault inception time (sec.)	Fault resistance (Ω)	Zone covered
1	10	LLL	1.3	1	Zone1
2	10	LLG	1.3	1	Zone1
3	10	LG	1.3	1	Zone1
4	10	LLL	1.3	100	Zone1
5	10	LLG	1.3	100	Zone1
6	10	LG	1.3	100	Zone1
7	10	LLL	1.3	300	Zone1
8	10	LLG	1.3	300	Zone1
9	10	LG	1.3	300	Zone1
10	130	LLL	1.4	1	Zone2
11	130	LLG	1.4	1	Zone2
12	130	LG	1.4	1	Zone2
13	130	LLL	1.4	100	Zone2
14	130	LLG	1.4	100	Zone2
15	130	LG	1.4	100	Zone2
16	130	LLL	1.4	300	Zone2
17	130	LLG	1.4	300	Zone2
18	130	LG	1.4	300	Zone2
19	250	LLL	1.5	1	Zone3
20	250	LLG	1.5	1	Zone3
21	250	LG	1.5	1	Zone3
22	250	LLL	1.5	100	Zone3
23	250	LLG	1.5	100	Zone3
24	250	LG	1.5	100	Zone3
25	250	LLL	1.5	300	Zone3
26	250	LLG	1.5	300	Zone3
27	250	LG	1.5	300	Zone3

The comparison included in Table 2 below shows that in earlier reported schemes for fault detection in presence of power swings, as the sampling rate is made optimum, detection time is reduced. But no single method is best considering optimum sampling rate, and all fault types with consideration of maximum value of fault resistance.

Alternatively, the proposed method is idealistic considering all the mentioned criteria. Thus, practical implementation of the proposed method would certainly prove to be ideal in view of EHV transmission line digital protection.

Table 2. Comparison of various fault detection techniques.

Ref. No.	Sampling Frequency	Type of Fault Detected	Fault Detection time	Max. Fault Res.(Ω)
(Pan & Kezunovic, 2010)	10KHz	Symmetrical	0.0025 msec.	Not mentioned
(Brahma, 2007)	40.96KHz	Symmetrical	0.1 sec.	100 Ω
(Alsyoufi & Hajjar)	20KHz	Symmetrical & Unsymmetrical	0.0232 sec.	100 Ω
Proposed work	10KHz	Symmetrical & Unsymmetrical	0.001 sec.	300 Ω

4. Conclusions

In this paper, a fast-acting fault sensing algorithm in presence of power swings is proposed which is based on discrete wavelet transform and multi resolution analysis. The novelty of work lies in the fact that the algorithm is quite simple as it uses only single variable i.e., current signal at relay location for detection of power swings and all types of faults in presence of swings. Simulation results prove that all faults are detected very efficiently within a short duration of 0.001sec.

The main contribution of work can be summarized as follows:

1. The advantage of using only current signal as single variable assures fast and efficient detection and less computational burden on the proposed algorithm.
2. The proposed technique is not dependent on system voltage and hence distortions in supply voltage will not affect the algorithm accuracy.
3. The algorithm uses a special type of Battle- Lemarie family mother wavelet having short support to enable signal detection at first level of signal decomposition both for power swing and fault.
4. The proposed simple, highly efficient, and quickly acting algorithm would certainly prove to be very useful specially for EHV transmission line protection.

Conflict of interest

The authors have no conflict of interest to declare.

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