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# Wavelet energy-based stable and unstable power swing detection scheme for distance relays

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**Abstract:** Distance relays are susceptible to maloperation during postfault power oscillations in the system. This unintended operation of relays may lead to power system blackout. It is due to their inability to distinguish a stable from an unstable power swing and to take a tripping decision appropriately. This research paper proposes a fast and wavelet energy-based method to detect stable and unstable power swings for distance relays. The proposed method computes the angular velocity of an equivalent machine developed from the measurements available at a bus. The energy in the low frequency band of the equivalent machine angular velocity will assist the tripping decisions of transmission line relays during power swings. Compared to the conventional method using blinders, the advantage of this method is that it requires less hardware and less time to know whether the resulting power oscillations after fault clearing are going to be stable or not. The performance of the proposed method has been evaluated on 5-bus system, WSCC 9-bus system, and IEEE 14-bus and 30-bus systems considering different test scenarios. The results show that using this method improves the performance of distance relays in detecting stable and unstable power swings.

**Key words:** Power system blackouts, distance relays, power swings, power system stability

## 1. Introduction

The biggest power failure in the world, the July 2012 Indian blackout left approximately 620 million people stranded in darkness. The committee investigating into the causes of this breakdown made the following observations [1]: (a) Lack of contingency awareness and real-time monitoring tools, (b) absence of security assessment and warning systems, (c) unintended operation of protection and improper coordination of control actions, (d) lack of enough reactive compensation, (e) human error & grid indiscipline. The remedial measures proposed by them are: (a) wide area monitoring and control, (b) ensuring the activation of all emergency controls and protection, (c) proper automation of smart grid, information flow and data management, (d) regulatory changes to strengthen system security and operation. Not only the Indian blackout, but also other major blackouts in history reveal that relaying problems and inadequate understanding of cascading events are two disabling factors of correct prediction and prevention. Protective relays can quickly identify and isolate faulted area in a power system to maintain security and reliability. However, when a transmission line is tripped

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due to faulty operation of a relay during power swings, faults, load switchings etc., the power flow on this line will be transferred to the other transmission lines. Those healthy lines may also be overloaded and new faults may develop, giving rise to cascade tripping of lines and generators.

A consolidated review on distance relay blocking schemes to prevent maloperation during power swings is discussed in [2]. The problem of zone 3 distance relay maloperation are addressed in [3] with possible solutions in three categories. These include anticipatory schemes, communication assisted schemes, and schemes that use the local data to enhance relay security. The technique presented in [4] consists of two levels of classifiers that segregate stressed conditions like power swings and voltage stability from fault. Features or the classifiers are computed from wide area measurements. A simple power swing detection method based on Taylor Series expansion is reported in [5]. In this research work, discrimination index is calculated and compared with threshold value to discriminate power swing and a fault. In [6], blocking third zone scheme using local measurements is proposed. From the local measurements like active power, reactive power and voltage at a particular bus, a single machine infinite bus equivalent is developed. Then the zero crossing of relative speed of this equivalent machine is used as a criteria to distinguish stable and unstable swings.

A method to detect slow and fast swings using moving average of current signals is developed in [7]. In [8], wavelet singular entropy-based technique is discussed to detect power swings and faults. Adaption of this method requires a lot of computation. Vulnerability of a relay for maloperation during stressed condition is assessed by relay ranking index in [9]. Use of PMUs for detection of power oscillations is expensive compared to the schemes using local area measurements. In most cases, cascading failures are usually triggered by the tripping of critical lines that are overloaded. Insufficient reactive power compensation is also a major contributing factor for such cascading events. This leads to severe voltage instability. If the primary controls are unable to prevent it, then load has to be shed as a last sort of emergency action. In [10], an algorithm that detects critical lines and sheds the loads intelligently is presented.

The novelty of the proposed method is that the tripping decision of the relay near to a bus is assisted by the energy computed locally, due to the fault anywhere (i.e. globally) in the system. Hence, this criteria think globally and act locally. The existing conventional protection utilizes the local data and tries to eliminate the fault as soon as possible. However, these relays are prone to maloperation during post fault power oscillations in the system. The time settings for the blinders used in these relays to discriminate power swings and fault conditions are very critical and system-dependent.

The organization of the paper is as follows: Section 2 of this paper discusses the mathematical background and process involved in the development of criteria to distinguish stable, unstable power swings. The proposed methodology is tested on 5-bus system [11], WSCC 9-bus system, and IEEE 14-bus and 30-bus systems to verify the suitability of this criterion for small and large systems. Simulated results are reported and discussed in Section 3. Section 4 concludes with the key issues and observations of this research work.

## 2. Proposed methodology

The methodology for detecting stable and unstable power swings is based on the wavelet energy of approximate coefficients computed at first-level decomposition of angular velocity signal obtained from the equivalent machine. The first stage is the development of equivalent machine system. The procedure used here for the determination of equivalent machine parameters and the machine angular velocity is different from that reported in [6]. This is developed from the local measurements obtained at a particular bus. As shown in Figure 1, local measurements obtained at bus A are bus voltage $(V)$, total active power $(P_{in})$, and reactive power

$(Q_{in})$ flowing into the bus. Equivalent machine with terminal voltage E$\angle 0^0$ is assumed to deliver $P_{in} + jQ_{in}$ into the bus with voltage designated as V$\angle{-\delta_{Eql}}$. This indicates that the equivalent machine is assumed to be placed behind bus A and connected to the bus through a reactance $X$. The distance relay under consideration is connected to one of the outgoing lines.

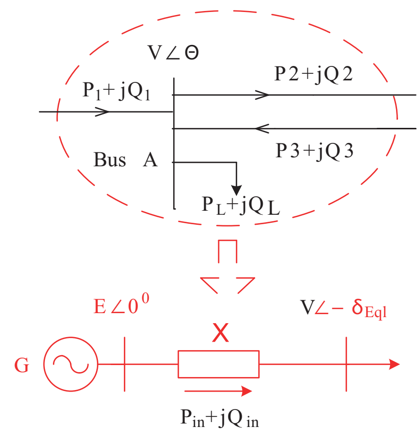


**Figure 1**. Equivalent machine system.

The power flow equations in the equivalent system are given as below:

$$P_{in} = \frac{EV}{X} \sin \delta_{Eql}, \tag{1}$$

$$Q_{in} = \frac{E^2}{X} - \frac{EV}{X} \cos \delta_{Eql}. \tag{2}$$

In the above equations, $V, P_{in}, Q_{in}$ are actual voltage, total power, and reactive power into bus A. E is no load internal voltage of the equivalent generator which is held constant($E$ should be chosen greater than $V$ for real solution). These are readily available at the bus. $X, \delta_{Eql}$ are the fictitious reactance of the line between the equivalent machine and the bus, and voltage angle with respect to the equivalent machine. Eliminating $\delta_{Eql}$ from Eqs. (1) and (2), the value of fictitious reactance X can be obtained from Eq. (3)

$$({P_{in}}^2 + {Q_{in}}^2)X^2 - 2E^2 Q_{in} X + E^4 - E^2 V^2 = 0. \tag{3}$$

As the above equation is quadratic, two different values of $X$ are obtained. A value of $X$ should be chosen in such a way that the equivalent machine system operating point lies in the stable region. The value of $X$ is not constant and updates after every sampling interval $\Delta t$, when the three locally available variables $V, P_{in}, Q_{in}$ are measured. Equivalent delta $\delta_{Eql}$ can be obtained from Eq. (1) as

$$\delta_{Eql} = \sin^{-1} \frac{P_{in} X}{EV}. \tag{4}$$

In the second stage, relative angular velocity of the equivalent machine is computed. It is obtained by calculating the rate of change of equivalent delta obtained in Eq. (4)

$$\omega_{Eql} = \frac{\delta_{Eql}(t) - \delta_{Eql}(t-1)}{\Delta t}. \tag{5}$$

As power swing takes place only when the fault is cleared, equivalent machine system is taken into account only after fault is cleared. This instant is obtained by observing the sudden rise in the bus voltage magnitude. Then the angular velocity of the equivalent machine is computed from Eq. (5) and averaged over three successive sampling time intervals to damp out spurious oscillations due to numerical differentiation.

Final part of the proposed methodology involves computation of wavelet energy. As Daubechies db4 is good at dealing transient stability problems, it is chosen as a mother wavelet [12]. Relative angular velocity signal is considered till 0.75 s after the fault clearance and it is decomposed till first level using Daubechies db4. Then the energy at this level is computed as the square of the RMS value of the approximate coefficients as

$$E_A = \frac{1}{N}\sum_{i=1}^{N} C_A(i)^2, \tag{6}$$

where $C_A(i)$ are the approximate coefficients and $E_A$ is the total energy of the approximate coefficients. Approximate coefficients correspond to the amplitudes of the frequency components in the low-frequency band of the relative angular velocity of the equivalent machine. Thus, this indirectly represents the change in equivalent kinetic energy of the system dynamics and therefore can be taken as a measure for assessing the system stability. Hence, energy of approximate coefficients will be used as a criterion to detect a stable and unstable power swing.

In [6], where the concept of equivalent machine is used, the authors did not consider the time variation of the bus voltage while deriving the gradient of power input to the bus under consideration. Moreover, the criterion used to identify stable power oscillations is based on zero crossing of the relative angular velocity of the equivalent machine. The detection of zero crossing is difficult in the presence of noise and also the time required to detect zero crossing varies from case to case. In the proposed method, both these two shortcomings are overcome through the use of energy concept and the detection time for stable oscillations is fixed at 0.75 s plus small computation time to obtain $E_A$.

## 3. Simulation studies and discussions

The proposed methodology is tested on 5-bus system, WSCC 9-bus system, and IEEE 14-bus and 30-bus systems as shown in Figures 2–5. Dynamic simulations are done in Power World Simulator, and the algorithm to identify stable and unstable system swings is developed in MATLAB. Distance relays with mho characteristics are considered for line protection with zone 1 setting 80%, zone 2 setting 120% of the line impedance, and zone 3 covering the longest length of the line connected to the line under first zone protection. Due to its high setting, the third zone relay is likely to operate under heavily loaded condition or system swings. However the third zone protection is intended only as secondary protection to take care of any contingency problem like failure of primary and second zone relays or breaker. The time delay setting for zone 3 is assumed to be 1 s. The sampling frequency at which the local measurements are sampled is 1000 Hz. The dynamic analysis of the 4 systems under consideration is done with the systems fully loaded when the possibility of maloperation of the third zone relay due to swings after the fault clearance is very likely.

In all the simulated cases, a three-phase fault is incepted at 1 s. The equivalent machine representation is used behind the bus to which the relay under consideration is connected. The location of the relay is indicated as red colored box in all four systems as shown in Figures 2–5. $P_{in}, Q_{in}$ entering the bus and the bus voltage $V$ are used to compute the equivalent machine parameters using Eqs. (3)–(5). Wavelet energy $E_A$ is obtained from Eq. (6). The resulting $E_A$ is used to supervise the operation of the third zone of the relay. From the various cases considered in the analysis (some give rise to instability), the critical value of $E_A$ that can distinguish stable and unstable operation of the system is obtained. This value of $E_A$ will be different for other locations of the relay and also is system-dependent. Thus, this $E_A$ has to be evaluated for each configuration independently. The operation of the third zone of the distance relay under consideration is controlled by the value of $E_A$ computed. If it is below the critical value (threshold), the relay is blocked. To verify the applicability of this method, 4 systems of increasing bus number are considered.

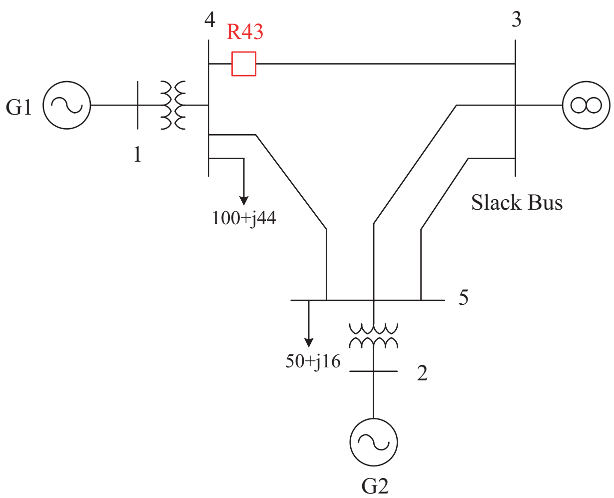


**Figure 2**. 5-bus system.

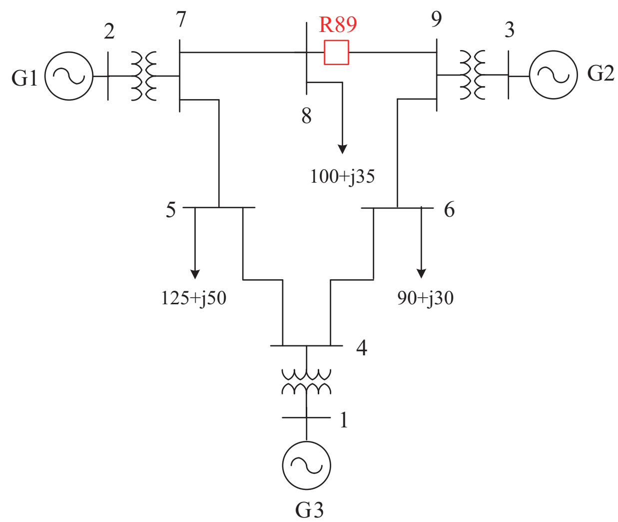


**Figure 3**. WSCC 9-bus system.

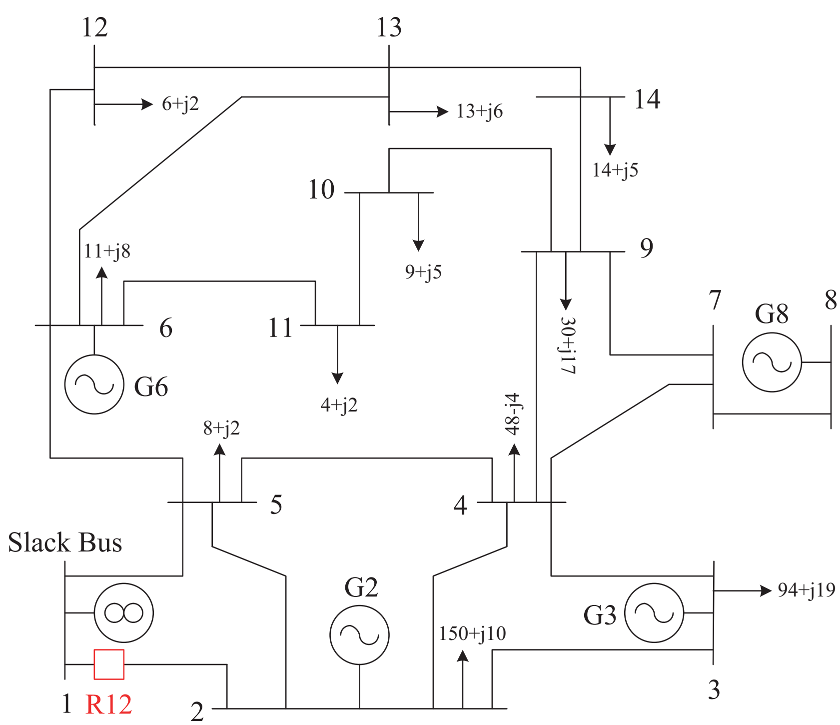


**Figure 4**. IEEE 14-bus test system.

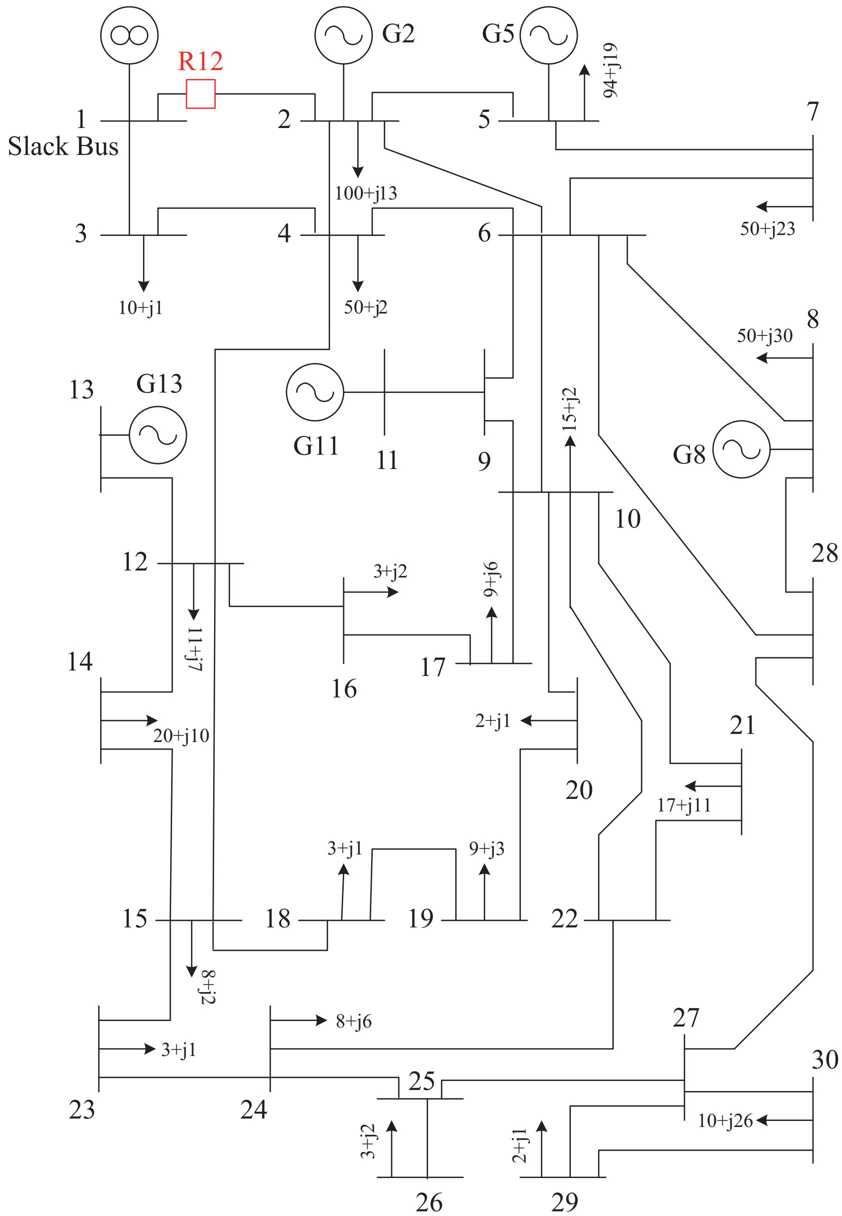


**Figure 5**. IEEE 30-bus test system.

### 3.1. 5-bus system

**Case 1:** Three-phase fault is incepted near bus 5 and cleared by opening double circuit line 5-3 in 0.15 s. It is observed that the impedance locus did not enter the third zone and the system is stable. The $E_A$ computed for this case is 1127.3.

**Case 2:** In this case, fault is incepted at bus 5 and cleared by opening line 5-3 in 0.30 s. The system is stable and the impedance locus entered the third zone at 1.349 s and left at 1.542 s. This stable power swing stayed in the third zone for less than its time delay setting. The $E_A$ computed for this case is 1089.1.

**Case 3:** Fault is incepted near bus 3 and cleared by opening double circuit line 3-5 in 0.45 s. The system became unstable. The $E_A$ computed for this case is 105,930. The impedance loci seen by the relay R43 for Cases 1–3 are shown in Figure 6.

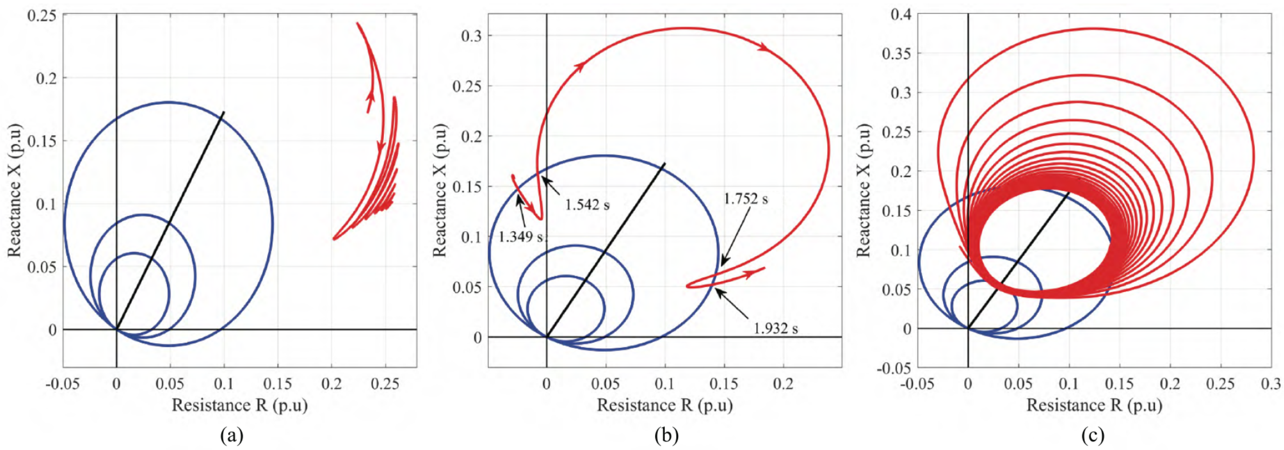


**Figure 6**. Impedance locus measured at mho relay R43 in 5-bus system for Cases 1–3.

The total energy of approximate coefficients (Level-1) for $\omega_{Eql}$ signal computed near R43 for different fault locations and fault clearing times are shown in Table 1. It is observed that an approximate boundary value of 20,000 for $E_A$ can distinguish a stable from an unstable power swing.

**Table 1**. Total energy of approximate coefficients (Level-1) for different fault locations and fault clearing times.

| Test system: 5-bus system | | Location of equivalent machine: Bus 4 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Clearing time (s) | | | | | | |
| | | 1.05 | 1.15 | 1.2 | 1.3 | 1.35 | 1.4 | 1.45 |
| Location of fault | Clearing action | Ea | Ea | Ea | Ea | Ea | Ea | Ea |
| Near bus 5 | Opening line 5-4 | 827.66 | 733.58 | 2551.4 | 8567.2 | 110,610 (Unstable) | | |
| Near bus 5 | Opening line 5-3(1) | 979 | 697.41 | 2628.7 | 1089.1 | 146,610 (Unstable) | | |
| Near bus 5 | Opening line 5-3 (1, 2) | 781.83 | 1127.3 | 2192.7 | 86,555 (Unstable) | | | |
| Near bus 3 | Opening line 3-5 (1) | 1264 | 751.18 | 761.94 | 7136.9 | 13,421 | 18,406 | 105,930 (Unstable) |
| Near bus 3 | Opening line 3-5 (1, 2) | 925.62 | 1061.9 | 1175.1 | 3881.6 | 5863.6 | 48,460 (Unstable) | |

### 3.2. WSCC 9-bus system

**Case 1:** Three-phase fault is incepted near bus 4 and cleared by opening the line 4-5 in 0.05 s. It is observed that the impedance locus did not enter the third zone and system is stable. The $E_A$ computed for this case is 1253.3.

**Case 2:** In this case, fault is incepted at bus 5 and cleared by opening the line 5-7 in 0.15 s. The system remained stable. It is observed that the impedance locus entered the third zone at 1.48 s and left at 1.807 s. This stable power swing stayed in the third zone for 0.327 s i.e. less than its time delay setting. The $E_A$ computed for this case is 2450.8.

**Case 3:** Fault is incepted near bus 5 and cleared by opening line 5-7 in 0.20 s. The system became unstable. The $E_A$ computed for this case is 9975.2.The impedance loci seen by the relay R89 for Cases 1–3 are shown in Figure 7.

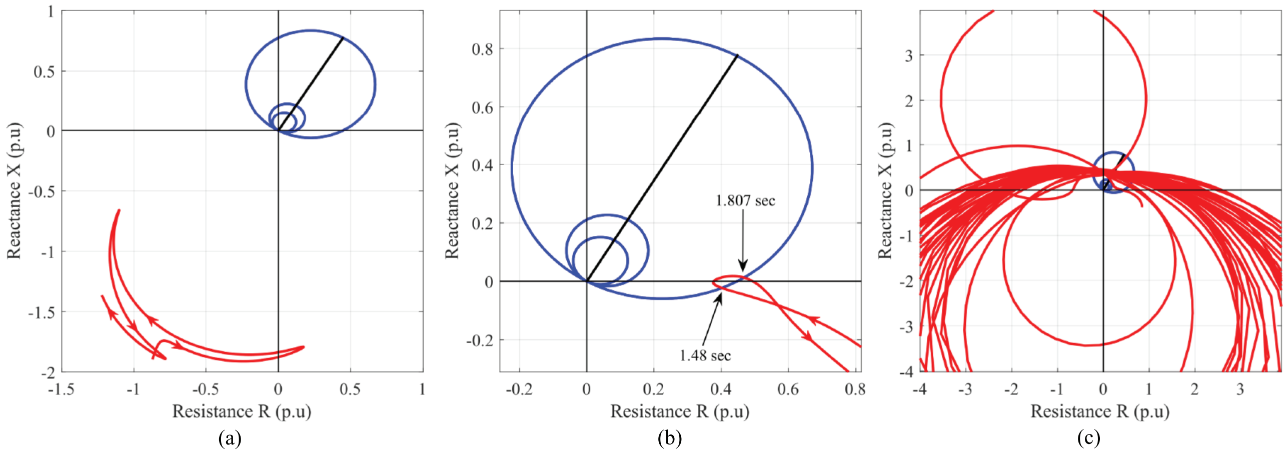


**Figure 7**. Impedance locus measured at mho relay R89 in WSCC 9-bus system for Cases 1–3.

The total energy of approximate coefficients (Level-1) for $\omega_{Eql}$ signal computed near R89 for different fault locations and fault clearing times are shown in Table 2. It is observed that an approximate boundary value of 8000 for $E_A$ can distinguish a stable from an unstable power swing.

**Table 2**. Total energy of approximate coefficients (Level-1) for different fault locations and fault clearing times.

| Test system: WSCC 9-bus system | | Location of equivalent machine: Bus 8 | | | | |
|---|---|---|---|---|---|---|
| | | Clearing time (s) | | | | |
| | | 1.05 | 1.1 | 1.15 | 1.2 | 1.25 |
| Location of fault | Clearing action | Ea | Ea | Ea | Ea | Ea |
| Near bus 4 | Opening line 4-5 | 1253.3 | 1075.5 | 1939.3 | 7047.4 | 9576.6 (Unstable) |
| Near bus 4 | Opening line 4-6 | 1477.66 | 1688.9 | 1699 | 2808.2 | 4210.6 (Unstable) |
| Near bus 5 | Opening line 5-7 | 2248.2 | 3363.6 | 2450.8 | 9975.2 (Unstable) | |
| Near bus 6 | Opening line 6-9 | 778.861 | 1349 | 2660.3 | 4975.7 | 4051.9 (Unstable) |
| Near bus 7 | Opening line 7-5 | 2958.2 | 9626.7 (Unstable) | | | |

### 3.3. IEEE 14-bus test system

**Case 1:** Three-phase fault is incepted near bus 11 and cleared by opening the line 11-10 in 0.05 s. It is observed that the impedance locus did not enter the third zone and system is stable. The $E_A$ computed for this case is 2247.1. The total energy of approximate coefficients (Level-1) for $\omega_{Eql}$ signal computed near R12 for different fault locations and fault clearing times are shown in Table 3.

**Case 2:** In this case, fault is incepted at bus 5 and cleared by opening the line 5-2 in 0.35 s. The system remained stable and the impedance locus entered the third zone at 1.672 s. This computed impedance stayed in the third zone for 0.332 s i.e., less than its time delay setting. The $E_A$ computed for this case is 9967.2.

**Case 3:** Fault is incepted near bus 9 and cleared by opening line 9-7 in 0.60 s. The system became unstable. The $E_A$ computed for this case is 25,983.

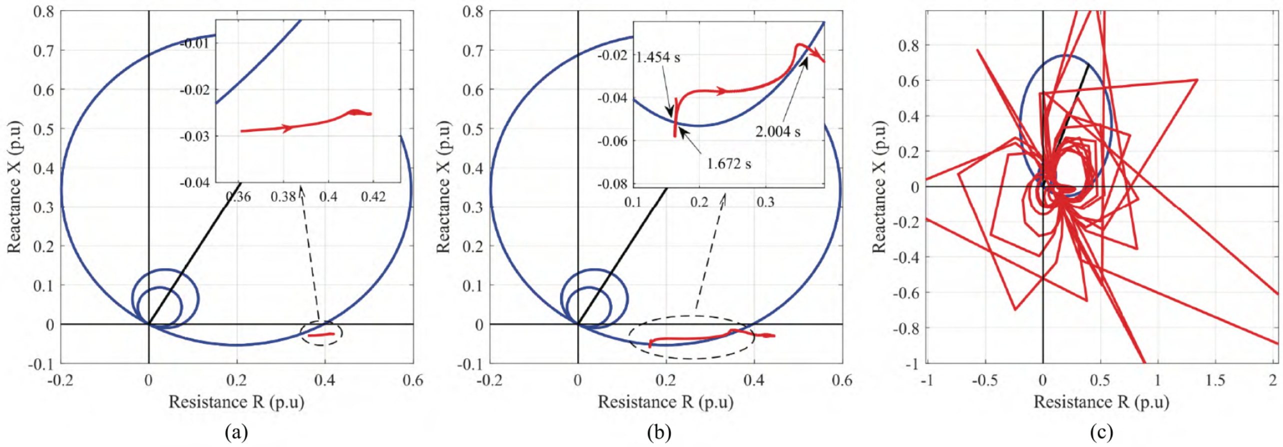


**Figure 8**. Impedance locus measured at mho relay R12 in IEEE 14 bus system for Cases 1–3.

Figure 8 shows the impedance locus seen by the relay R12 for Cases 1–3. It is observed that an approximate boundary value of 14000 for $E_A$ can distinguish a stable from an unstable power swing.

**Table 3**. Total energy of approximate coefficients (Level-1) for different fault locations and fault clearing times.

| Test system: IEEE 14-bus system | | Location of equivalent machine: Bus 1 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Clearing time (s) | | | | | | |
| | | 1.05 | 1.1 | 1.2 | 1.3 | 1.35 | 1.4 | 1.6 |
| Location of fault | Clearing action | Ea | Ea | Ea | Ea | Ea | Ea | Ea |
| Near bus 2 | Opening line 2-3 | 8008.6 | 8806.3 | 179870 (Unstable) | | | | |
| Near bus 2 | Opening line 2-4 | 8337.6 | 9697.5 | 93,666 (Unstable) | | | | |
| Near bus 4 | Opening line 4-3 | 6547.3 | 8521.6 | 9145.6 | 50373 (Unstable) | | | |
| Near bus 5 | Opening line 5-2 | 6126.4 | 8000.9 | 8520.5 | 9978.8 | 9967.2 | 170360 (Unstable) | |
| Near bus 5 | Opening line 5-4 | 5914.4 | 7955.4 | 8918.4 | 11,688 | 12,657 | 135070 (Unstable) | |
| Near bus 9 | Opening line 9-7 | 3435.7 | 5369.1 | 7526.9 | 9639.5 | 10,216 | 10,544 | 25,983 (Unstable) |
| Near bus 11 | Opening line 11-10 | 2247.1 | 3731.6 | 5519.1 | 7008.9 | 7547.4 | 7918.5 | 8266.4 |
| Near bus 12 | Opening line 12-13 | 1601.2 | 2781.5 | 4224.6 | 5256.8 | 5595.6 | 5791.7 | 5803.1 |
| Near bus 14 | Opening line 14-13 | 1591.7 | 2804 | 4273.4 | 5288.2 | 5565.8 | 5683.2 | 5498.2 |

### 3.4. IEEE 30-bus test system

**Case 1:** Three-phase fault is incepted near bus 28 and cleared by opening the line 28-6 in 0.25 s. It is observed that the impedance locus did not enter the third zone and system is stable. The $E_A$ computed for this case is 3585.4.

**Case 2:** In this case, fault is incepted at bus 8 and cleared by opening the line 8-6 in 0.50 s. It is observed that the impedance locus entered the third zone at 1.192 s. This measured impedance stayed in the third zone for 0.662 s i.e. less than its time delay setting. The $E_A$ computed for this case is 5420.5.

**Case 3:** Fault is incepted near bus 6 and cleared by opening the line 6-2 in 0.35 s. The system became unstable. The $E_A$ computed for this case is 126,700. The impedance locus seen by the relay R12 for Cases 1–3 is shown in Figure 9.

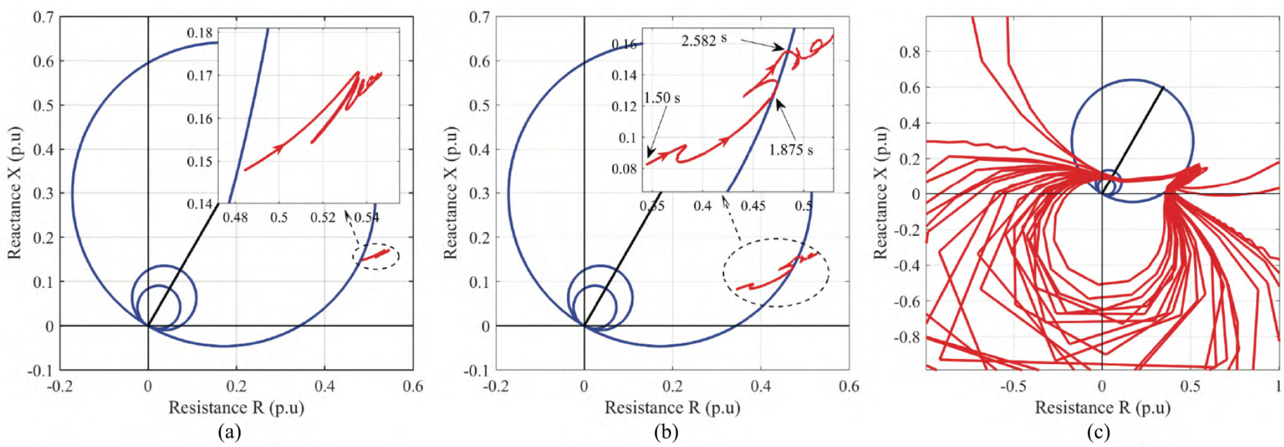


**Figure 9**. Impedance locus measured at mho relay R12 in IEEE 30-bus system for Cases 1–3.

The Total energy of approximate coefficients (Level-1) for $\omega_{Eql}$ signal computed near R12 for different fault locations and fault clearing times are shown in Table 4. It is observed that an approximate boundary value of 10000 for $E_A$ can distinguish a stable from an unstable power swing.

### 3.5. Discussion of results

In all the simulated cases, a boundary value of $E_A$ is identified beyond which a particular system is found to be unstable. It is also examined that the energy computed at the relay location is assisting the mho relay in blocking decisions during power swings. The following cases show the effectiveness of the proposed method.

- In WSCC 9-bus system, when a fault is incepted near bus 4 and cleared by opening the double circuit line 4-6 in 0.25 s: It was observed that the impedance locus did not enter the third zone and system was unstable. The $E_A$ computed for this case is 4210.6. In this case, the line where the relay R89 is located does not show any instability even though some machines are going unstable. It means that this relay will not trip due to the ensuing power swing. Hence, there is no need to block this relay. Moreover, the energy computed for this case is less than its boundary value (i.e. 8000).

- In IEEE 14 bus system, when a fault is incepted near bus 5 and cleared by opening the line 5-4 in 0.35 s which led to a stable power swing: It was observed that the impedance locus entered the third zone at 1.35 s and left at 2.35 s. The impedance locus stayed in the third zone for 1 s i.e. equal to zone 3 setting. The $E_A$ computed for this case is 12,657, which is less than its boundary value of 14,000. As the system

**Table 4**. Total energy of approximate coefficients (Level-1) for different fault locations and fault clearing times

| Test system: IEEE 30 bus system | | Location of equivalent machine : Bus 1 | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Clearing time (sec) | | | | | | |
| | | 1.05 | 1.25 | 1.3 | 1.35 | 1.4 | 1.5 | 1.55 |
| Location of fault | Clearing action | Ea | Ea | Ea | Ea | Ea | Ea | Ea |
| Near bus 2 | opening line 2-5 | 7220.3 | 154550 (Unstable) | | | | | |
| Near bus 2 | opening line 2-4 | 6202.1 | 62345 (Unstable) | | | | | |
| Near bus 4 | opening line 4-3 | 6194.7 | 6010 | 6175.1 | 7633 | 174,400 (Unstable) | | |
| Near bus 4 | opening line 4-6 | 5169.6 | 5658.5 | 6032.8 | 7490.5 | 118,820 (Unstable) | | |
| Near bus 6 | opening line 6-2 | 6082.5 | 6016.7 | 6873.3 | 126,700 (Unstable) | | | |
| Near bus 7 | opening line 7-5 | 2262.6 | 2891.5 | 2986.2 | 3157 | 3352.9 | 3774.4 | 3948 |
| Near bus 8 | opening line 8-6 | 3526.7 | 3809.8 | 3920.1 | 4113.8 | 4381.2 | 5420.5 | 99,095 (Unstable) |
| Near bus 10 | opening line 10-22 | 1436.5 | 1762.4 | 1754.4 | 1782.4 | 1839.4 | 1974.1 | 2024.6 |
| Near bus 15 | opening line 15-14 | 793.58 | 1071.1 | 1077.6 | 1097 | 1138.2 | 1238.7 | 1276.6 |
| Near bus 17 | opening line 17-16 | 830.82 | 1142.6 | 1141.7 | 1163.4 | 1198.4 | 1285 | 1319 |
| Near bus 23 | opening line 23-15 | 348.75 | 538.36 | 546.73 | 566.43 | 582.23 | 617.49 | 625.2 |
| Near bus 24 | opening line 24-22 | 456.65 | 692.74 | 697.52 | 717.94 | 735.92 | 778.2 | 789.27 |
| Near bus 28 | opening line 28-6 | 3007.5 | 3585.4 | 3628.2 | 3733.7 | 3893.5 | 4217.3 | 4376.2 |
| Near bus 30 | opening line 30-27 | 77.28 | 108.61 | 108.77 | 110.97 | 108.64 | 112.29 | 113.25 |

is stable, the relay R12 should not operate. In addition, the time to initiate blocking signal is sum of 0.75 s and time required to compute $E_A$. From the simulations, it is less than 1 s, which is less than the zone 3 setting. Thus, the relay is blocked from tripping.

- In IEEE 30-bus system, when fault is incepted near bus 4 and cleared by opening the line 4-6 in 0.25 s: This led to a stable power swing. It was observed that the impedance locus entered the third zone at 1.157 s after the fault inception and left at 3.348 s. The impedance locus stayed in the third zone approximately for 2.191 s i.e. more than zone 3 setting. It resulted in a stable power swing. Thus, the relay R12 should be blocked from operation. The $E_A$ computed for this case is 5658.5 and it is less than its boundary value of 10,000. Hence, the relay is blocked from tripping. As discussed, the blocking signal is initiated within 1 s. Impedance locus measured by mho relays in the above cases are shown in Figure 10.

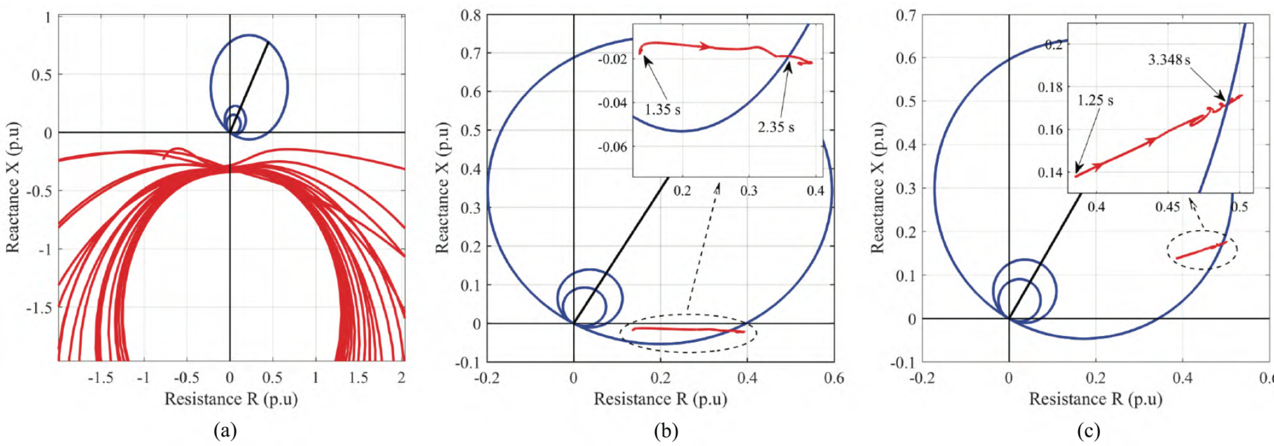


**Figure 10**. (a) Impedance locus measured at mho relay R89 in WSCC 9-bus system, (b) impedance locus measured at mho relay R12 in IEEE 14 bus system, (c) impedance locus measured at mho relay R12 in IEEE 30-bus system.

Different simulated cases show the following scenarios: (1) System is stable following fault clearance, and the impedance locus has not entered the relay characteristics. (2) System is unstable following fault clearance, and the impedance locus has not entered the relay characteristics. (3) System is stable after fault clearance, and the impedance locus has entered the relay characteristics. (4) System is unstable after fault clearance, and the impedance locus has entered the relay characteristics. (5) System is stable, and the impedance locus stayed in the third zone for more time than the third zone time setting. Hence, from these different situations and their corresponding energies, a definite boundary value for $E_A$ can be specified to distinguish between a stable power swing and unstable power swing.

The proposed methodology is summarized as below:

- When the impedance locus has not entered the third zone and the energy computed is more than its boundary value (i.e. unstable power swing), there is no need for blocking. The relay does not pick up.
- When the impedance locus enters the third zone and the energy computed is more than its boundary value (i.e. unstable power swing), the relay is permitted to trip.
- When the impedance locus enters the third zone and the energy computed is less than the boundary value (i.e. stable power swing), the relay will be blocked from tripping.
- Based on these considerations and the results of the dynamic analysis performed on the above mentioned 4 systems, for different cases of fault locations and clearing times, a suggested energy boundary for distinguishing stable and unstable power swings to avoid maloperation of the relay can be estimated for each system.

In the analysis conducted, the systems are heavily loaded and subjected to three-phase faults at different locations in the neighborhood of location of the relay under consideration with increasing fault clearing times. Single-phase faults cause lesser disturbance in the system and may not cause severe power swings to effect the third zone relay operation after fault clearance. A similar situation prevails under light-load conditions and fault locations far away from the relay under consideration. Thus, in this paper only three-phase faults in the neighborhood of the relay are considered.

Based on the analysis done here the entry and exit instants of time of the impedance seen by the relay under consideration crossing the relay third zone characteristic are indicated for the cases in Figures 6–10. In conventional protection scheme using blinder the difference in the time instants when the impedance seen by the relay crosses the characteristics of the main relay and the blinder is used for distinguishing faults as well as stable and unstable power swings. The basic principle adapted by the conventional scheme and the proposed method are different. The proposed method predicts the system instability much faster so that some corrective measures can be employed in time to save the system which is not possible in the conventional system using blinders. In all cases studied, the relative angular velocity of the equivalent machine is sampled at 1000 Hz over a duration of 0.75 s after fault clearance and the sampled signal is used to evaluate the level 1 approximate coefficients of the wavelet transform from which the energy $E_A$ is obtained. The value of $E_A$ makes it possible to identify stable power swings in about 0.75 s after fault clearance.

## 4. Conclusions

This paper introduces the use of wavelet energy as a criterion to detect stable and unstable power swings for distance relays. This is the first time the concept of energy derived from the first-level approximate coefficients of wavelets obtained from the relative angular velocity of the equivalent machine is used to supervise the third zone operation of the associated relay. The analysis carried on different test systems showed that a definite energy boundary exists between stable and unstable scenarios. Hence, the $E_A$ computed is compared with the critical value (energy boundary) of the system to differentiate between a stable and an unstable power swing. The efficacy of this method is that it is fast and also easy to estimate the critical value for a system. This is far advantageous than conventional method employing blinders to set a precise threshold value to detect power swings. Another special feature of this proposed method is that it uses only the locally available data measured at the bus where the relay is located. Keeping in view all further requirements, this research work will be extended to develop an efficient relaying algorithm to identify lines for optimal islanding of interconnected systems under contingencies.

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