Khodaparast and Khederzadeh *Protection and Control of Modern Power Systems* (2016) 1:16
DOI 10.1186/s41601-016-0026-9

Protection and Control of
Modern Power Systems

ORIGINAL RESEARCH Open Access

# Adaptive concentric power swing blocker

Jalal Khodaparast and Mojtaba Khederzadeh*

## Abstract

The main purpose of power swing blocking is to distinguish faults from power swings. However, the faults occur during a power swing should be detected and cleared promptly. This paper proposes an adaptive concentric power swing blocker (PSB) to overcome incapability of traditional concentric PSB in detecting symmetrical fault during power swing. Based on proposed method, two pairs of concentric characteristics are anticipated which the first one is placed in a stationary position (outer of zone3) but the position of the second pair is adjustable. In order to find the position of the second pair of characteristic, Static Phasor Estimation Error (SPEE) of current signal is utilized in this paper. The proposed method detects the abrupt change in SPEE and puts the second pair of characteristic in location of impedance trajectory correspondingly. Second concentric characteristic records travelling time of impedance trajectory between outer and inner zones and compares to threshold value to detect symmetrical fault during power swing. If recorded time is lower than threshold, three-phase fault is detected during power swing. Intensive studies have been performed and the merit of the method is demonstrated by some test signals simulations.

**Keywords:** Concentric PSB, Phasor estimation error, Power swing, Symmetrical fault during power swing

## Introduction

Distance relay malfunction has raised concerns about blackouts in power systems. Distance relays make decisions based on entering of impedance trajectory in protected zones. When a fault occurs in a protected line, the impedance trajectory enters in distance relay zones and the relay operates. However, this impedance penetration may also occur during power swing condition. During a power swing the voltage and current fluctuate simultaneously, causing fluctuation in the measured apparent impedance at the distance relay, which may enter the relay tripping zones. This condition causes relay malfunction and may lead to consecutive events (cascading outages) and even a blackout eventually [1–3].

To avoid this malfunction, Power Swing Blocker (PSB) is installed in modern distance relay [4]. The main task of PSB is discriminating power swing from fault and block distance relay from operating during power swing. Moreover, it should detect any fault during power swing and unblock distance relay. However, due to the symmetric nature of power swing, detection of symmetrical faults during power swing is more difficult than unsymmetrical faults. Therefore, this issue attracts attentions of many researchers at the moment.

There are various suggestions in the literature as to how to deal with this issue. The most traditional method is utilizing rate of change of impedance for power swing detection [4]. However, this method cannot detect fault during power swing when impedance trajectory crosses concentric characteristics during power swing (it is exemplified in Fig. 4). New methods based on voltage phase angle are presented in [5] and [6] but high resistance and symmetrical faults are not considered in these references. Fault detection based on differential power is another proposed method that makes use of auto-regression technique to predict samples in the future [7]. However this method needs lots of simulations to select appropriate parameters for the auto-

* Correspondence: m_khederzadeh@sbu.ac.ir
Electrical Engineering Department, Shahid Beheshti University, Tehran 165895371, Iran

regression technique. Application of time frequency transforms is another solution. Wavelet transform and S-transform are presented in [8] and [9] respectively, to detect power swing but they require high sampling rate, which is a requirement of most Time-Frequency transforms. Another method based on adaptive neuro-fuzzy system is proposed in [10]. This method requires many simulations in different conditions for training and even retraining in new case. Mathematical morphology is presented in [11] for detecting symmetrical fault during power swing and it is based on monitoring shape of signal. Although this method uses time domain transformation, selection of processing function and its length is difficult. Moving average is a low-pass filter that is presented in [12] to discriminate power swing from fault. The moving average varies periodically during power swing, while it becomes either positive or negative consistently during fault. However, utilization of all three phase currents even in symmetrical fault increases computational burden in this method. In [13], a method based on maximum rate of change of three-phase active and reactive powers is proposed. However, the mathematical demonstration of the proposed index is based on a somewhat impractical hypothesis that considers impedance without resistive component. Combination of Park's transformation and moving data window is presented in [14] to extract power coefficents during fault and power swing. These coefficient are approximately zero during power swing and significant during fault. Computational burden of calculation of power coefficients limits the application of this method. Reference [15] proposes a method based on fundamental frequency component that is created in instantaneous three-phase active power after inception of a symmetrical fault. However, it assumed that the fault resistance is negligible. Reference [16] proposes a technique based on negative sequence component of current and cumulative sum (CUSUM) for detecting three-phase fault during power swing in series compensated line. A new method based on extracting created transient of current signal by least square dynamic phasor estimation is proposed in [17]. The challenge of this method is high computational burden of dynamic phasor estimation.

The purpose of this paper is to modify the traditional concentric PSB to enable it for detecting three-phase fault during power swing. In this paper, Phasor Estimation Error (PEE) is employed as a quantity with high abrupt at fault initiation that helps the proposed method in determining the location of second pair of concentric PSB. According to proposed method, two indices are used in this method for detecting fault during power swing, which these indices complete each other. The first index (IX1) is transient monitor that shows occurrence of transient in signal and determines the location of second pair of characteristic and the second index (IX2) that is the output of second concentric characteristics as final index for detecting three-phase fault during power swing.

### Static phasor estimation error

Static Phasor Estimation Error (SPEE) is calculated by static phasor estimation process in every sample and can be used as a quality measure of phasor estimation. In phasor calculation process, windowed signal is utlized for every sample of time. According to Fig. 1, when a transient occurs in the power system, there will be a seri of windows, contain pre and post transient data which are illustrated in shaded box in Fig. 1. It is obvious that the calculated phasors resulted from just pre or just post data of transient periods are accurate, which are illustrated in unshaded box in Fig. 1. The calculated phasors based on the shaded windows (boxes) are not accurate which can be used as a detecter of transient in any signal. Therefore SPEE can be formulated as:

$$SPEE_n = \sum_{n=r-N_1}^{n=r} \left| S_n - \widehat{S_n} \right| \tag{1}$$

where $r$ is the first sample of time window, $S_n$ is the real sample, which is measured by relay and $S^\wedge_n$ is recumputed sample of $S_n$ obtained based on static phasor estimation.

## Discussion

### Limitation of traditional concentric PSB

In normal situation, the measured impedance is far away from the distance relay protection zones. However, when a fault initiates, the measured impedance moves in the complex plane (R, X) rapidly from load point to characteristic of line impedance. As a result of the electrical property of a fault, the rate of change of impedance is very high but it is very slow during power swing a result of the mechanical property of power swing. Traditional concentric PSB utilizes this difference to discriminate power swing from fault. To achieve this goal, two concentric impedance characteristics (outer and inner zones) along with a timer are used in traditional concentric PSB. The required time for impedance movement between outer and inner zones during quickest power swing is considered as threshold value. If the recorded time is lower than

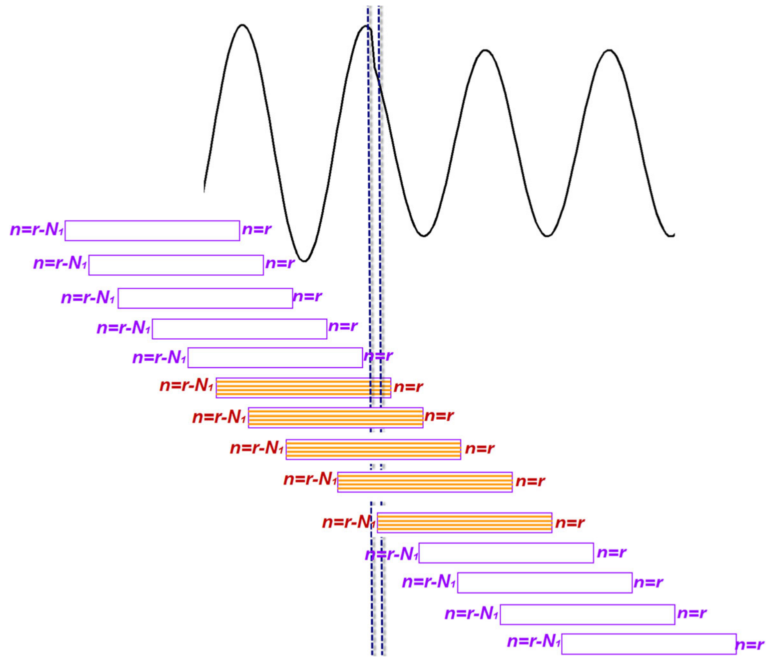


**Fig. 1** Concept of *PEE* ($N_1$ is sample number in one cycle and *r* is the last sample inserted in window)

the threshold value, it is detected as a fault and in contrast, if the recorded time is higher than threshold, it is detected as power swing.

In order to analyze the performance of traditional concentric PSB in discriminating power swing from fault, a series of tests are carried out on a two-machine equivalent system, shown in Fig. 2. The data of the power system, are: $E_B = 1\angle 0$, $E_A = 1\angle\delta(t)$, $Z_A = 0.25\angle 75^0$, $Z_B = 0.25\angle 75^0$, $Z_{Line} = 0.5\angle 75^0$. The power system frequency is $50\,Hz$ and simulation time step is $500\,\mu s$.

*Case1:* first test is programmed to examine capability of traditional CPSB in detecting power swing. In order to simulate the power swing, displacement angle of source *A* is considered as:

$$\delta(t) = \delta_0 + k\cdot e^{-t/\tau}\cdot \sin\left(2\pi\cdot f_{slip}\cdot t\right) \quad (2)$$

where $k = 5$ is constant scaling coefficient, $\tau = 0.3$ is the damping time constant and $f_{slip} = 1Hz$ is the slip frequency. Impedance trajectory of this case is shown in Fig. 3. According to this figure, power swing starts at $t = 0.4\ s$ with impedance value *1.88–0.24i*, which is outside of the relay outermost zone. After power swing initiation, impedance starts to move and come near the relay zones. Before entering the relay's outermost zone, two circular concentric characteristics (outer and inner zones) are located to record the travelling time of impedance trajectory between outer and inner zones. This recorded time is compared with threshold value for detecting power swing. Therefore, if threshold value is selected accurately (threshold value is selected based on traveling time in fastest power swing), traditional CPSB can detect power swing in this condition.

*Case2:* A second test is programmed to show capability of traditional CPSB in detecting symmetrical fault during power swing in special condition. Similar to the previous case, power swing is simulated by displacement angle of

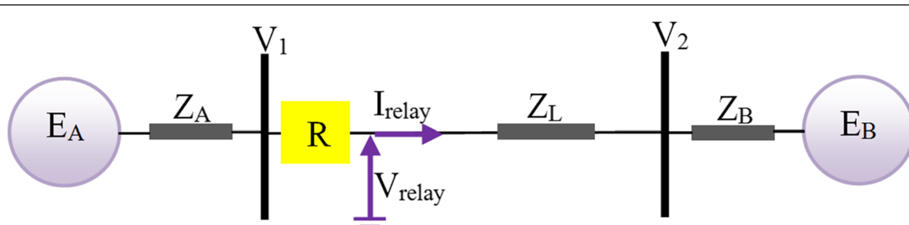


**Fig. 2** Simple two-machine-system

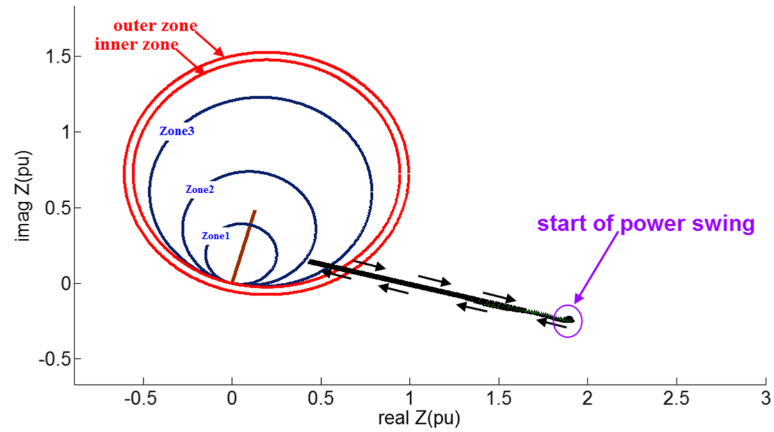


**Fig. 3** Capability of concentric PSB in pure power swing detection

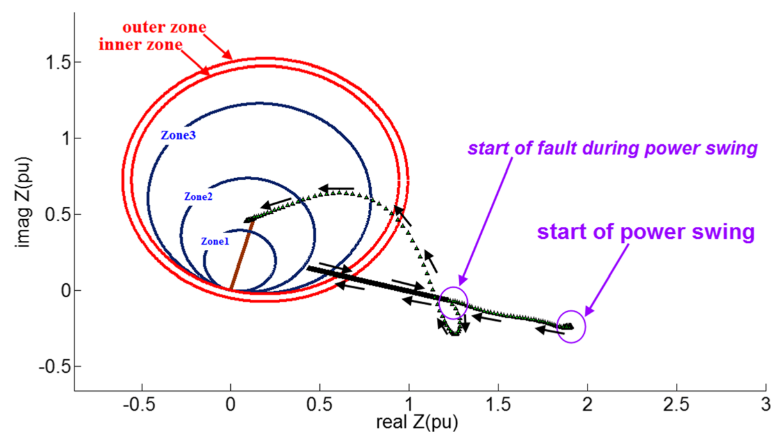


**Fig. 4** Capability of concentric PSB in power swing detection and fault during power swing

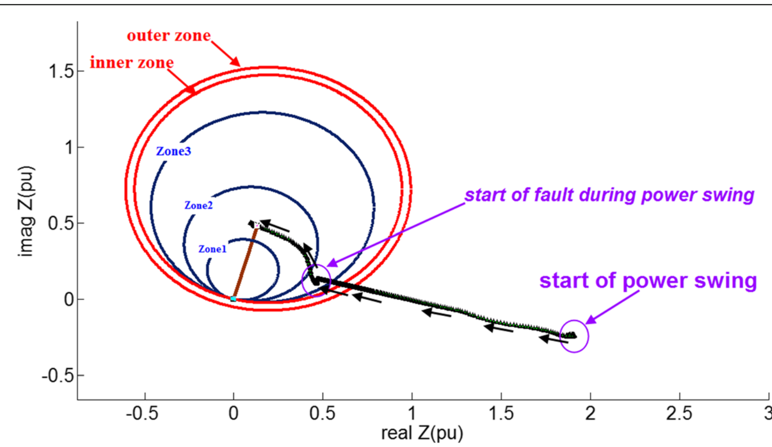


**Fig. 5** Incapability of concentric PSB for detecting fault during power swing

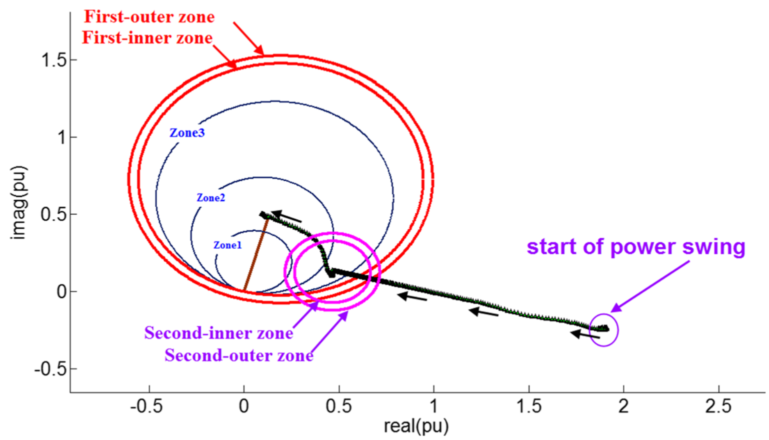


**Fig. 6** Capability of proposed new concentric PSB for detecting symmetrical fault during power swing

source $A$ as Eq. (2). A three-phase fault is simulated in right end of the protected line at $t = 0.85\,s$ during power swing.

The impedance trajectory of this case is shown in Fig. 4. According to the figure, after power swing initiation, impedance moves toward distance zones so that it crosses the CPSB for the first time and then the timer records the traveling time between outer and inner zones. Therefore, power swing can be detected by comparing the recorded time with threshold value and then distance relay is blocked. As a consequence of power swing, impedance trajectory moves back and gets away from the distance zones and so leaves the outer zone of CPSB.

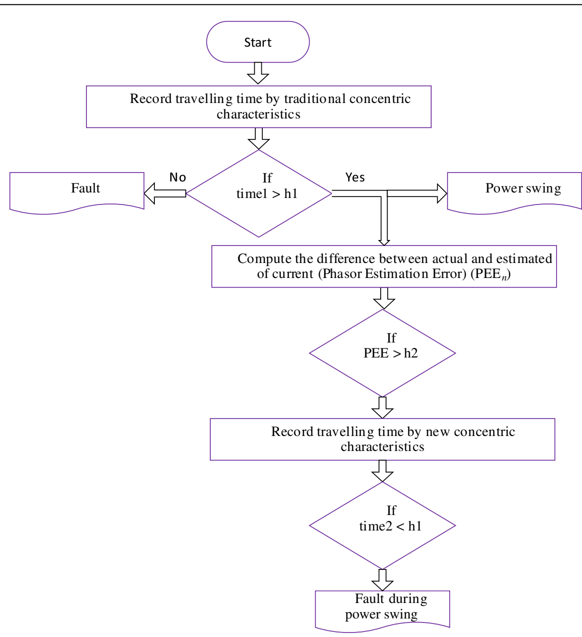


**Fig. 7** Flowchart of proposed method

Next a three-phase fault occurs at $t = 0.85\,s$ during power swing. This causes the impedance trajectory crosses CPSB again during fault and so a new travelling time is recorded by timer, which can be used for detecting fault individually. Hence, traditional CPSB can detect both power swing and fault during power swing in this case.

*Case3:* A third test is simulated to show the condition in which traditional CPSB cannot detect a three-phase fault during power swing. Impedance trajectory of this case is shown in Fig. 5. Power swing is programmed similar to the two previous cases. According to Fig. 5, as a result of power swing, impedance trajectory crosses CPSB for the first time and the travelling time is recorded by timer, which can be used for detecting power swing. However, a fault occurs at $t = 0.55\,s,$ when the impedance trajectory is inside the inner zone of CPSB. According to Fig. 5, impedance trajectory does not cross the traditional CPSB again during fault. This condition shows inability of traditional CPSB in three-phase fault detection during power swing.

Although, distance relay can easily detect unsymmetrical faults with various faulted loops by

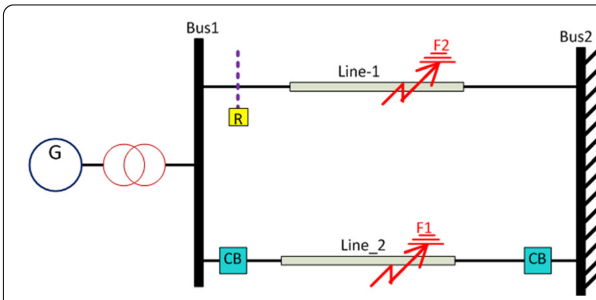


**Fig. 8** SMIB power system with two parallel transmission lines

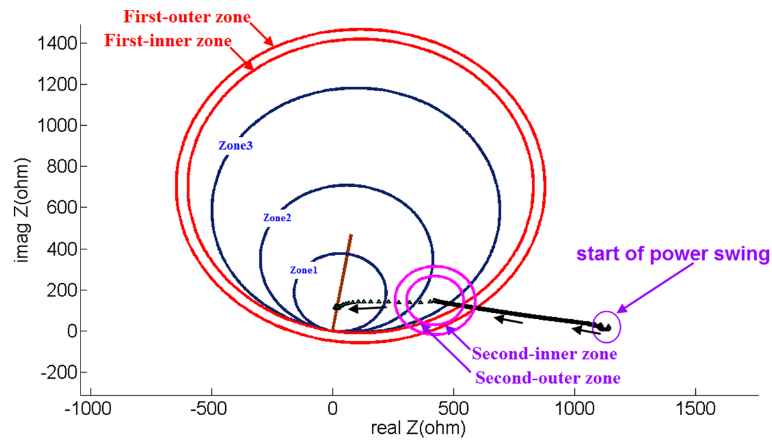


**Fig. 9** Impedance trajectory for power swing at =1 sec and three-phase fault at t = 1.9 sec at 25% line during stable power swing in SMIB

assessing the negative sequence of current signal, it is faced by challenge in symmetrical faults during power swing because of inconsiderable amount of negative sequence during three-phase fault.

## Methods

### Proposed adaptive concentric psb

According to motioned simulations and explanations, traditional concentric PSB has limitation for detecting symmetrical fault during power swing and cannot detect it in special condition. When a symmetrical fault occurs, while impedance trajectory of power swing is inside of inner zone of CPSB, this kind of CPSB cannot detect fault because there is no second cross through zones of the CPSB during fault period.

In order to solve this problem, adaptive CPSB is proposed in this paper. According to proposed method, second pair of CPSB is programmed, which its location is adapted by PEE, for detecting symmetrical fault during power swing. This idea is shown in Fig. 6. According to this figure, proposed method provides two independent pairs of CPSB for power swing and symmetrical fault during power swing. Therefore, recorded time by second PSB is used for detecting fault during power swing.

Another key point of this proposed method is detection of the location of impedances trajectory (the place in complex plane) for placing the second CPSB. In order to achieve this goal, phasor estimation error (PEE) is employed in this paper. By monitoring PEE during power swing, abrupt change of PEE can be used as primary indicator of symmetrical fault initiation and then the second CPSB is set at corresponding impedance in complex plane.

Hence, the proposed method in this paper includes two steps. In the first step, first CPSB is placed farther zone3 to discriminate power swing from fault. Recorded time by this CPSB is compared to predefined threshold

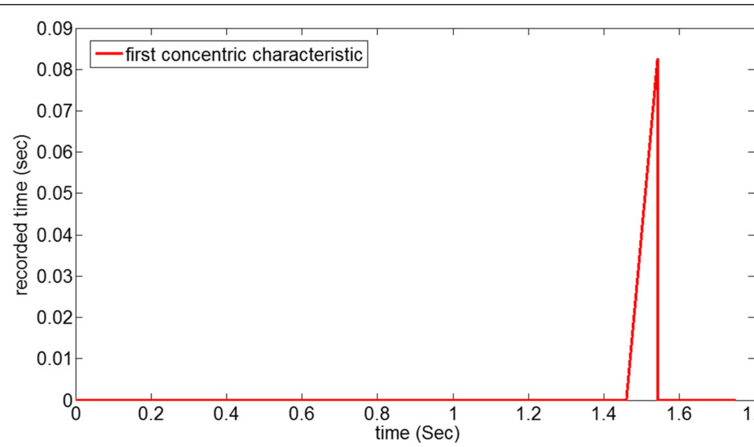


**Fig. 10** Recorded time by first concentric characteristic

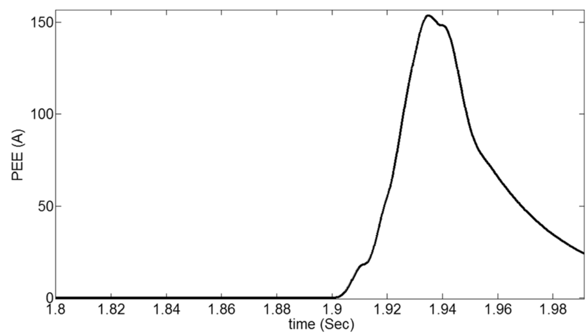

**Fig. 11** Analyzing PEE during power swing in SMIB power system

(h1) so that it is detected as power swing if it is higher than threshold otherwise it is detected as fault. The second step of proposed method is employed when power swing is detected by first step. In the second step, PEE is calculated during power swing continuously and analyzed (compare to predefined threshold (h2)) to anticipate three-phase fault during power swing. In order to verify this anticipation, the second CPSB is placed where impedance trajectory presents at this time. Recorded time by the second CPSB is compared to the predefined threshold (h1) so that it is detected as symmetrical fault during power swing if it is lower than threshold value. Therefore combination of these two pairs of CPSB provides a complete method which can detect power swing and three-phase fault during power swing in different situations. Flowchart of the proposed method is shown in Fig. 7.

## Results

Simulation part of this paper is divided into three parts. In the first part, the proposed method for detecting three-phase fault during power swing is examined in single machine to infinite bus (SMIB) and in the second part; the performance of the proposed method in three-machine power system is verified and in the last section, the performance of the proposed method is examined in IEE 39-Bus power system.

### Simulation results of the proposed method in single machine to infinite bus (SMIB)

In order to validate performance of the proposed method (shown in flowchart (Fig. 7)) in discriminating three-phase fault from power swing, power system shown in Fig. 8 is considered, which its data are presented in [8]. A distance relay is considered at bus 1 in the upper line (line with impedance 76.8 + 469.98i). A three phase fault (F1) is simulated at the middle of lower line which occurs at t = 1 s and is cleared after 0.03 s by opening the breakers at both ends (CB1, CB2). This event causes a stable power swing in the line between buses 1 and 2 and is observed by the relay R. Therefore, distance relay should be blocked by power swing blocker during power swing. Moreover, A three-phase fault (F2) initiates at t = 1.9 s (at 25% protected line) during power swing which should be detected by power swing blocker and then distance relay should be unblocked.

Impedance trajectory of this condition is shown in Fig. 9. According to this figure, the stable power swing causes the impedance trajectory enters into protected zone 3, which could lead to malfunction of the distance relay. In order to prevent this malfunction, first pair of CPSB is designed farther zone3 to detect power swing. Travelling time between first-outer and first-inner zone is shown in Fig. 10. According to this figure, impedance

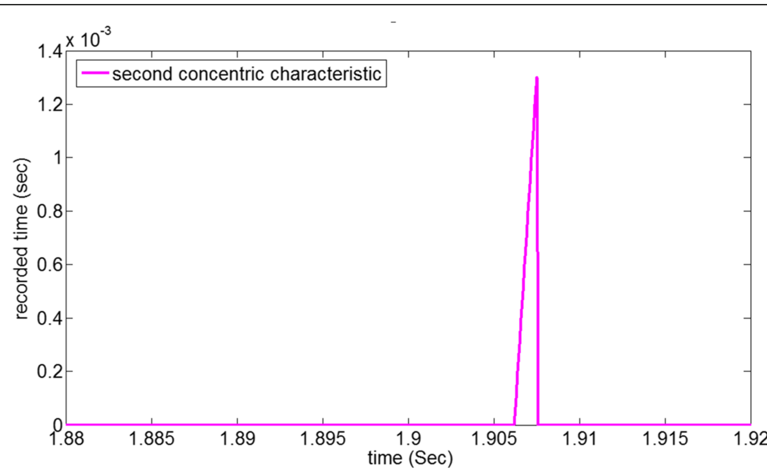

**Fig. 12** Recorded time by second concentric characteristic in SMIB

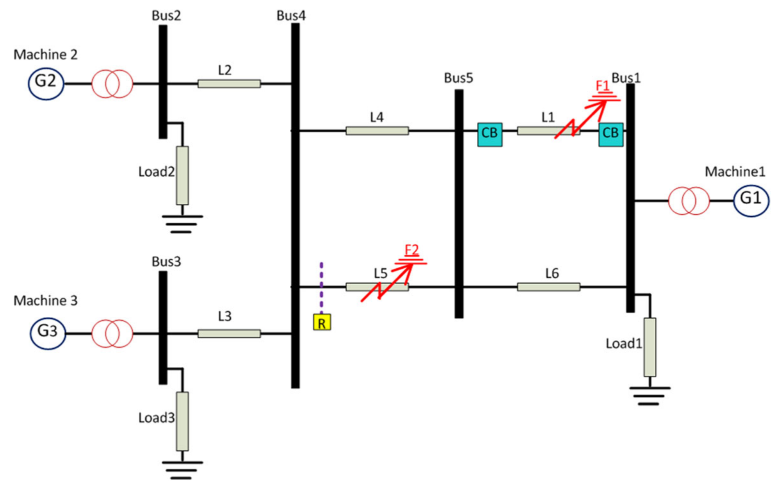


**Fig. 13** Three-machine power system

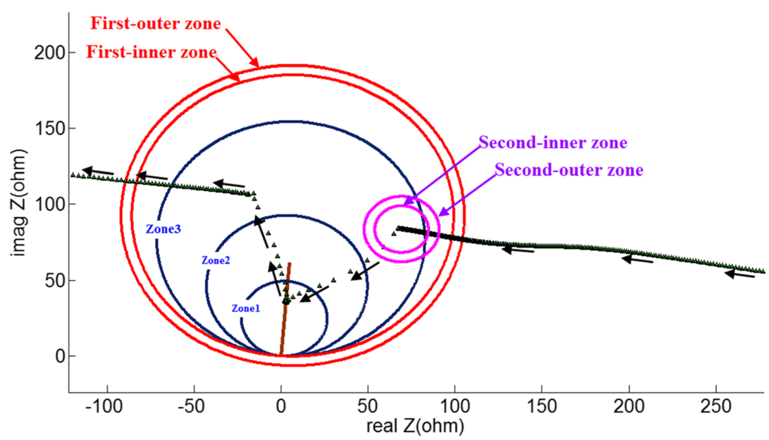


**Fig. 14** Impedance trajectory for power swing at =1 sec and three-phase fault at t = 1.9 sec at 25% line during stable power swing in Three-machine power system

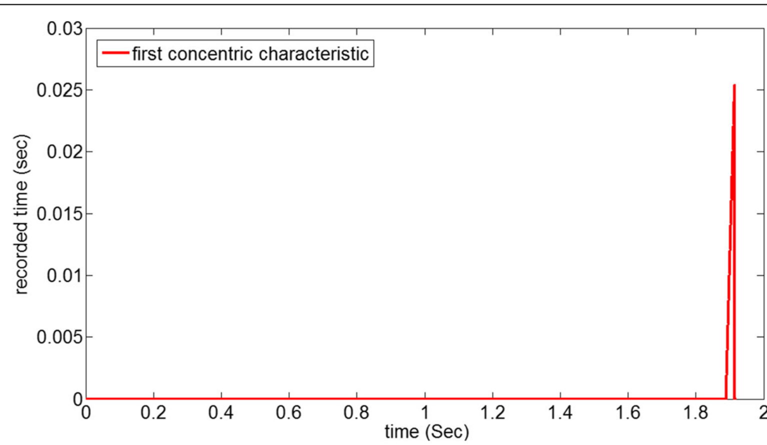


**Fig. 15** Recorded time by first concentric characteristic

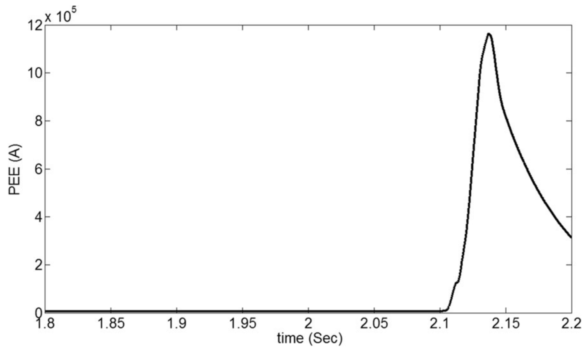


**Fig. 16** Analyzing PEE during power swing in Three-machine power system

trajectory enters first-outer zone at t = 1.465 s and enters first-inner zone at t = 1.54 s that results in 0.085 s recorded time by first CPSB. By comparing recorded time with threshold value (0.01 sec), power swing can be detected.

Based on the proposed method, PEE of current signal is monitored continuously during power swing. PEE of the current signal is shown in Fig. 11. According to this figure, a new transient happens at t = 1.9 s which is anticipated to be three-phase fault. In order to verify this anticipation, the second CPSB is designed (as shown in Fig. 9) and recorded time by this CPSB is shown in Fig. 12. According to this figure, impedance trajectory enters outer zone at *t* = *1.906 s* and enters second-inner zone at *t* = *1.907 s* which result in recorded time close to *0.0013se*. By comparing recorded time with threshold value (0.01 sec), it can be detected that this is symmetrical fault during power swing.

### Simulation results of three-machine power system

In order to examine the proposed method in larger power system, the three-machine power system shown in Fig. 13 is considered [18]. A three-phase fault is simulated at 90% of the line connecting buses 5 and 1. The fault (F1) occurs at *t* = *1 s* and is cleared after *0.25 s*. This event causes an unstable power swing that is observed by the distance relay. Moreover, another three-phase fault (F2) initiates at *t* = *2.1 s* (during unstable power swing) in 57% protected line.

Impedance trajectory of this condition is shown in Fig. 14. According to this figure, the unstable power swing causes the impedance trajectory enters into protected zone 3. First CPSB is designed farther zone3 at the first step of proposed method and the process of recording time by CPSB (between first-outer and first-inner zones) is shown in Fig. 15. According to this figure, impedance trajectory needs *0.026 s* for travelling between first-outer and first-inner zones. By comparing the recorded time with threshold value (0.005 sec), it can be understand that this is power swing.

PEE of current signal is monitored during unstable power swing detection. PEE of current signal is shown in Fig. 16. According to this figure, a new transient happens at *t* = *2.1 s* which is anticipated to be a three-phase fault. In order to verify this anticipation, the second CPSB is designed (as shown in Fig. 14) and recorded time by this CPSB is shown in Fig. 17. According to this figure, impedance trajectory needs 0.0008 sec for travelling between two zones of second CPSB. By comparing recorded time with threshold value (0.005 sec), it can be understudied that this is symmetrical fault during power swing.

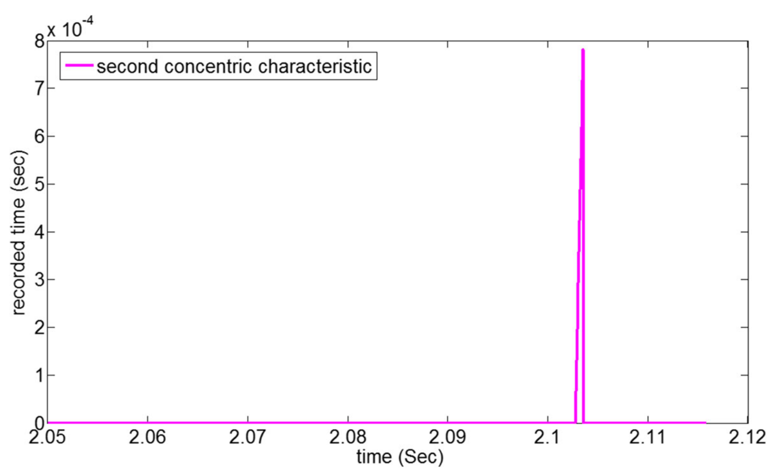


**Fig. 17** Recorded time by second concentric characteristic in Three-machine power system

### Simulation results of IEEE 39-Bus power system

IEEE 39-Bus power system is examined as a large test system (Fig. 18) in this paper. A three-phase fault (F1) is simulated at 50% of the line connecting buses 10 and 13. The fault occurs at t = 1 s and is cleared after 0.2 s. This event causes an unstable power swing and is observed by the distance relay (R). In order to examine the performance of the proposed CPSB, another three-phase fault (F2) is simulated at 100% of the protected line (line connecting buses 4 and 14) during unstable power swing. The impedance locus for this condition is shown in Fig. 19. According to this figure, at the first the impedance starts to move at t = 1.2 s and enters into the protective relay's characteristics of distance relay due to the power swing. In this condition, the distance relay is blocked by the first CPSB; meanwhile, another three-phase fault (F2) occurs at t = 1.9 s. So the impedance leaves the power swing locus immediately and reaches to the fault impedance point. As is shown in Fig. 19, since the three-phase fault occurs after the impedance trajectory leaves the first CPSB characteristics (special condition); the first CPSB is not capable of detecting the fault.

According to Fig. 19 and proposed strategy, first CPSB characteristics are designed farther zone3 for a distance relay to discriminate fault from power swing. Travelling time between first-outer and first-

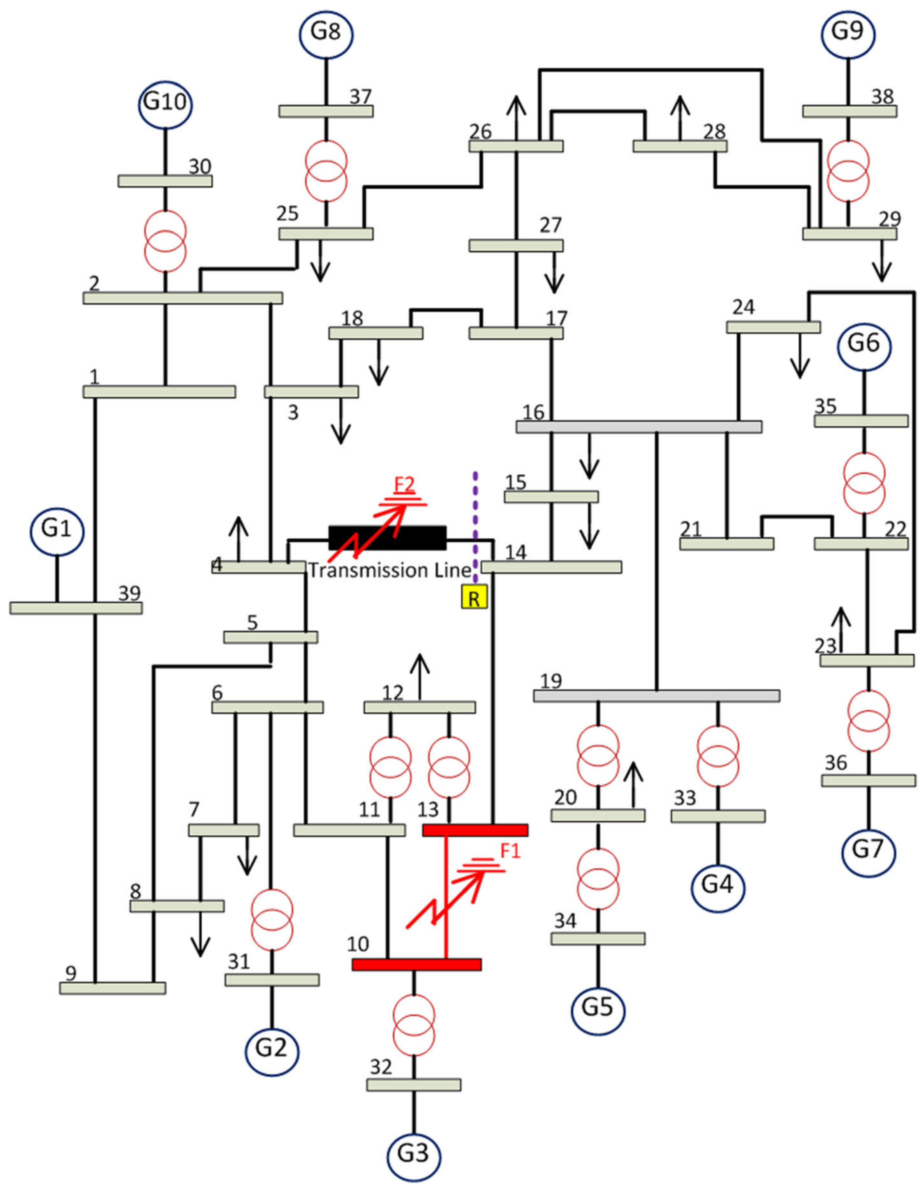


**Fig. 18** IEEE 39-Bus power system

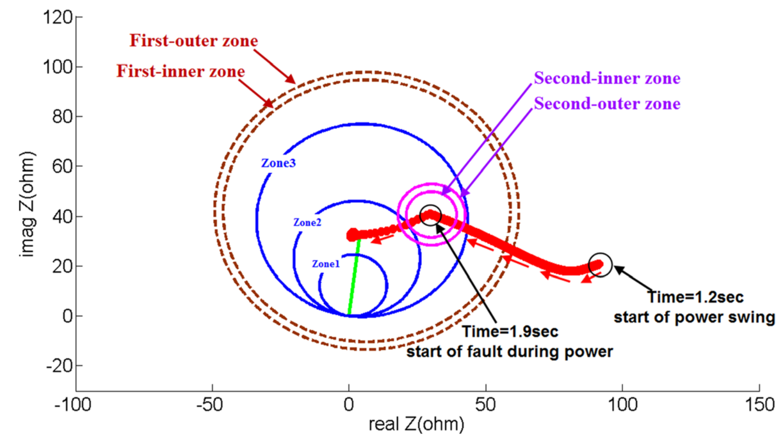


**Fig. 19** Impedance locus of three-phase fault during power swing in IEEE 39-Bus

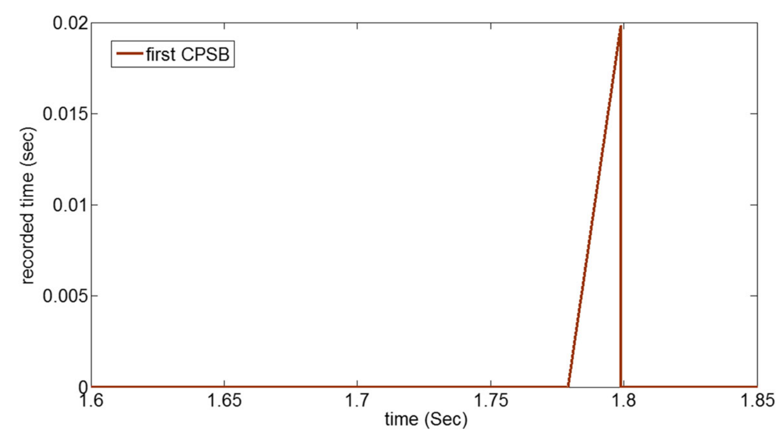


**Fig. 20** Recorded time by first CPSB in IEEE 39-Bus

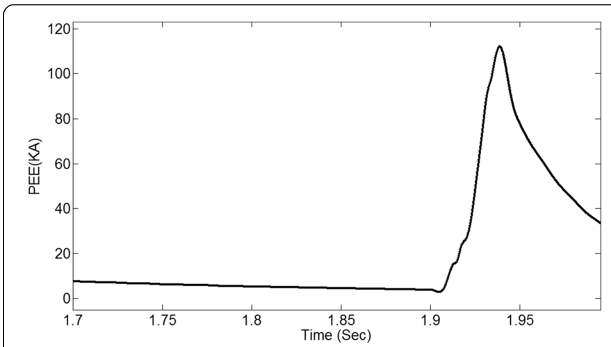


**Fig. 21** PEE during power swing in IEEE 39-Bus

inner zone is shown in Fig. 20. According to this figure, impedance trajectory enters outer zone at t = 1.78 s and enters inner zone at t = 1.8 s which result in 0.02 s recorded time by first CPSB. By comparing recorded time with threshold value (0.005 sec), it can be understand that this is power swing. Based on proposed strategy, PEE of current signal is monitored during time after power swing detection. PEE of current signal is shown in Fig. 21. According to this figure, a new transient starts at t = 1.9 s which is anticipated to be a three-phase fault. In order to verify this anticipation, second CPSB is designed (as shown in Fig. 19) and recorded time by this CPSB is shown in Fig. 22. According to this figure, impedance trajectory enters second-outer zone at t = 1.907 s and enters second-inner zone at t = 1.908 s which result in 0.001 s

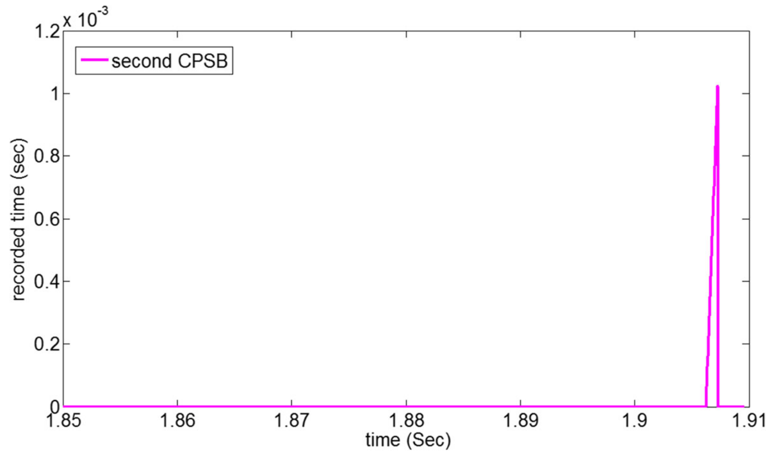


**Fig. 22** Recorded time by second CPSB in IEEE 39-Bus

recorded time by second CPSB. By comparing recorded time with threshold value (0.005 sec), it can be understudied that this is symmetrical fault during power swing.

## Conclusion

Measured apparent impedance by a distance relay moves into relay operating zones during power swing as a consequence of disturbance in power system that causes malfunction of distance relay. Traditional CPSB is designed inside of distance relay to prevent this malfunction by blocking distance relay during power swing. However, if a fault occurs during power swing, it should be detected and distance relay is blocked. Traditional CPSB is a common method for detecting power swing. However, it has limitation in detecting symmetrical fault during power swing. Therefore, adjustable concept of this method is proposed in this paper to overcome this difficulty. According to the proposed method, two pairs of CPSB are employed; the first CPSB is used for discriminating fault from power swing and the second CPSB is used for detecting symmetrical fault during power swing. According to results, the proposed method demonstrates its ability to unblock distance relay in three-phase fault during power swing.

### Authors' contributions

JK, Ph.D. student, brings up the idea of adaptive procedure, performed the primary simulations and drafted the manuscript. MK, JK Ph.D. supervisor, participated in enriching the manuscript (in theoretical idea and simulation section (IEEE 39-Bus power system)) and carried out the revising the manuscript (response to the reviewers and editing grammatical and lexical mistakes). Both authors read and approved the final manuscript.

### Competing interests

The authors declare that they have no competing interests.

Received: 26 May 2016 Accepted: 15 November 2016
Published online: 01 December 2016

### References


1. Kundu, P., & Pradhan, K. (2014). "Synchrophasor-assisted zone 3 operation". *IEEE Trans Power Del, 29*(2), 660–667.
2. Nayak, P., Pradhan, K., & Bajpai, P. (2015). "Secured zone 3 protection during stressed condition". *IEEE Trans Power Del, 30*(1), 89–96.
3. Horowitz, S., & Phadke, A. (2006). "Third zone revisited". *IEEE Trans Power Del, 21*(1), 23–29.
4. IEEE PSRC WG D6. (2005). "Power swing and out of step considerations on transmission lines", *A report to power system relaying committee of the IEEE power engineering society*. IEEE PES (Power and Energy Society).
5. Mechraoui, A., & Thomas, D. W. P. (1995). *"A New Blocking Principle with Phase and Earth Fault Detection during Fast Power Swings for Distance Protection", IEEE Transactions on Power Delivery, 10(3).*
6. Mechraoui, A., & Thomas, D. W. P. (1997). *"A New Principle for High Resistance Earth Fault Detection during Fast Power Swings for Distance Protection", IEEE Transactions on Power Delivery, 12(4).*
7. Ganeswara, J., & Pradhan, A. (2012). "Differential power based symmetrical fault detection during power swing". *IEEE Trans Power Del, 27*(3), 1557–11564.
8. Brahma, S. (2007). "Distance relay with out of step blocking function using wavelet transform". *IEEE Trans Power Del, 22*(3), 1360–1366.
9. Mohamad, N., Abidin, A., & Musirin, I. (2014). "Intelligent power swing detection scheme to prevent false relay tripping using S_Transform". *International Journal of Emerging Electrical Power systems, 15*(3), 195–311.
10. Zade, H., & Li, Z. (2008). "A novel power swing blocking scheme using adaptive neuro-fuzzy inference system". *Electr Power Syst Res, 78*(7), 1138–1146.
11. Gautam, S., & Brahma, S. (2012). "Out-of-step blocking function in distance relay using mathematical morphology". *IET Generation, Transmission & Distribution, 6*(4), 313–319.
12. Rao, J., & Pradhan, K. (2015). "Power swing detection using moving averaging of current signals". *IEEE Trans Power Del, 30*(1), 368–376.
13. Lin, X., Gao, Y., & Liu, P. (2008). "A novel scheme to identify symmetrical fault occurring during power swings". *IEEE Trans Power Del, 21*(1), 73–78.
14. Andanapalli, K., & Varma, B.R.K. (2014). *"Parks transformation based symmetrical fault detection during power swing"*,(pp. 1-5). Guwahati: Power Systems Conference (NPSC) Eighteenth National.
15. Mahamedi, B., & Zhu, J. (2012). "A novel approach to detect symmetrical faults occurring during power swings by using frequency components of instantaneous three phase active power". *IEEE Trans Power Del, 27*(3), 1368–1376.
16. Nayak, P., & Bajpai, P. (2013). "A fault detection technique for the series-compensated line during power swing". *IEEE Trans Power Del, 28*(2), 714–722.
17. Khodapaast, J., & Khederzadeh, M. (2015). "Three-Phase Fault Detection During Power Swing by Transient Monitor". *IEEE Transactions on power system, 30*(5), 2558–2565.
18. Moravej, Z., Pazoki, M., & Khederzadeh, M. (2014). "Impact of UPFC on Power Swing Characteristic and Distance Relay Behavior". *Power Delivery IEEE Transactions on, 29*, 261–268.