Out-of-Step Detection based on Phasor Measurement Unit

ZAID S. AL-SHAMAAIN[1], HUSSEIN. D. AL-MAJALI[1], BILAL. H. AL-MAJALI[2]
[1]Department of Electrical Engineering, Faculty of Engineering
Mu'tah University,
Al-Karak,
JORDAN

[2]Electronic and Electrical Engineering, Faculty of Engineering
Brunel University London,
Uxbridge,
UNITED KINGDOM

Abstract: - The electrical power systems operate as a huge, interconnected network that extends across a large area. In the power system, there is an equilibrium between generated power and a load. Any disturbance in the system, such as a fault or a change in load, will lead to imbalance and electromechanical oscillations. As a result, the power flow between two areas varies. This is known as a power swing." Large system disturbances could lead to large rotor angle deviations between groups of generators, resulting in a loss of synchronism between generators or between interconnected systems. This is known as an out-of-step condition. To avoid equipment damage and power outages, the interconnected area must be isolated as soon as possible before the electrical system loses synchronization. In this paper, PMU data is used to measure the current, voltage, and phase angle of the three phases at both ends of two interconnected area power systems. The measured data is then used to distinguish between a power swing or fault condition and predict the future phase angle difference during the disturbances to evaluate the system stability condition. If a swing is detected, then it will be ascertained whether the swing is stable or not. The performance of the proposed method has been tested on a simulated system using MATLAB / Simulink software.

Key-Words: - Phasor Measurement Unit, Current Detection Element, Phase Angle Difference, Phasor Current Difference, Out of step trip, Stability system.

Received: November 25, 2022. Revised: November 26, 2023. Accepted: December 12, 2023. Published: December 31, 2023.

1 Introduction

Typically, power systems operate near or at their nominal frequency. Under steady-state operation, there is a balance between generated and consumed active and reactive powers. However, electromechanical oscillation will occur when the system recovers from disturbances caused by faults, line switching, generator disconnections, or a change in a large load. During this time, the rotor angle varies. If the swing is stable, the fluctuations will decrease. During severe disturbances, however, the oscillations do not remain stable, resulting in even more angle separation between the areas. This results in large swings in power flow as well as changes in voltages and currents. Eventually, there is a loss of synchronization, often known as an out-of-step condition, [1].

During power swing, the load impedance may cross the operating zone of the relay, causing unwanted tripping of transmission lines and cascading outages and power blackouts, [2], [3]. In the case of a power swing, the Power Swing Block (PSB) acts to block distance relay element operation, allowing the power system to return to a stable operating condition, [4], [5]. The PSB's primary function is to distinguish between fault and power swing.

Out of step trip (OST) distinguishes between stable and unstable power swings and initiates system area separation at predetermined network nodes. When an interconnected area system loses synchronization, the areas must be separated at predetermined places to maintain load generation balance, avoid equipment damage, and power outages. To maintain the stability of the power system, [6], [7], [8].

A difference in the rate of change of the positive sequence impedance vector has traditionally been applied to the PSB and OST to detect power swings and out-of-step conditions. The operation of distance relays starts before the impedance enters the operating zone of the protective relay. The traditional method for detecting power swing is to measure the rate of change of impedance and the time it takes for the impedance vector to pass through a particular zone. When the impedance vector enters the zone, a timer starts and stops when it leaves. If the time taken for measurement exceeds the preset value, a power swing is detected.

A current differential protection technique that can detect faults in a transmission line by comparing the instantaneous current data collected from PMU at both ends of the line has been provided in, [9], [10], [11]. It works effectively when intercircuit and cross-country faults are evolving. It also works for faults that occur during power swings.

The load angle measurements of synchronous generators can be utilized to detect an out-of-step condition, [12]. The suggested method measures the phase difference of the positive sequence voltages using an estimation algorithm, [13] and PMU data, [14], [15], at both ends. When the estimated phase angle value exceeds a threshold value, the power swing is assumed to be unstable, and the system loses synchronism.

To detect a power swing as well as current fault with high accuracy and evaluate the system performance, in this paper an out of step detection method is proposed simultaneously using positive phase angle difference and positive sequence current from the PMU measurements placed at both end of the interconnected area.

This paper is organized in five sections: section 1 presents a brief overview of power swing phenomena and distance relay element operation; section 2 presents conventional power swing detection methods; and section 3 presents the proposed detection method, the proposed detection algorithms, and their performance. The simulation results and discussion are presented in Section 4, and finally, the conclusion is organized in Section 5.

2 Conventional Power Swing Detection Methods

There are several methods that are proposed to detect out-of-step condition in a power system based on local-measurements. These methods are briefly summarized next.

2.1 Conventional Rate of Change of Impedance

During normal system operation, the measured impedance is the load impedance, and its locus is far from the relay operating zone, [16]. When a fault occurs, the impedance point moves instantaneously into the relay operating zone; however, during a power swing, the impedance point moves slowly on the impedance plane. The elapsed time required by the impedance vector to pass through a zone is limited by two additional concentric impedance characteristics that are used to calculate the rate of change of impedance. The inner concentric zone setting should be larger than the largest tripping characteristic, [17], [18], [19].

Power swing can be detected before the impedance locus enters the operational characteristic, which is advantageous. The important parameters in this method are the delta impedance and the timer. To find the optimal settings, extensive stability studies are required. The drawback is that the maximum load of the transmission line is limited by the outer zone. This is referred to as load encroachment.

2.2 Continuous Impedance Calculation

The power swing is determined using a continuous impedance calculation in this method. For instance, an impedance calculation is performed for each 4ms time step and compared to the previous step's impedance. If there is a deviation, the system is considered to be out of synchronization. The next step's impedance is predicted based on the previous two values. If the prediction is correct, a ten-power swing is detected. This technique doesn't require the use of delta time or delta impedance settings. The detection might fail if the changing impedance vector is faster than the relay processing speed, [16].

2.3 Blinder Schemes

A. Single blinder scheme

A single blinder method uses only one set of blinder characteristics. It can also be utilized with auxiliary logic for out-of-step trip functions. However, it can't differentiate between a fault and an OOS condition until the fault has passed through the second blinder within the given time limit. When an unstable power swing is detected, this approach can be utilized to prevent automatic reclosing. The primary advantage of this method is that it may be used to prevent load encroachment, [20].

B. Dual blinder scheme

The two-blinder scheme and the concentric characteristics scheme both operate on the same basis. When the impedance vector passes through the outer blinder, the timer starts and stops when it passes through the inner blinder. If the measured time exceeds the delta time settings, a power swing is detected. All elements of distance will be blocked. If an unstable power swing is detected, the mho element may trip immediately or after the swing has passed through, [21], [22]. The advantage of this technique is that the distance protection settings have no effect on the power swing detection settings. However, determining the optimal settings requires extensive stability studies.

2.4 R-Rdot Scheme

The R-dot scheme is the apparent resistance rate of change that is supplemented by the OST relay. The control output of an R-dot relay is described as Y2 = (R2-R1) + T1 dR/dT, where Y2 is the control output and R is the apparent resistance measured by the relay. R1 and T1 are relay setting parameters. When the power swing trajectory crosses a switching line, an output in the R-dot plane is generated. For traditional OST relays, the apparent resistance rate is enhanced by a vertical line in the R-dot plane offset by R1, which is the relay setting parameter. System separation occurs when output Y2 becomes negative. For small dR/dT and low separation rates, the R-dot method operates similarly to a conventional relay scheme. However, for large dR/dT, a larger negative value of Y2 is produced, causing tripping to occur earlier due to the high separation rates. The technique has the same problems as the blinder scheme in that it requires extensive simulation studies under various contingency conditions to set the relay characteristics. However, determining optimal settings requires extensive stability analysis, [23].

2.5 Swing Center Voltage Method

The swing center voltage (SCV) technique is a voltage-based method discussed in, [24]. When the angular separation between two source-equivalent systems approaches 180 degrees, the SCV is a point of zero voltage between them. The electrical center is the location of zero voltage.

The SCV approach calculates the maximum rate of change of voltage at the electrical center. Detection is normally accomplished at a voltage angle separation of close to 180 degrees. When tripping occurs under these conditions, the circuit breaker is subjected to twice the rated stress. As a result, the operation of the circuit breaker is delayed until the voltage angle separation is less. Furthermore, estimating the SCV using local measurements of the voltage phasor is only valid when the impedance angle is 90 degrees.

3 The Proposed Detection Method

The Kundur two area system, which consists of two areas connected by two weak tie lines, is the most suitable test system for the study of out-of-step condition. The tie line serves as the system's electrical center. If a fault happens on one of the tie-lines, the power swing will be created with swing center on the second tie-line.

The test system consists of four generators divided into two symmetrical areas linked by two tie lines. Area 1 has a load of 967MW and a generation capacity of 1400MW. The load in Area 2 is 1767MW, and the generation is 1463MW. Each tie line transfer approximately 200MW.

The relay is implemented at bus 1. Phasor Measurement Units (PMU) are placed on buses 1 and 2. The line is tripped after a fault occurs on Tie line -2. As a result, there is a power imbalance in the other Tie line, causing power swing, During the swing, another fault occurs in the line and is detected by the current differential method. PMUs placed at the buses calculate the voltage and current of the three-phase line at a sampling rate of 64 samples per cycle. The PMU data is then used to measure the positive sequence voltage and current phasors using the Discrete Fourier Transform.

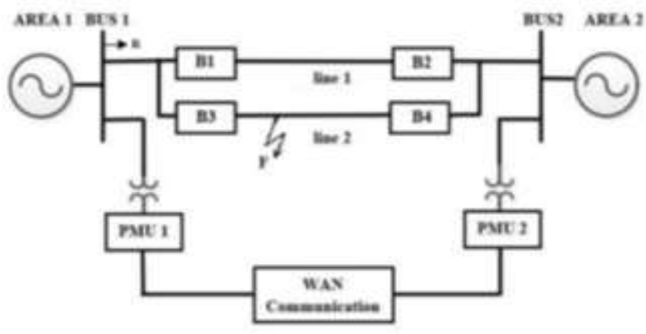

Fig. 1: Block diagram of simulated system

3.1 Out-of-step Detection Method

A. Phase difference calculation

The phase difference between the two area (Area1 and area 2) are obtained by calculating the phase difference between the positive sequence voltage data of the two ends from PMUs.

B. Calculation of predicted values of phase difference

The prediction is obtained by using the phase difference values for present time and previous time, the future value can be predicted by the equations below.

$$\delta_p = \delta_\alpha + \lambda\, d_\alpha + \mu\, d_{\alpha-1} \quad (1)$$

Where,

$$\begin{aligned} d_\alpha &= \delta_\alpha - \delta_{\alpha-1} \\ d_{\alpha-1} &= \delta_{\alpha-1} - \delta_{\alpha-2} \\ d_{\alpha-2} &= \delta_{\alpha-2} - \delta_{\alpha-3} \end{aligned} \quad (2)$$

$$\begin{aligned} d_\beta &= \delta_\beta - \delta_{\beta-1} \\ d_{\beta-1} &= \delta_{\beta-1} - \delta_{\beta-2} \\ d_{\beta-2} &= \delta_{\beta-2} - \delta_{\beta-3} \end{aligned} \quad (3)$$

$$\lambda = \frac{d_\alpha\, d_{\beta-2} - d_\beta d_{\alpha-2}}{d_{\alpha-1} d_{\beta-2} - d_{\beta-1} d_{\alpha-2}} \quad (4)$$

$$\mu = \frac{d_{\alpha-1}\, d_\beta - d_{\beta-1} d_\alpha}{d_{\alpha-1} d_{\beta-2} - d_{\beta-1} d_{\alpha-2}} \quad (5)$$

δp: predicted relative phase angle
δα, δβ: phase angles

The phase difference δp is predicted for time TD using 8 data points as shown in Figure 2. These are the phase difference at the present time δα and three values (δα-1, δα-2, and δα-3) at negative increments of time TD. Also, the phase difference value δβ at the time TM before the current time and three values (δβ-1, δβ-2, δβ-3) in the negative increment TD at that time. Where TM is the time difference that takes a sample point between δα and δβ (in our case TM= 10ms and TD= 20ms), TD is the time difference between each pair of sample points.

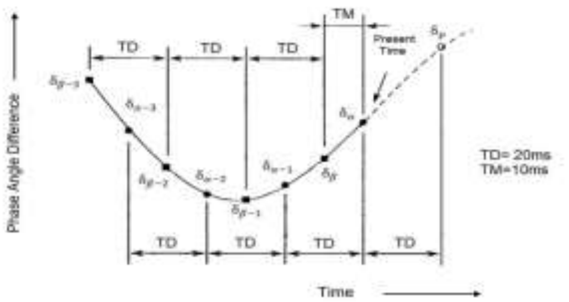

Fig. 2: Method of predicting phase angle

When the predicted phase angle difference value δp obtained by Eq.1 exceeds a critical threshold value, then it's judged that the power swing between the two generator groups will lose synchronism. The value δ_critical is predetermined by the system configuration. The value chosen must be such that it does not operate during a stable swing. The predicted and measured values are shown in Figure 3. When the predicted phase angle difference value exceeds a minimum threshold value, the power swing is assumed to be unstable, and the system will lose synchronism, [25]. The value of is determined by the system conditions and is carefully chosen so that the system does not malfunction during a stable swing. Many research used new techniques to convert DC to AC in order to link with grid, [26], [27] and other research used to convert AC to DC were used HVDC system, [28], [29], [30].

A current swing detection element, in addition to the phase angle difference limit, should be operated to confirm that the system will lose synchronism in the near future. Figure 3 shows a swinging condition with both actual and predicted phase differences. The predicted value is 20ms earlier than the actual value.

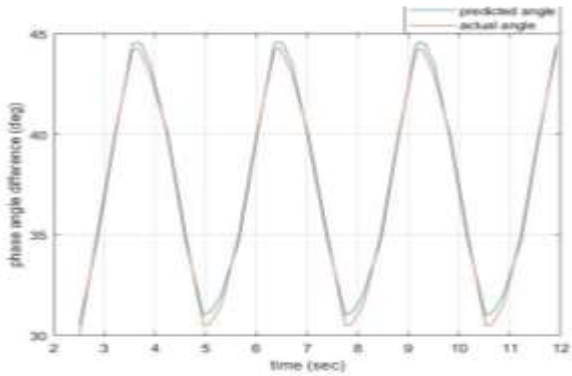

Fig. 3: Predicted and measured phase difference

In Figure 3, which illustrates the predicted and measured phase angle difference values that are almost closed to each other during the test of the method's performance, that means the accuracy is very high when applying the proposed prediction method.

C. Current swing detection element

This element serves as a second check criterion to determine the detected out of step from the predicted phase difference value. By using a current input to detect oscillation, it operates when the swing is unstable and off when it is stable. Figure 4 shows the logical diagram of the current swing

DOI: 10.37394/232016.2023.18.36

detection element, Table 1 shows the logical operation of current swing detection element during power swing.

The current swing detection element consists of two detection blocks: a magnitude of change detection block to measure the size of the current fluctuation and a rate of change detection block to ascertain whether a power swing is present. The element works with AND of these two blocks.

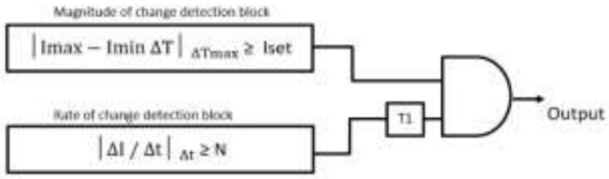

Fig. 4: Current swing detection element

Table. 1. logic operation of current swing detection element, 1: operate, 0: not operate

Power Swing Type	Output
Stable	0
un-stable	1

The Imax and Imin are the maximum and minimum values of the positive sequence current during the predetermined time period ΔT max. The magnitude of change detection block is operated if Iset is greater than a predetermined value, Iset and ΔT max are determined by simulation. ΔI / Δt represents the rate of change of the current value over the small-time interval Δt. The rate of change detection block acts when ΔI / Δt is greater than a constant N and continues for a longer period of time than time T1. If both elements are operated, the current swing detection element gives a positive output, that means unstable power swing was detected. ΔTmax=2 sec, Δt=5ms and T1=20ms.

3.2 Fault Detection Method

The main criterion for fault detection and load conditions is the difference in positive sequence current phasor at both ends. A threshold value is determined by carefully comparing the steady-state and power-swing condition. If the difference exceeds a certain threshold, the algorithm detects a fault.

3.3 Flow Chart of the Proposed Detection Method

A proposed detection method for out-of-step conditions based on the phase angle difference of the positive sequence voltage and phasor current difference of the positive sequence current from PMU measurements is illustrated in the flowcharts, which are shown in Figure 5 and Figure 6 respectively.

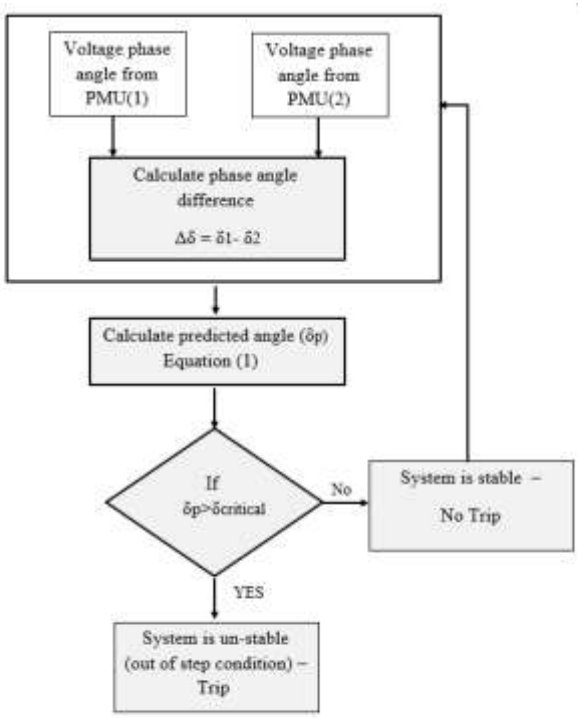

Fig. 5: Flow chart for the proposed out-of-step detection method based on phase angle difference

The voltage phase angle from both PMUs at both ends works as an input for the proposed flow chart that is shown in Figure 5 After the phase difference is calculated, the predicted phase angle difference is obtained from equation (1), then the predicted angle δp is compared with δ_critical to determine the swing type, whether stable or not, to provide a decision for out of step relays.

The phasor current magnitude from both PMUs at both ends works as an input for the proposed flow chart shown in Figure 6 after the phasor current difference and current rate of change are calculated at a predetermined time. The obtained values are compared with the setting current and constant factor N, then the swing type will be classified as stable or not to provide a decision for out-of-step relays, which works as a second check criteria with the phase angle prediction algorithm that was discussed before.

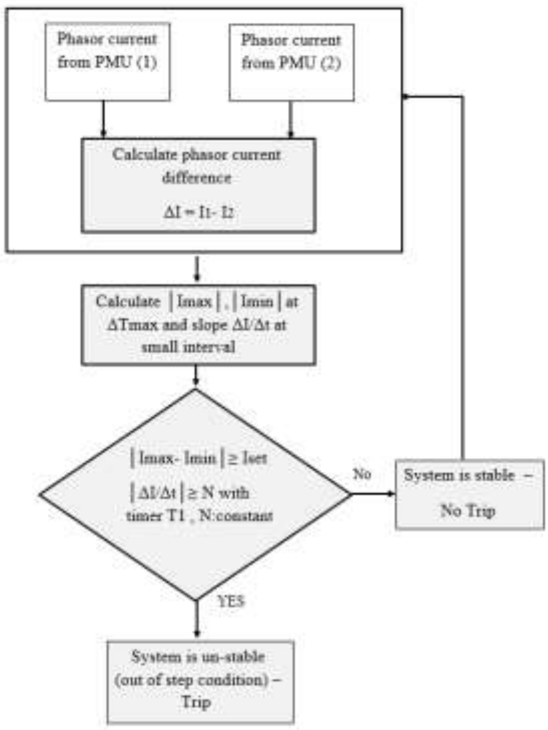

Fig. 6: Flow chart for the proposed out-of-step detection method based on phasor current difference

4 Results and Discussion

The performance of the proposed detection scheme has been tested on the system given in Figure 1. A three-phase fault is a worst case that has been created in the system in the case of a transient fault, which has been created here at about 0.5s and cleared at 1s and $\delta\_critical$ = 100°, Iset value= 3.4kA. The predicted angle, actual angle, prediction accuracy, and current swing element operation are calculated at different sizes of fault (fault resistance and ground resistance), and the phase angle predicted value is very close to the actual value with very high accuracy (around 99.9%) at stable or unstable conditions, which is also compatible with the current swing element operation.

Table 2 shows the simulation results of predicted phase angle difference with actual phase angle difference in degree and the prediction accuracy at different sizes of faults.

When the predicted angle is greater than the critical angle (in this case, $\delta\_critical$=100 °) and the output of the current swing operation element is positive (mean=1), then it judges whether the system will lose synchronism or an unstable condition will occur. On the other hand, if the predicted angle is less than the critical angle and the output of the current swing operation element is negative (mean =0), then it judges the system to be stable.

The fault detection technique detects a fault when the difference in current phasors at both ends exceeds the threshold value (in this case, 3.4 kA). This technique can detect current fault magnitude and current difference rate of change in both steady-state and power-swing conditions; mutual coupling and series impedance imbalances have no effect on its performance. The fault is detected as a current fluctuation (current rate of change A/ms), and a current difference starts increasing until reaching the maximum value (in this case around 10KA) during the transient fault which is simulated at switching time start from (0.5sec and clear around 1sec). as shown in Figure 7.

Table 2. Simulation results for different size of fault

Sn	Type of fault	Fault resistance (Ω)	Ground resistance (Ω)	Actual Angle (deg)	Predicted Angle (Deg)	Prediction accuracy percentage	Power swing type	Current swing element operation
1	Three-phase	0.001	0.001	140.7	139.26	98.98	Unstable	1
2	Three-phase	3	0.01	136.93	136.89	99.97	Unstable	1
3	Three-phase	0.5	0.01	155.61	154.33	99.17	Unstable	1
4	Three-phase	2.5	7.5	148.39	148.45	99.96	Unstable	1
5	Three-phase	0.25	0.4	148.17	146.8	99.07	Unstable	1
6	Three-phase	8	0.4	63.69	63.37	99.49	Stable	0
7	Three-phase	50	100	10.73	10.68	99.50	Stable	0
8	Three-phase	15	40	21.8	21.7	99.50	Stable	0
9	Three-phase	5	15	98.86	98.43	99.56	Stable	0

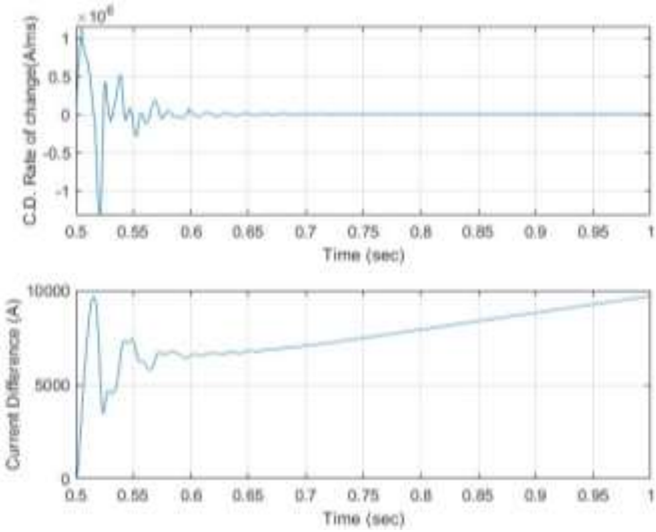

Fig. 7: A fault current magnitude and rate of change detected

The difference in positive sequence current at both ends before and after transient fault is shown in Figure 8 and Figure 9 respectively.

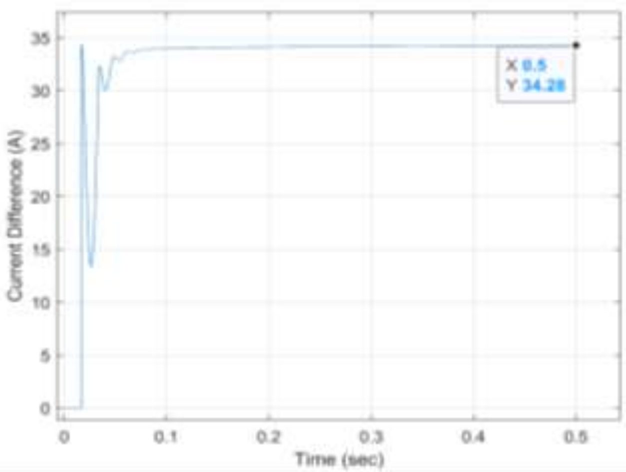

Fig. 8: Difference in positive sequence current at both ends during normal condition.

During the normal condition, as shown in Figure 8, the current difference at both ends of the tie lines starts fluctuating during the power system turn-on until the system reaches a steady-state point (in this case after 0.1sec). After this point (0.1sec), the current remains constant (around 34.3 A) as long as there is no fault in the system.

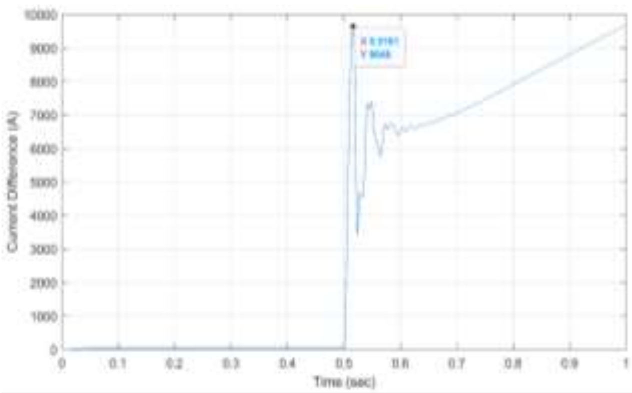

Fig. 9: Difference in positive sequence current at both ends during fault condition

As shown in Figure 9, the current difference starts fluctuating around 9.6 KA and starts increasing sharply during the transient fault (in this case, the switching time starts at 0.5sec and clears at 1sec), so the fault current during an abnormal condition can be detected with high accuracy and a short detection time by the proposed method.

The phase angle difference of the positive sequence voltage at both ends during the normal condition is shown in Figure 10. The phase angle difference starts fluctuating during the operating condition, and the angle oscillation begins decreasing until the system reaches a steady-state point (in this case, around 0.15 sec). After this point, the phase angle difference will remain constant (around 26.6°) as long as the system is in normal operation.

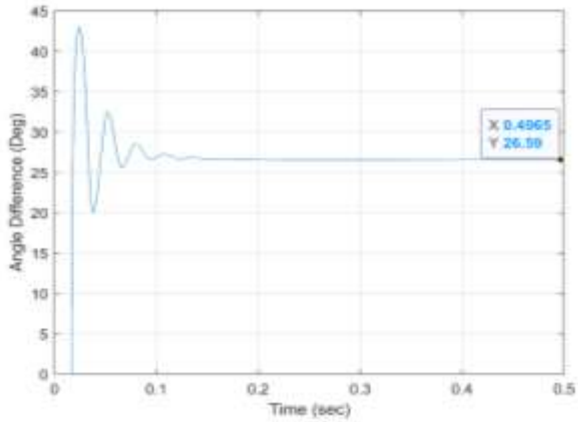

Fig. 10: Phase angle difference of the positive sequence voltage at both ends during normal condition.

When a fault occurs at switching time from 0.5s to 1sec on a faulted line, the unbalance between load and generation on the other line causes a power swing. The relay is prevented from operating if the oscillations are small and the swing is stable because the predicted phase angle difference is still less than the critical value, which in this case is 100°.

On the other hand, if the predicted angle goes above $\delta\_critical = 100°$ and the current swing detection operates, then the unstable power swing is declared, and the relay must be tripped quickly to separate the asynchronous area from the overall system to avoid system collapse.

Figure 11 shows the plot of the phase difference between the two buses without a proposed protection scheme during an unstable swing. It is clear that the phase angle difference begins to fluctuate and increase during the fault time duration (from 0.5sec to 1sec) and that after the fault (1.1sec), the phase angle difference between two interconnected areas starts to separate above 180°. The system loses stability around 1.15 sec, and the system will lose the synchronization.

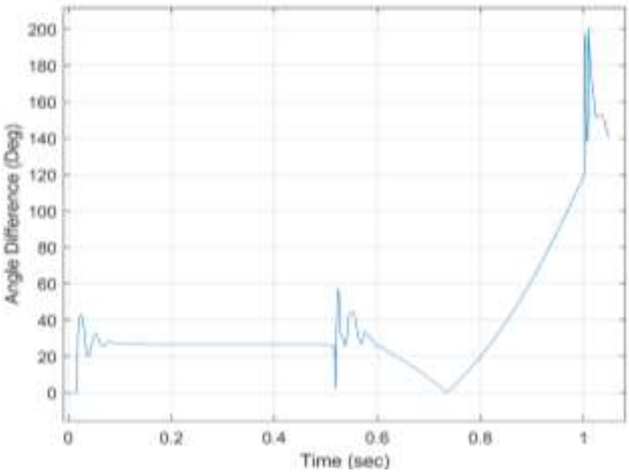

Fig. 11: System without protection scheme.

Figure 12 represents the phase angle difference plot of the same case with the proposed protection scheme. The predicted angle passes the critical value at around 0.97s, and the current swing detection element detects the current size, causing the system to be declared unstable and the relay to trip at around 0.98s. As a result of this method, the swinging condition can be predicted in advance, increasing the decision time for the OST function.

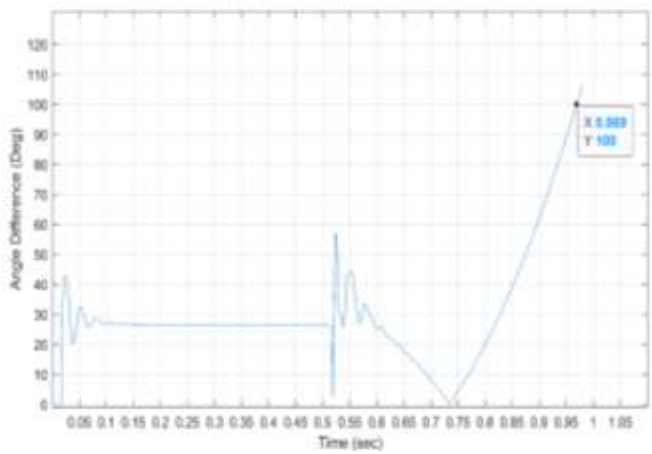
Fig. 12: System with proposed protection scheme.

5 Conclusions

This paper presents a new out-of-step detection method for multi-machine systems using wide-area measurements based on PMUs. Two schemes are proposed: one based on positive phase angle difference calculation between two interconnected areas at different fault sizes, which evaluates system condition based on predicted angle, and the other based on phasor current difference calculation between interconnected areas, which works as a second check criteria where both algorithms work simultaneously. The proposed method can detect stable and unstable power swings and faults with high speed and accuracy (around 99%) without being affected by system parameters.

The angle prediction time is relatively short (around 20ms), making it compatible with current swing element operation. To validate the proposed method, a different fault resistance range (1mΩ up to 100Ω), and fault time durations (at switching times of 0.5sec and clear at 1sec) were created in the system to evaluate the accuracy of the phase angle prediction scheme with current swing detection elements during stable and unstable power swings using MATLAB/Simulink software.

Nomenclature:

δp = Predicted relative phase angle difference

δα, δβ = phase angles difference measured values at different time

d_{α}, $d_{\alpha-1}$, $d_{\alpha-2}$ = difference in the phase angle of the first samples

d_{β}, $d_{\beta-1}$,$d_{\beta-2}$ = difference in the phase angle of the second samples

λ, μ = ratio of phase angle difference

I_{max} = maximum value of the positive sequence current

I_{min} = minimum value of the positive sequence current

ΔT_{max} = time period that is determined by the simulation

N = constant number that is used as a comparator with a current rate of change

I_{set} = setting current that is determined by the simulation

$\Delta I/\Delta t$ = current rate of change

References"

[1] P. Kundur, "Power Stability and Control," *The EPRI Power System Engineering Series*, New York: McGraw Hill Inc., 2004.

[2] B. Patel, "A new technique for detection and classification of faults during power swing," *Electric Power Systems Research*, vol.175, p.105920,2019/10/01/2019.

[3] R. Emami and A. Abur, " External system line outage identification usihg phasor measurement units" *IEEE Transactions on Power Systems*, Vol.28, No. 2, 2013, pp. 1035-1040.

[4] A. Haddadi, I. Kocar, U. Karaagac, H. Gras, and E. Farantatos, "Impact of Wind Generation on Power Swing Protection," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 1118-1128, 2019, doi: 10.1109/TPWRD.2019.2896135.

[5] K. Tuttelberg, M. Loper and J. Kilter, "Correcting Systematic Errors in Corona Losses Measured with Phasor Measurement Units", *IEEE Transactions on Power Delivery*, Vol.34, No.6, 2019, pp. 2275-2277.

[6] S. Kumer, B. Tyagi, V.Kumer and S. Chohan, "Optimization of Phasor Measurement Units Placement Under Contingency Using Reliability of Network Components" *IEEE Transactions on Instrumentation and Measurement*, Vol.69, No.12, 2020, pp9893-9906

[7] X. Wang, D.Shi, Z. Wang, C. Xu, Q. Zhang, X. Zhang and Z. Yu, "Online Calibration of Phasor Measurement Unit Using Density-Based Spatial Clustering", *IEEE Transactions on Power Delivery*, Vl.33, No.3, pp. 1081-1090

[8] D. Georgakopoulos and S. Quigg, "Precision Measurement System for the Calibration of Phasor Measurement Units", *IEEE Transactions on Instrumentation and Measurement*, Vol.66, No.6, 2017, pp.1441-1445

[9] F. A. Gorjayi and H. M. Rad, " Aphysics-Aware MIQP Approach to Harmonic State Estimation in Low-Observable Power Distribution Systems Using Harmonic Phasor Measurement Units" *IEEE Transactions on Smart Gride*, Vol.14, No.3, 2023, pp. 2111-2114

[10] A. Xue, F. Xu, J. Xu, J. H.Chow, H. You and T. Bi, "Correction of Phasor Measurement Independent of Transmission Line Parameters", *IEEE Transactions on Smart Grid*, Vol.11, No.1, 2020, pp. 346-356.

[11] A. A. Elsayed and M. A. Mohamed, "Optimal Micro-PMU Placement Based on Hybrid Current Channels Selection for Distribution Grids", *IEEE Transactions on Industry Applications*, Vol.56, No.6, pp. 6871-6881

[12] I. Ivanković, D. Brnobić, R. Rubeša and M. Rekić, "Line Differential Protection with Synchrophasor Data in WAMPAC System in Control Room," *2020 3rd International Colloquium on Intelligent Grid Metrology (SMAGRIMET)*, Cavtat, Croatia, 2020, pp. 72-78, doi: 10.23919/SMAGRIMET48809.2020.9264020.

[13] H. D. Al-Majali and S. Al-Dhalaan, “A Snubber Configuration for Modified Bridge Converter” *Electric Power Components and Systems (Taylor & Francis)*, Vol.34, No.11, 2006, PP. 1177-1190.

[14] D. M. Timofeev and T. G. Klimova, "Analysis of Possibility of Using Pmu Based Methods for Providing the Correct Operation of Distance Protection," *2018 International Youth Scientific and Technical Conference Relay Protection and Automation (RPA)*, Moscow, Russia, 2018, pp. 1-14, doi: 10.1109/RPA.2018.8537231.

[15] I. Višić, I. Strnad and T. Tonković, "Real Time Load Angle Application for Synchronous Generator Protection Purposes," *2019 2nd International Colloquium on Smart Grid Metrology (SMAGRIMET)*, Split, Croatia, 2019, pp.1-5.

[16] P. Kundu, J. Ganeswara Rao, P. K. Nayak and A. K. Pradhan, "Wide area measurement based out-of-step detection technique," *2010 Joint International Conference on Power Electronics, Drives and Energy Systems & 2010 Power*, India, New Delhi, India, 2010, pp. 1-5, doi: 10.1109/PEDES.2010.5712569.

[17] "IEEE/IEC International Standard - Measuring relays and protection equipment - Part 118-1: Synchrophasor for power systems - Measurements," in IEC/IEEE 60255-118-1:2018, vol., no., pp.1-78, 19 Dec. 2018, doi: 10.1109/IEEESTD.2018.8577045.

[18] G. Lee, S. H. Kim and Y. -J. Shin, "Time-Synchronized Measurements and Applications for Monitoring of Intelligent Electric Power Systems," *2018 IEEE International Conference on Big Data and Smart Computing (BigComp)*, Shanghai, China, 2018, pp. 751-755, doi: 10.1109/BigComp.2018.00143.

[19] “Power Swing and Out-of-Step Considerations on Transmission Lines”, IEEE PSRC WG D6, A report to the Power System Relaying Committee OF the IEEE Power Engineering Society, 2005, [Online]. https://www.ewh.ieee.org/r6/san_francisco/pes/pes_pdf/OutOfStep/PowerSwingOOS.pdf (Accessed Date: January 11, 2024).

[20] Y.-J. Lee, O.-S. Kwon, J.-Y. Heo, and C.-H. Kim, “A Study on the Out-of-Step Detection Algorithm Using Time Variation of Complex

Power-Part II: Out-of-Step Detection Algorithm and Simulation Results," *Energies*, vol. 13, no. 7, p. 1833, Apr. 2020, doi: 10.3390/en13071833.

[21] Y. Hamid, "An adaptive impedance-based out-of-step detection of synchronous generator without any network reduction," *IET Generation, Transmission & Distribution*, vol. 14, Mar. 2020, doi: 10.1049/iet-gtd.2019.0850.

[22] Y. Ma, Q. Huang, Z. Zhang and D. Cai, " Application of Multi-synchrosqueezing Transform for Sub synchronous Oscillation Detection Using PMU Data", *IEEE Transactions on Industry Applications*, Vol.57, No.3, 2021, pp. 2006-2013.

[23] V. A. Ambekar and S. S. Dambhare, "Comparative evaluation of out of step detection schemes for distance relays," *2012 IEEE Fifth Power,* India Conference, Murthal, India, 2012, pp. 1-6, doi: 10.1109/PowerI.2012.6479500.

[24] N. Fischer, G. Benmouyal, D. Hou, D. Tziouvaras, J. Byrne-Finley, and B. Smyth, "Tutorial on power swing blocking and out-of-step tripping," in *Proc. 39th Annu. Western Protective Relay Conf.*, Spokane, WA, USA, Oct. 2012.

[25] Q. Verzosa, "Realistic testing of power swing blocking and out-of-step tripping functions," *2013 66th Annual Conference for Protective Relay Engineers*, College Station, TX, USA, 2013, pp. 420-449, doi: 10.1109/CPRE.2013.6822056.

[26] H. D. Al-Majali, "Abnormal Harmonics Generated by Modified HVDC Converters" *Electric Power Components and Systems (Taylor & Francis)*, Vol.35, No.6, 2006, PP 639 – 654.

[27] N/ M. Manousakis and G. N. Korres, "Optimal Allocation of Phasor Measurement Units Considering Various Contingencies and Measurement Redundancy", *IEEE Transactions on Instrumentation and Measurement*, Vol.69, No.6, 2020, pp.3403-3411.

[28] H. D. Al-Majali, B. H. Al-Majali and Z. S. Almajali ," Reduced Harmonics Generated and Reactive Volt-Ampere absorption of HVDC Converter Using By-Pass Switch", WSEAS Transaction on Control and Systems, Vol.15, pp 218 -227, 2020, https://doi.org/10.37394/23203.2020.15.23.

[29] P. Briff, J. C. Zabalza, J. Nicholls and K. Vershinin, "Turn-Off Delay Compensations of Series-Connected IGBTs for HVDC Applications", *IEEE Transactions on Power Electronics*, Vol.35, No.11, 2020, pp. 11294-11298.

[30] H. D. Al-Majali and B. H. Al-Majali, "Fast and Continuous Control of a Modified HVDC Converter", *WSEAS Transaction on Control and Systems*, Vol.19, PP.326-332, 2019.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.