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Research Article

Power Swing and Fault Detection in the Presence of Wind Farms Using Generator Speed Zero-Crossing Moment

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Nowadays, due to the entry of wind power plants into the power systems, which causes changes in the network parameters, power swing detection has become more important. Changes in the wind speed and noncontinuity of the wind power plants lead to changes in the power swing characteristic. Therefore, the impedance seen by the distance relay is changed, and so the maloperation of the relay during the stable power swing may occur. This paper proposes a new method to detect power fluctuations based on the synchronous generator speed while it is independent of the network parameters. Based on the proposed method, the generator speed at any moment does not pass through zero during the stable power swing. In contrast, it passes through zero by occurring fault types with high and low fault resistance, fault types during power swing, and an unstable power swing. Therefore, the method prevents maloperation of distance protection. It is worth noting that the proposed method is applicable for distance protection in any power system with and without wind power plants, such as in the distance protection of compensated transmission lines. The obtained results indicate that the proposed method detects power fluctuations in a short time.

1. Introduction

The power system stability has a significant role in maintaining the reliability of the system at a desirable level. Nowadays, with the increase of distributed generation resources, the most important of which is the wind farm, the impedance characteristics of the network can change. This makes it difficult to detect the power fluctuations (power swings and all fault types) by distance protection.

Under the steady-state conditions of the power system, all generators operate in synchronous mode. When a disturbance occurs in the system, such as losing a large part of the load or generator disconnection, the system must adapt to the new operating state. In order to balance the generation and consumption, the rotor angle must be in a new position. This process is accompanied by an oscillatory behavior called the power swing.

In an overview, power swings can be divided into stable and unstable ones. In the stable power swing, the rotor angle must be kept at a new working point for the lost power

compensation. The distance relay must be blocked during a stable power swing. In contrast, the rotor angle during the unstable power swing continuously increases and does not reach the stabilization point. In this situation, the relay must be tripped. Moreover, the distance relay must be tripped for the fault condition without any undesired time delays. It is worth noting that the stable power swings are classified into two types in terms of the oscillation, including those with an oscillation frequency of less than 7 Hz (slow power swing) and greater than 7 Hz (fast power swing) that the relay must be able to detect both [1]. Until now, several methods have been proposed for detecting the stable power swings from the unstable ones and fault types. Generally, these methods can be categorized as conventional, signal analysis, and intelligent methods.

The concentric characteristic as a conventional method has been proposed for stable power swing detection [2]. During a stable power swing, the rate of impedance change is found to be lower than that during the fault. The drawback of this method is that it fails to detect the fast power swing and

also the fault during power swing [3]. The blinder scheme has been used for the detection of power swings [4, 5]. This method has been suggested to eliminate the disadvantages of the concentric characteristic although having its own drawbacks. First, it maloperates in detecting the stable power swing. Also, it requires sophisticated network analysis for determining the threshold in order to distinguish the fault from the power swing [5]. Since the blinder scheme requires grid studies and may maloperate in the stable power swing detection, the decreased resistance method has been proposed [6]. The resistance significantly changes at the beginning of the fault, and these changes are continuous during the fault period. This feature is employed to discriminate power swing from fault [6]. The drawback of this method is the inability to detect a stable power swing with low frequency at the power angle of 180° [7]. The swing center voltage method has been proposed in [8] in order to detect the stable power swing with low frequency. It remains constant when the fault occurs while it changes continuously during the power swing. There is some delay in the detection of the three-phase fault using this method. Moreover, it is not constant when a single-phase to ground fault with high fault resistance occurs [9]. In [10], a superimposed current method has been proposed for the detection of power swing from fault. However, the method maloperates when the three-phase fault occurs at a power angle close to 180° and a single-phase to ground fault with high resistance occurs during the power swing [9]. In [11], three-phase active and reactive power changes have been used to detect power swing from symmetrical fault. This method may operate inaccurately during a stable power swing and just performs well for the symmetrical fault [12]. In [13], a negative-sequence current-based technique has been proposed for detecting all types of faults during the power swing in a series-compensated line. In [14], a method based on the sign of the half-cycle superimposed positive-sequence current has been presented for fault detection in the compensated transmission line with thyristor-controlled series capacitor to connected doubly-fed induction generator based wind farms.

Another category of power swing and fault detection method is based on signal analysis such as fast Fourier transform (FFT) [14], wavelet transform (WT) [15], S transform (ST) [16], and Peroni method [10]. The problem of FFT is the determination of a threshold value for each power fluctuation [14]. WT fails at local frequencies [15]. ST is not able to detect a high-resistance fault during the stable power swing [16]. Peroni method is only capable of detecting the three-phase fault and fails to identify the asymmetric ones [17]. The voltage and current phasor analysis has been used to detect the power swing, symmetric and asymmetric faults, and fault during power swing. It should be noted that the settings of this method are very difficult to identify the stable and unstable power swings [18]. In [19], Teager-Kaiser energy operator has been applied to instantaneous current signal for fault detection during power swing in the compensated transmission line with a thyristor-controlled series capacitor.

Artificial intelligence algorithms such as ANFLS [20], SVM [21], and PNN [22] have been used to identify power
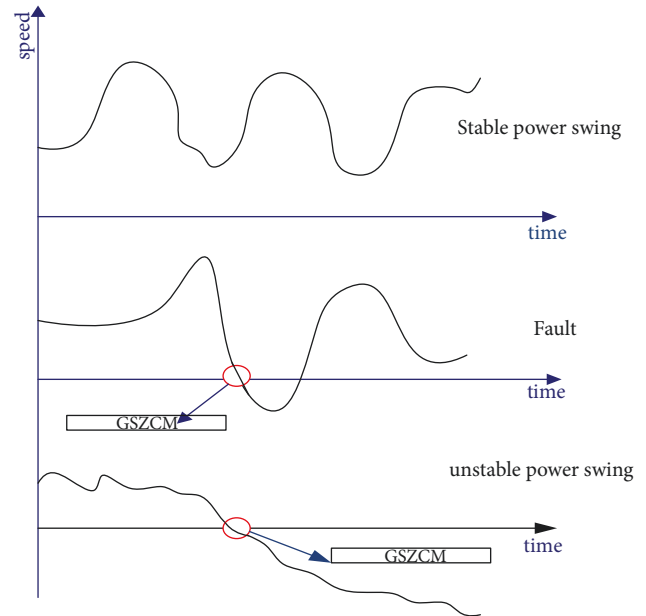

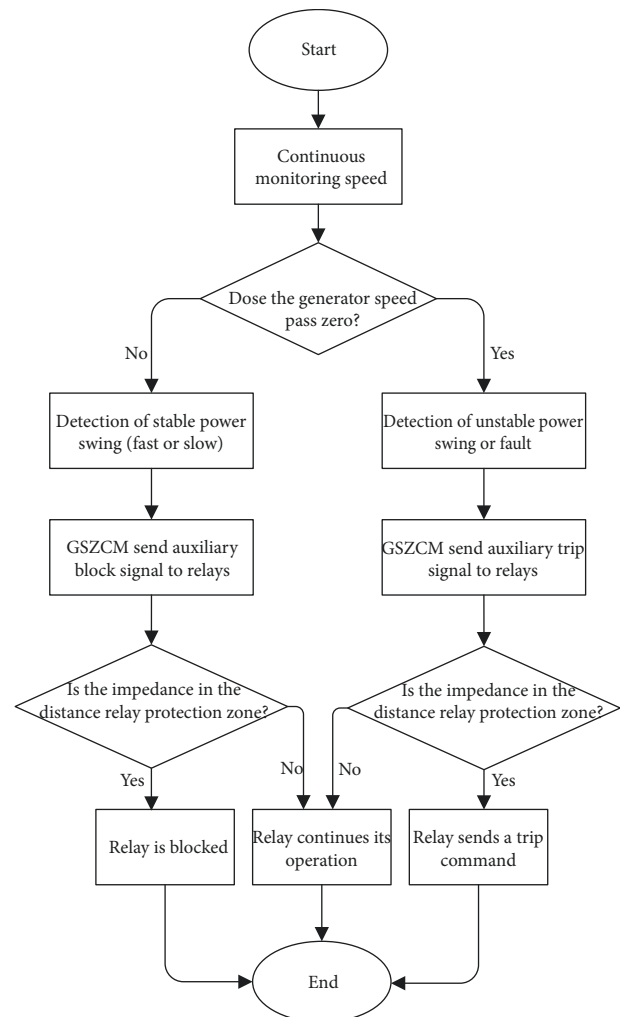Figure 1: Generator speed during stable and unstable power swing and fault.

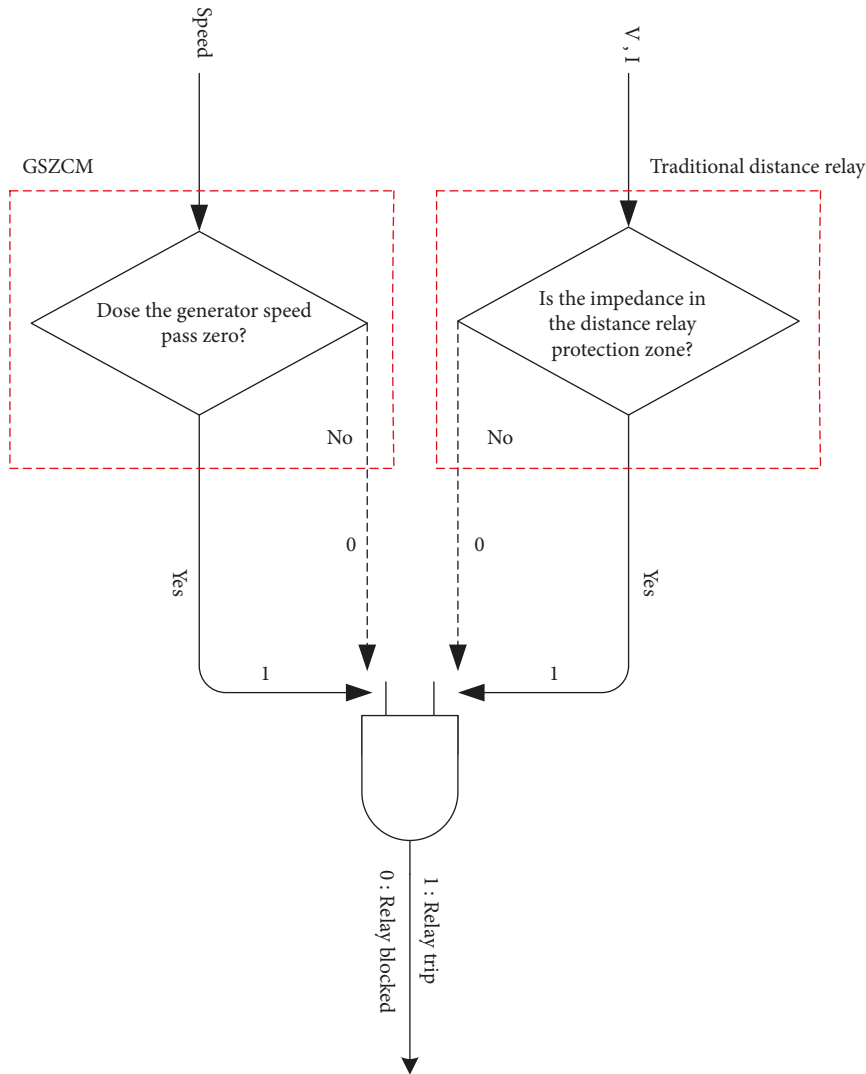Figure 2: The proposed method for power fluctuations' detection.

FIGURE 3: Command circuit of distance relay based on the proposed method.

fluctuations. These algorithms receive signals such as the rate of positive-sequence impedance, positive- and negative-sequence current, and the SCV (swing center voltage) as inputs and give appropriate outputs based on the training given to them. One of the advantages of these methods is that they can take as many inputs as possible. In addition, they perform well in high-resistance faults. They can also detect faults during the power swing, but how to train these methods is complex and challenging [22].

Nowadays, with the increased penetration of wind plants into power networks, the creation of high-reliability protection has become an important issue. One of these protections is distance protection, whose main task is to detect fault and power swing based on the impedance changes. In the presence of wind plants, the impedance changes increase, which may lead to distance protection maloperation.

In order to overcome the above-mentioned drawbacks based on the reviewed papers, the present study proposes a new method for power fluctuations detection in distance protection with and without wind power plants. The method is based on the generator speed zero-crossing moment
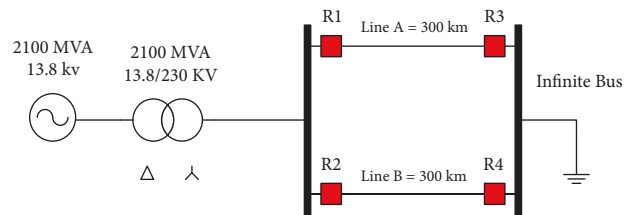

FIGURE 4: SMIB, 230 kV test system example.

(GSZCM) concept. Based on the proposed method, the synchronous generator speed at any moment does not pass through zero when the stable power swing occurs. However, if fault types with high and low fault resistances, fault during power swing, and an unstable power swing occur, generator speed passes through zero. In a nutshell, the contributions of this paper are listed as follows:
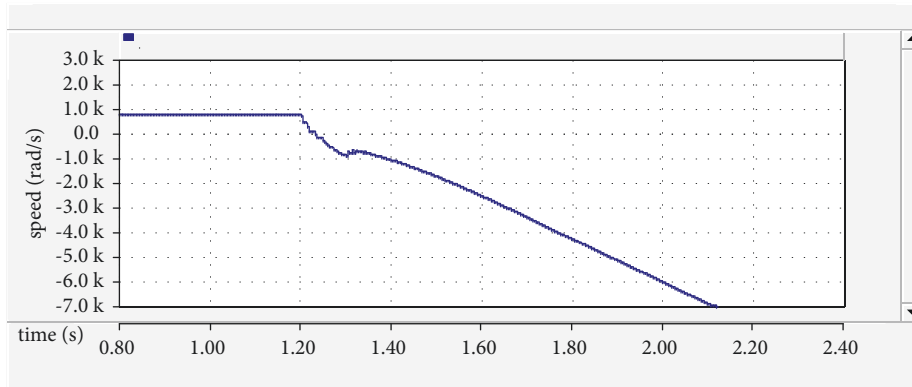
(i) A new method is proposed for the detection of stable and unstable power swings, fault types, and fault during power swing with and without wind power plants
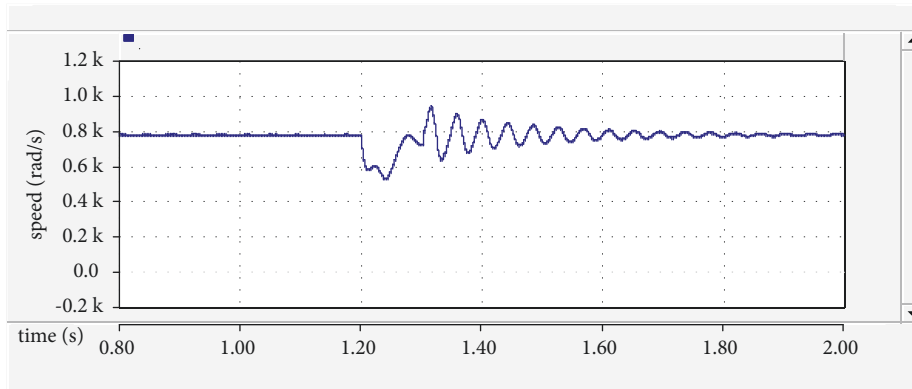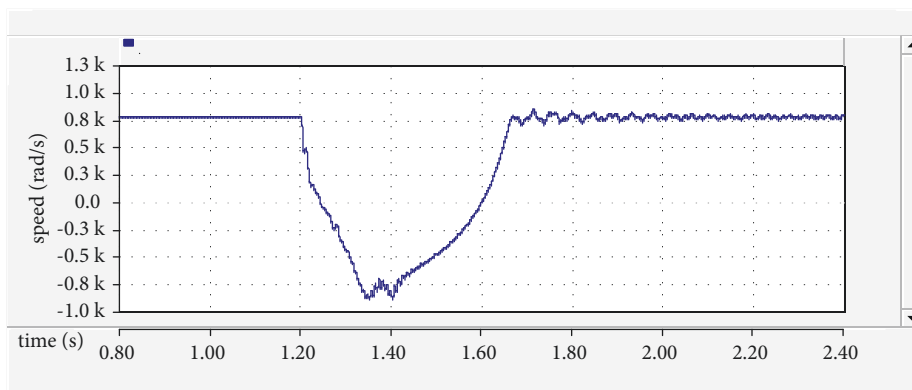
(a)
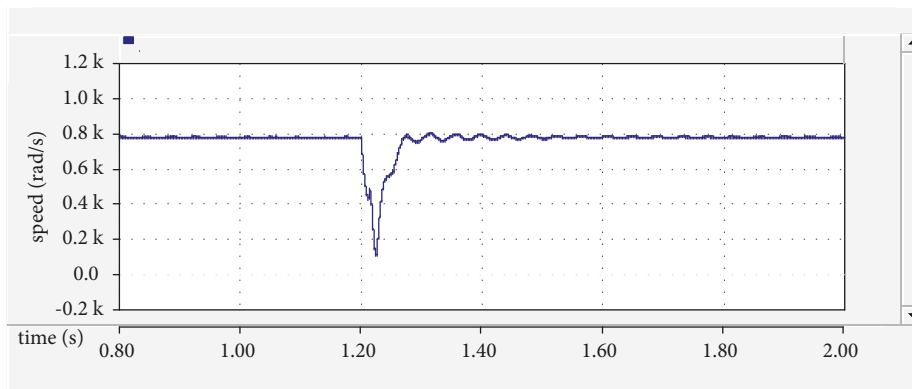
(b)

(c)

(d)

FIGURE 5: Synchronous generator speed in the SMIB test system during (a) slow stable power swing, (b) fast stable power swing, (c) unstable power swing, and (d) three-phase fault.
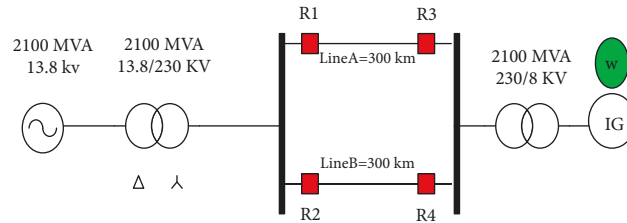
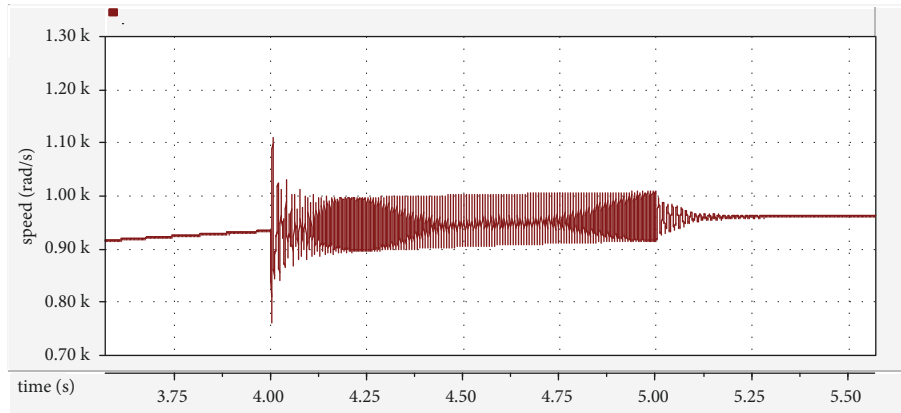FIGURE 6: The two-circuit transmission line in the presence of a wind turbine.

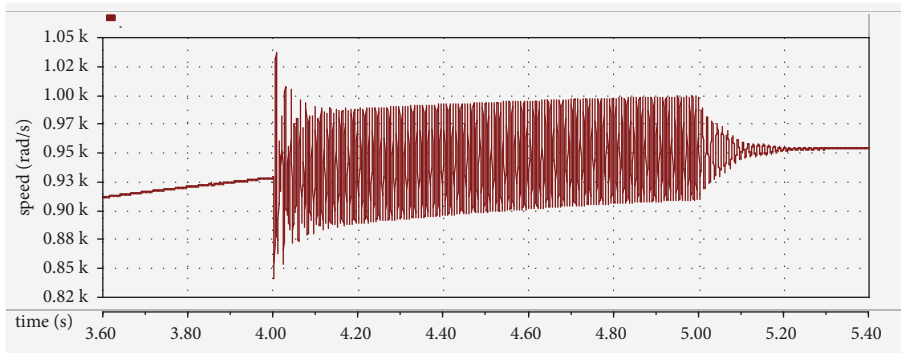FIGURE 7: Synchronous generator speed during slow power swing.

FIGURE 8: Synchronous generator speed during fast power swing.

(ii) The main property of the method is the lack of need for primary stability studies to find relay settings

(iii) The method is independent of any of the network parameters, such as impedance transmission lines

(iv) The method is applicable for the distance protection of compensated transmission lines

The obtained results show that the proposed method is a reliable scheme that can identify the slow and fast stable power swings from unstable ones and fault types with high and low fault resistance. This feature causes the third zone protection blocking during the stable power swing to prevent unnecessary tripping of distance relays and maintain power supply continuity.

2. The Proposed Method

When impedance variations are high in the network, the impedance-based algorithms are unable to detect the power oscillations [16]. For example, the line switching, the generator disconnection, and the loss of heavy loads can cause high impedance variation. Moreover, when the grid is connected to a wind farm, due to changes in wind speed or generation power of the farm, the impedance variations are intensified. In this situation, it will be very difficult to identify the power fluctuations (stable and unstable power swings and fault types with and without power swing). Due to this point and also considering the drawbacks of the previous methods, providing a method that is independent
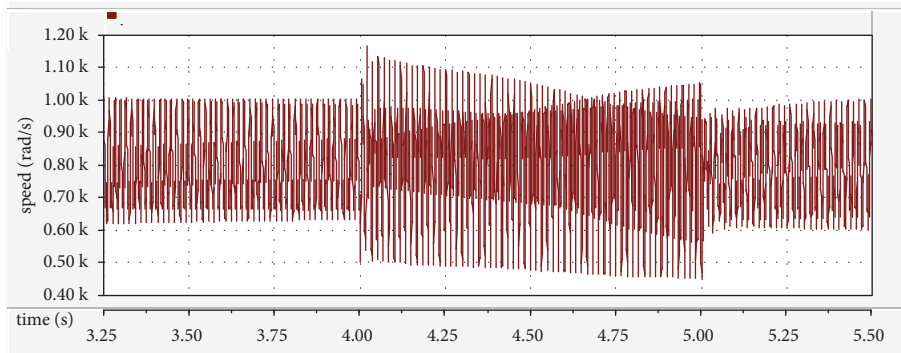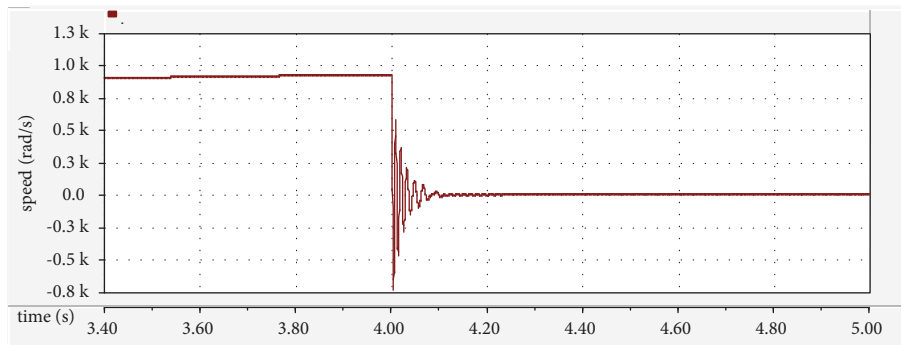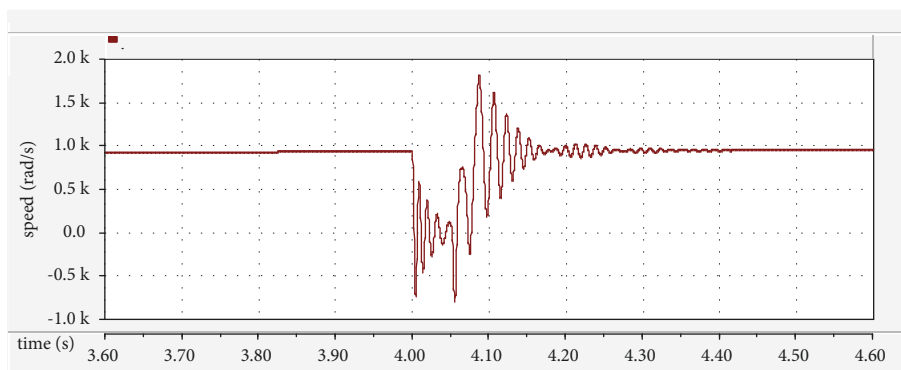
FIGURE 9: Synchronous generator speed during power swing with a power angle near 180°.

TABLE 1: Fault characteristics in test system.

| Case	Type	Location	Resistance (Ω)
1	ABC	80% of line A	1
2	ABC	50% of line A	1
3	AB	80% of line A	30
4	AB	50% of line A	30
5	AB-G	80% of line A	30
6	AB-G	50% of line A	30
7	A-G	80% of line A	50
8	A-G	50% of line A	50

(a)

(b)

FIGURE 10: Synchronous generator speed for (a) case 1 in Table 1 and (b) case 2 in Table 1.

of the network parameter (voltage, current, and impedance) variations and can send the correct command to the relay in the shortest time in order to prevent the relay maloperation is interesting and of high importance.

The proposed GSZCM method is based on the synchronous machine speed for power fluctuations detection. Several investigations have described how to measure the speed of the generator [23, 24]. During the stable power
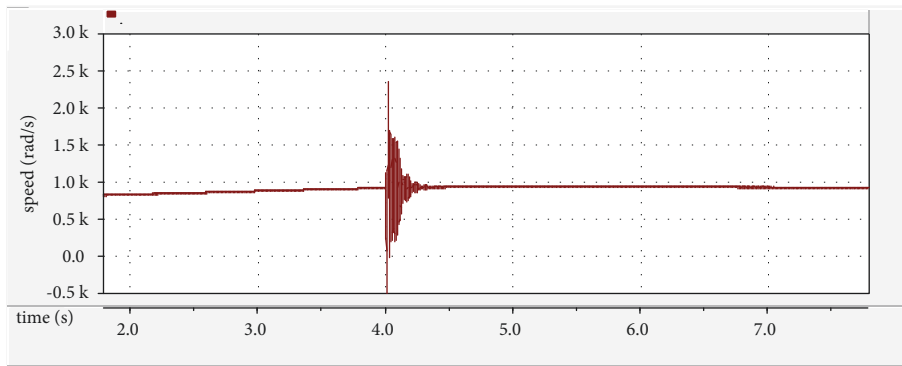
(a)
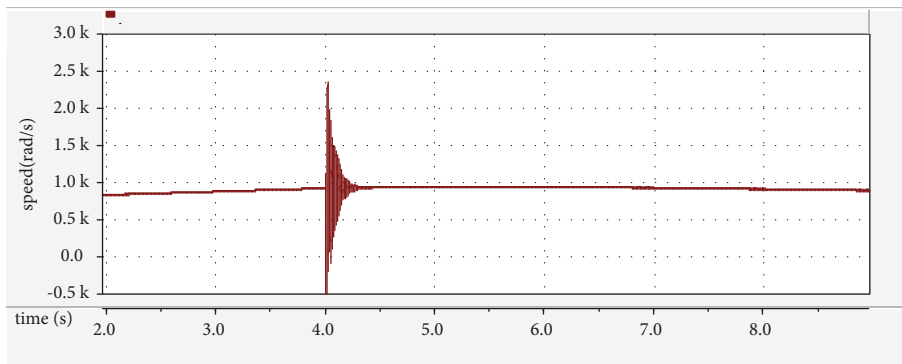
(b)

Figure 11: Synchronous generator speed for (a) case 3 in Table 1 and (b) case 4 in Table 1.

(a)

(b)
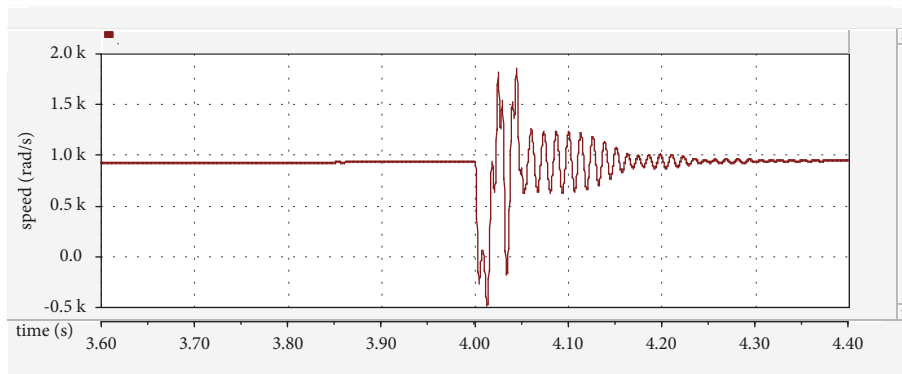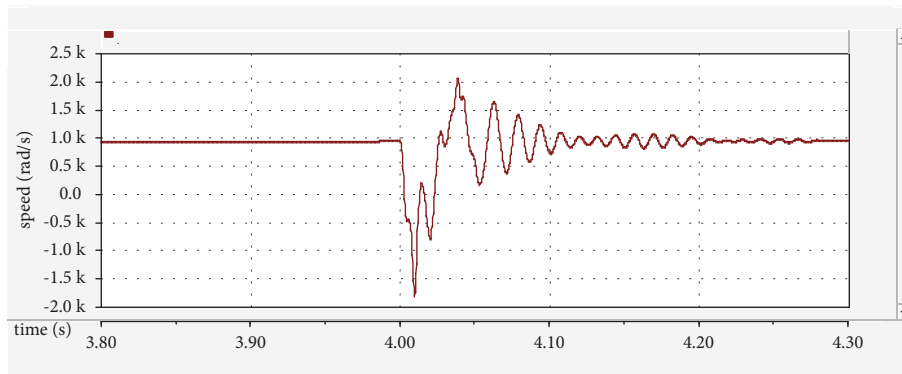
Figure 12: Synchronous generator speed for (a) case 5 in Table 1 and (b) case 6 in Table 1.

TABLE 2: Fault detection time using the proposed method.

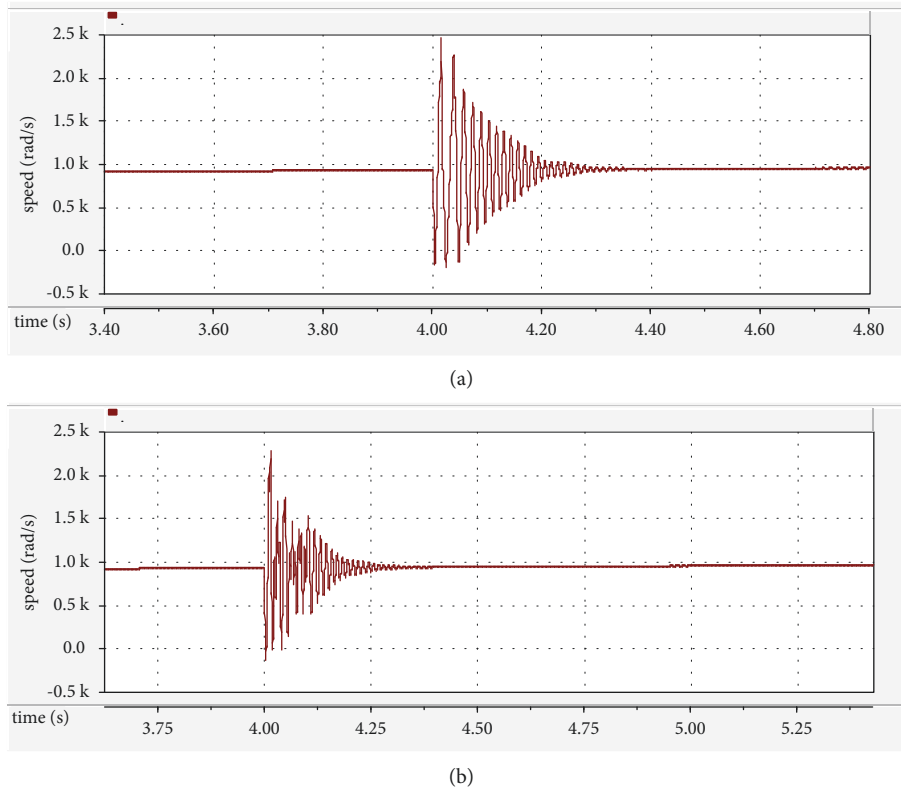| Type	Location	Occurrence time (s)	Detection time (s)
ABC	80% of line A	4 : 00	4 : 00
ABC	50% of line A	4 : 00	4 : 001
AB	80% of line A	4 : 00s	4 : 00
AB	50% of line A	4 : 00	4 : 00
AB-G	80% of line A	4 : 00	4 : 00
AB-G	50% of line A	4 : 00	4 : 00
A-G	80% of line A	4 : 00	4 : 001
A-G	50% of line A	4 : 00	4 : 00

(a)

(b)

FIGURE 13: Synchronous generator speed for (a) case 7 in Table 1 and (b) case 8 in Table 1.

swing, the generator speed at any moment does not pass through zero, as shown in Figure 1. However, during the occurrence of fault types with high and low fault resistance, fault types during power swing, and also the unstable power swing, the synchronous generator speed passes through zero, as depicted in Figure 1.

It is worth mentioning that the proposed method can improve the distance protection of transmission lines in different situations, such as the distance protection of compensated transmission lines. The flowchart of the method is shown in Figure 2. Based on this figure, the method has two main blocks, which are explained in the following:

(i) *First Block.* The first block detects slow and fast stable power swings. In this situation, the generator speed does not pass through zero, and so, the GSZCM block sends an auxiliary block signal to relays via the telecommunication system. In the following, the relay is blocked if the impedance seen by the relay is in its protection zone; otherwise, the relay continues its operation.

(ii) *Second Block.* Unstable power swing and fault types with and without power swing are detected in the second block. In this situation, the generator speed passes through zero, and so, the GSZCM block sends an auxiliary trip signal to relays via the telecommunication system. In the following, the relay sends a trip signal if the impedance seen by the relay is in its protection zone; otherwise, the relay continues its operation.

Another feature of the proposed method is that it can be implemented for the existing distance relays in order to overcome the drawback of the PSB function (it is based on the impedance trajectory) when impedance variation is high.

FIGURE 14: Synchronous generator speed for an unstable power swing.

FIGURE 15: Synchronous generator speed for three-phase fault during power swing.
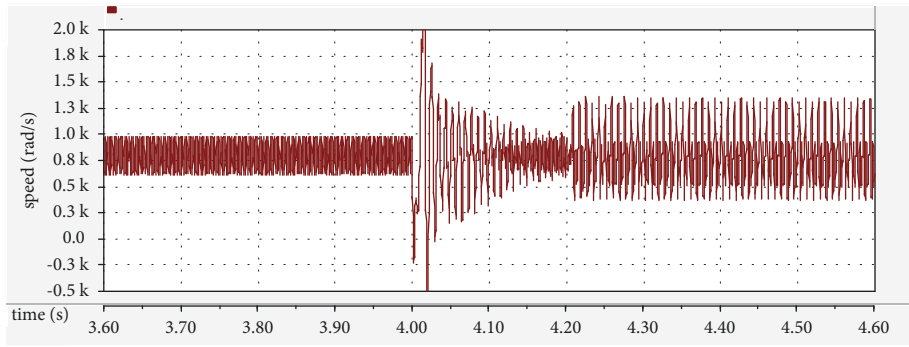

(a)

(b)

FIGURE 16: Synchronous generator speed during (a) stable power swing and (b) unstable power swing.

(a)

(b)

(c)

(d)

FIGURE 17: Synchronous generator speed during (a) three-phase fault, (b) double-phase-to-ground fault, (c) double-phase fault, and (d) single-phase-to-ground fault.
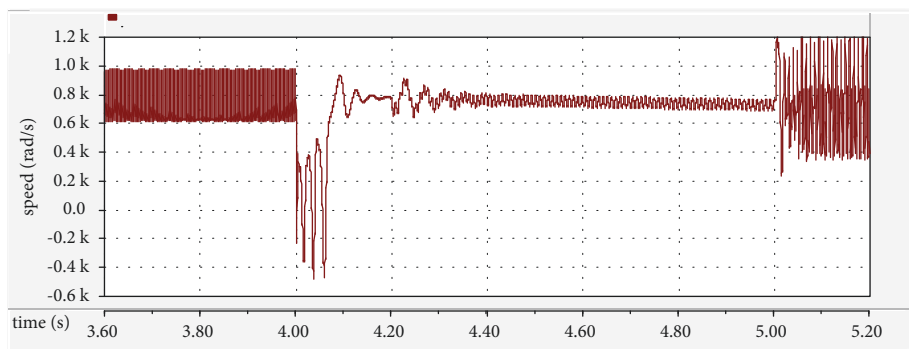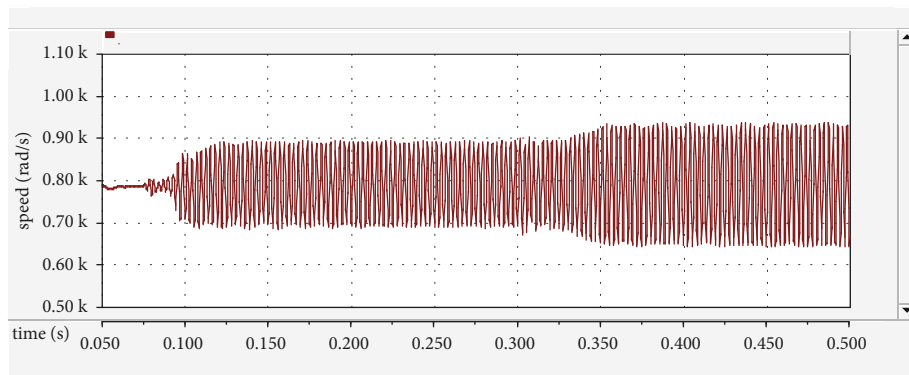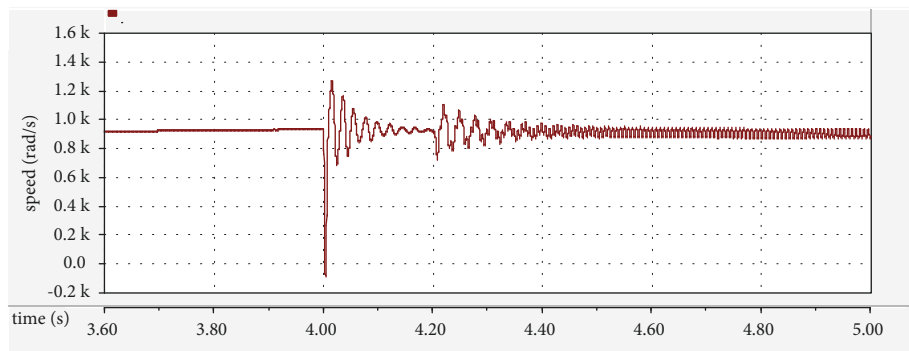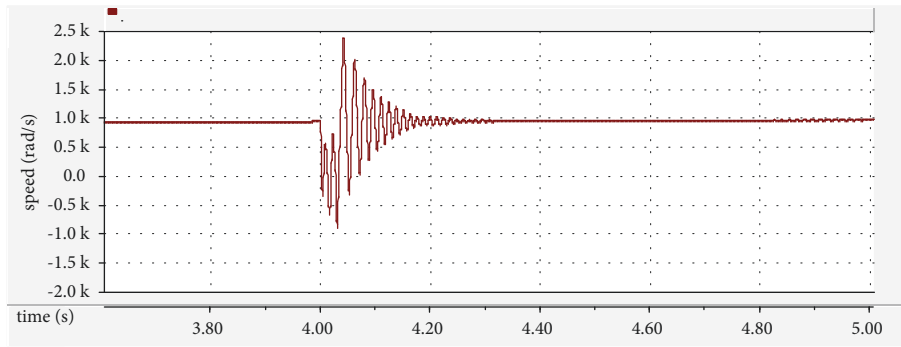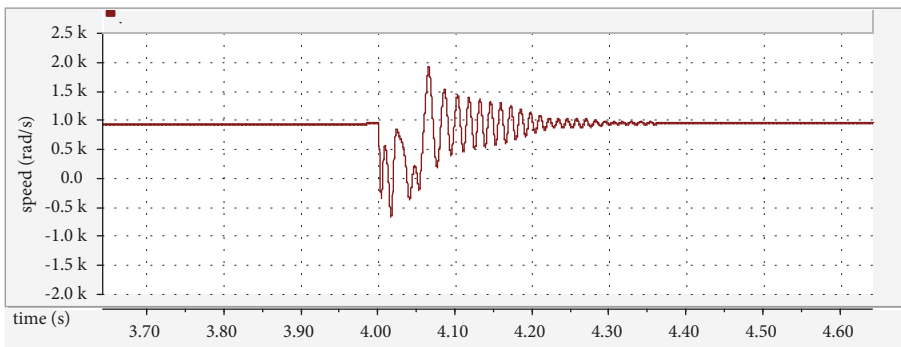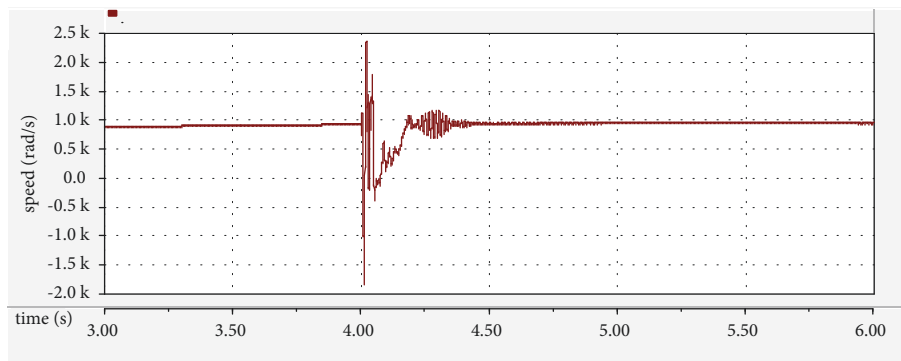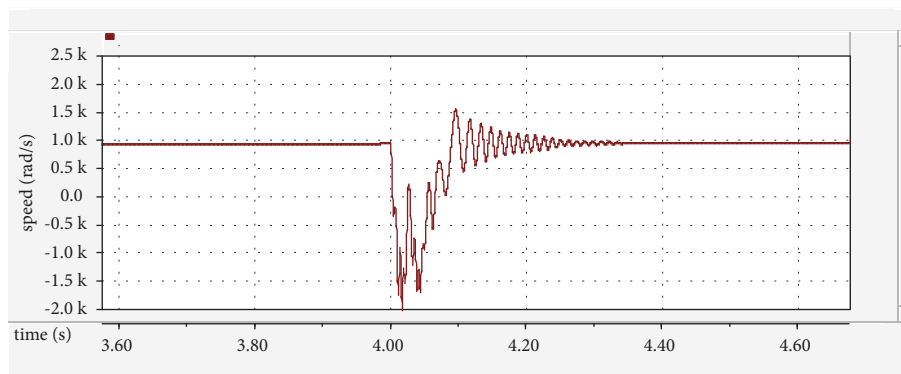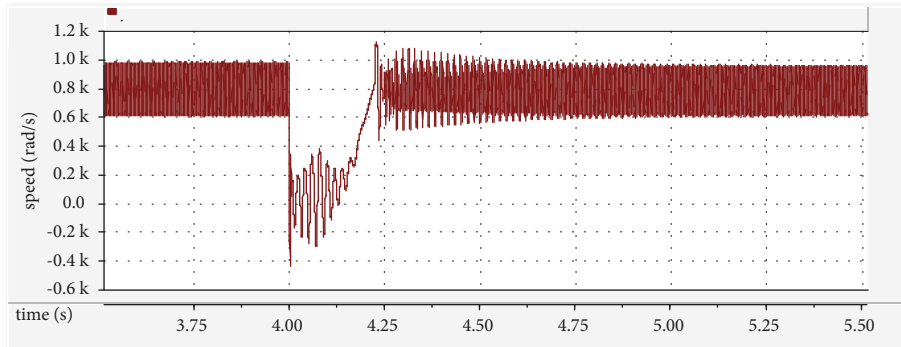
FIGURE 18: Synchronous generator speed for three-phase fault during power swing.

Figure 3 shows the command circuit of the distance relay based on the method. A small 230 kV test system as a single machine infinite bus (SMIB) as shown in Figure 4 is used to evaluate the efficiency of the method. The system consists of a synchronous generator, a double-circuit transmission line, and an infinite bus. The system data are given in [16]. A three-phase fault is applied to 1/3 of line B to create the power swing in R1, and then the proposed method is tested for this relay. PSCAD software is employed to simulate the test systems.

Based on Figure 5, the generator speed does not cross zero during the slow and fast stable power swings. However, the speed crosses zero during the unstable power swing and three-phase fault. These achievements confirm the efficiency of the proposed method.

3. Simulation Studies

In order to validate the performance of the presented method in different conditions, the following three cases are considered.

Case 1: a double-circuit transmission line in the presence of a wind turbine generator (WTG) with wind generator Type-2 is used to test the proposed method. It is worth noting that a Type 2 wind turbine makes use of wound rotor induction generators which are directly connected to the WTG step-up transformer [25]. All details for all types of WTG controls can also be found in [26].

Case 2: the method is applied to a double-circuit transmission line in the presence of a WTG with wind generator Type-5 with a series compensator transmission line. A Type 5 wind turbine consists of a typical WTG variable-speed drive train connected to a torque/speed converter coupled with the asynchronous generator. The torque/speed converter changes the variable speed of the rotor shaft to a constant output shaft speed [27, 28].

Case 3: the IEEE 9-bus test system as a large system is used to demonstrate the performance of the proposed method.

3.1. Case 1: Double-Circuit Transmission Line in the Presence of Wind Turbine (Wind Generator Type-2). One of the factors which cause changes in the network parameters is the
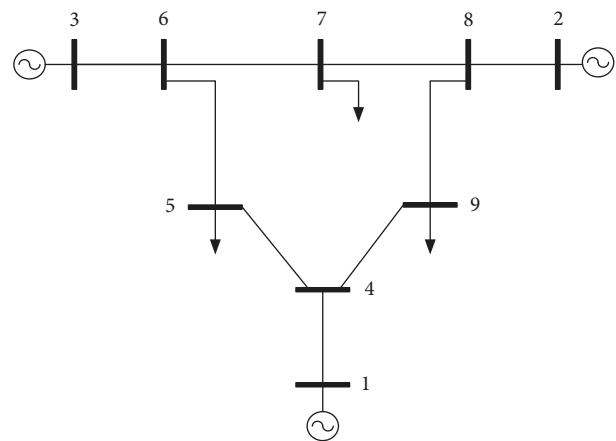

FIGURE 19: IEEE 9-bus test system.

presence of a wind power plant in the system [27]. Wind farms lead to the relay maloperation in detecting the power swing and fault by changing the impedance seen by the distance relay [27]. For this purpose, the system shown in Figure 6 is considered to illustrate the performance of the proposed method in this condition.

In order to check the power swing mode, line B is removed from the circuit at 4 s to generate the stable power swing online A. Then, the synchronous generator speed is measured at this moment. As can be seen in Figure 7, the generator speed does not pass through zero during the stable power swing. It should be noted that wind turbines with variable wind speeds are considered for a more detailed investigation.

Figure 8 exhibits the synchronous generator speed during the fast power swing. Based on the presented results, the proposed method is capable of detecting this type of power swing as well, because the generator speed does not pass through zero during this oscillation.

Detection of the power swing at a power angle close to 180° is very important. The generator speed during the power swing at this angle is shown in Figure 9. It can be seen that the generator speed is more than zero all of the time. Therefore, the power swing around this angle is detected using the proposed method, while some of the previous methods, such as decreased resistance method [7], fail to detect the power swing at a power angle close to 180°.

9-bus test system data

Bus	V [kV]	δ [deg]	P [pu]	Q [pu]
1	17.1600	0.0000	0.7163	0.2791
2	18.4500	9.3507	1.6300	0.0490
3	14.1450	5.1420	0.8500	-0.1145

Line

From Bus	To Bus	R [pu/m]	X [pu/m]	B [pu/m]
4	5	0.0100	0.0680	0.1760
4	9	0.0170	0.0920	0.1580
5	6	0.0320	0.1610	0.3060
8	9	0.0390	0.1738	0.3580
7	6	0.0085	0.0576	0.1490
8	2	0.0119	0.1008	0.2090

Load

Bus	P [pu]	Q [pu]
5	1.25	0.50
7	0.90	0.30
9	1.00	0.35

Figure 20: 9-bus test system data.

To investigate the performance of the proposed method during the fault, the synchronous generator speed is obtained during the different faults according to Table 1. Figures 10–12 show the generator speed in these conditions. Moreover, Table 2 presents the moment of fault detection using the method.

Figure 10 shows the variation of generator speed during the occurrence of two three-phase faults in 80% and 50% of line A with fault resistance 1 Ω at 4 s, respectively. According to the obtained results, the generator speed passes through zero in a short time after the fault occurrence. Therefore, three-phase faults are detected using the proposed method, and the distance relay sends trip commend.

In order to investigate the performance of the proposed method during the asymmetric faults, the generator speed is obtained during the single-phase-to-ground faults, double-phase-to-ground faults, and double-phase faults, as shown in Figures 11–13, respectively. Based on the presented results, it can be concluded that at the moment of asymmetric fault occurrence, the generator speed passes through zero, and the faults are successfully detected in a short time using the method.

It should be noted that the method is capable of detecting an unstable power swing. As can be seen in Figure 14, when the power swing reaches the unstable boundary at 4 s, the synchronous generator speed passes through zero. Therefore, the distance relay based on the proposed method has no maloperation during the unstable power swing.

In order to check the performance of the method in the detection of fault during power swing, generator speed is obtained for the three-phase fault during the power swing, as shown in Figure 15. In this case, at first, a stable power swing is created in the system, and then a three-phase fault occurs at 4 s. It can be seen that the synchronous generator speed does not pass through zero during a stable power swing (before 4 s), but it passes through zero as soon as the fault occurs. As a result, the method identifies the fault during power swing immediately.

3.2. Case 2: Double-Circuit Transmission Line in the Presence of Wind Turbine with Series Compensator (Wind Generator Type-5).

Usually, the presence of compensators in the network will cause changes in the network parameters and impedance seen by the distance relay. Therefore, it may cause the maloperation of distance protection during the power fluctuations. An efficient power fluctuation detection method is essential to overcome this drawback. In order to show the efficiency of the proposed GSZCM method, the system of Figure 6 is assumed to be compensated with a fixed series compensator with a compensation level of 70% in the A-line. A metal oxide varistor is used for the protection of the compensator. Figure 16 shows the synchronous generator speed during the stable and unstable power swings. As can be seen in this figure, the generator speed does not pass through zero during the stable power swing in the compensated system, while it passes through zero during the unstable one. Therefore, the stable and unstable power swings are detected using the proposed method, and also, the distance protection is blocked during the stable power swing based on the proposed command circuit.

Figure 17 shows the generator speed when the three-phase, double-phase-to-ground, double-phase, and single-phase-to-ground faults occur in the series-compensated system. Based on the presented results, it can be seen that generator speed crosses through zero in all fault types. As a result, distance protection based on the proposed method detects fault types in a short time and sends a trip signal to the circuit breaker.

Figure 18 shows the synchronous generator speed when a three-phase fault occurs during the stable power swing at 4 s. The obtained result shows that the method detects this case because the generator speed crosses through zero. The presented achievements indicated that the proposed method is capable of detecting the power fluctuations by changing the type of wind turbine and/or placing the compensator at the beginning of the line.
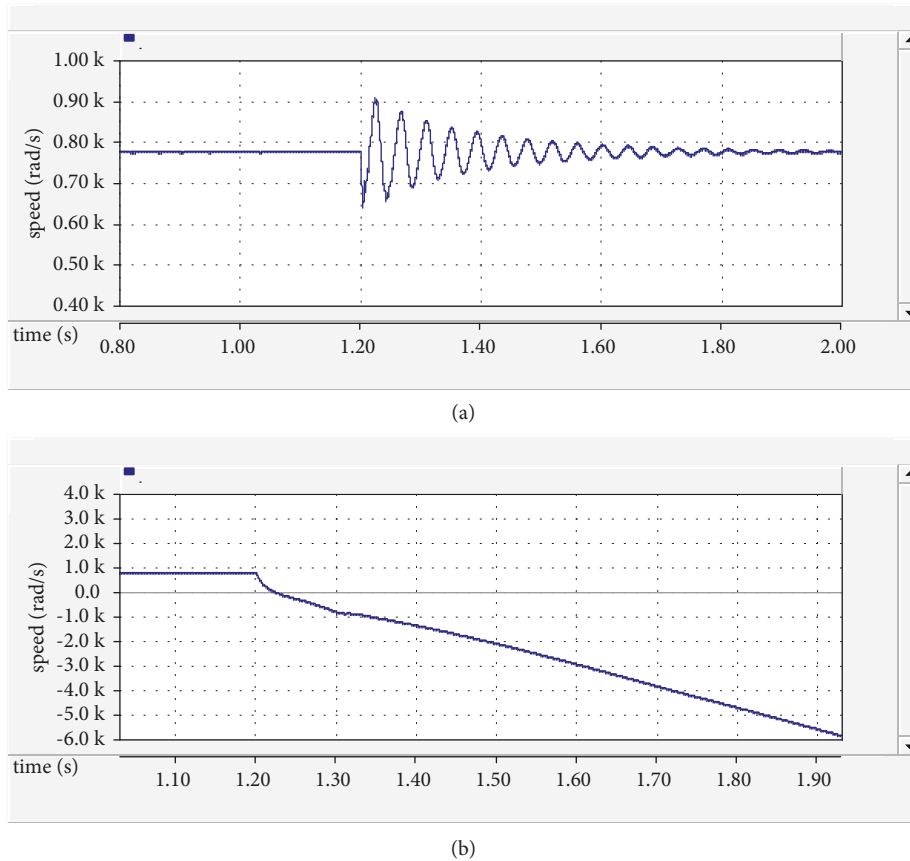
(a)

(b)

FIGURE 21: Synchronous generator speed of bus 3 during (a) stable power swing and (b) unstable power swing.

3.3. Case 3: IEEE 9-Bus Test System. In order to illustrate the capability of the proposed method in detecting the power fluctuations in a larger system, the method is tested on the IEEE 9-bus test system, as shown in Figure 19. The system includes three synchronous generators and the system data are given in [2] which is presented in Figure 20. The distance relay near bus 6 in line 6–7 is selected for the study. Figures 21(a) and 21(b) show the generator speed of bus 3 during the stable and unstable power swings with line 5–6 outage, respectively. Moreover, the generator speed during the three-phase, single-phase-to-ground, double-phase-to-ground, and double-phase faults in line 5–6 at 1.2 s is shown in Figures 22(a)–22(d), respectively.

Based on Figure 21(a), the generator speed does not pass through zero during the stable power swing, so distance protection is blocked. The proposed method detects unstable power swing based on Figure 21(b) because the generator speed crosses through zero. According to the presented results in Figures 22(a)–22(d), the generator speed passes through zero in all fault types. Therefore, distance protection detects fault types in a short time and sends a trip signal to the circuit breaker based on the proposed command circuit.

To investigate the effect of the wind farm on the performance of the proposed method, it is assumed that a wind farm with Type 2 is replaced instead of a synchronous generator in bus 2 with the same power in Figure 19. The distance relay near bus 6 in line 6–7 is selected for the study and the disturbance occurred at 1.2 s. Figures 23(a) and
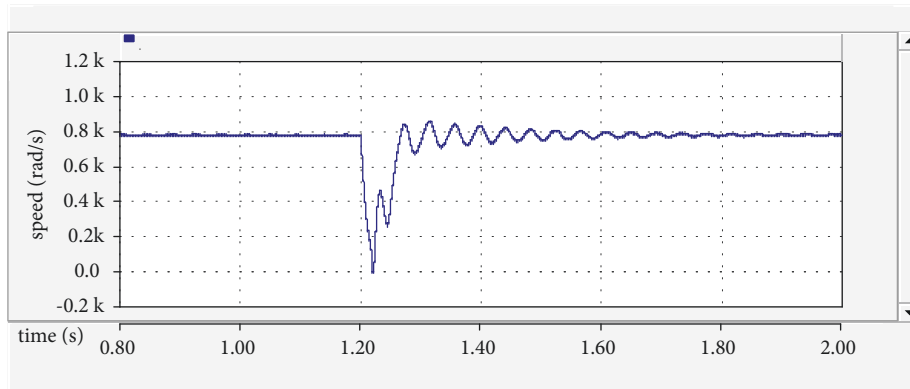
23(b) show the generator speed of bus 3 during the stable and unstable power swings, respectively. It can be seen that the generator speed does not pass through zero during the stable power swing and it passes through zero during the unstable power swing. Moreover, the generator speed crosses through zero during different fault types as shown in Figure 24. Therefore, the distance relay is blocked during the stable power swing and it is sent a trip signal during an unstable power swing and fault. Based on the presented results, the proposed method detects disturbances with and without a wind farm.

3.4. Comparison of the Proposed Method with Previous Methods. Based on the presented results in [15, 18] and obtained results in this study, Table 3 shows a comparison between the proposed method and other methods based on the different indices, including detection of symmetric fault from power swing, detection of asymmetric fault from power swing, simple simulation, and simple implementation.

According to Table 3, some methods such as the conventional blinder scheme cannot detect symmetrical fault [18]. Moreover, other methods like the SCV tracer cannot detect asymmetrical fault [18]. While symmetrical and asymmetrical faults with and without power swing are detected using the proposed GSZCM method. In addition, the proposed method has a simple simulation and simple implementation. Therefore, the proposed method can be
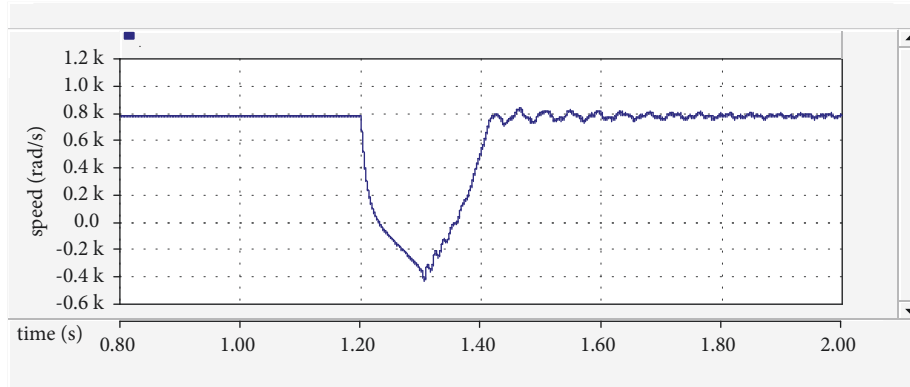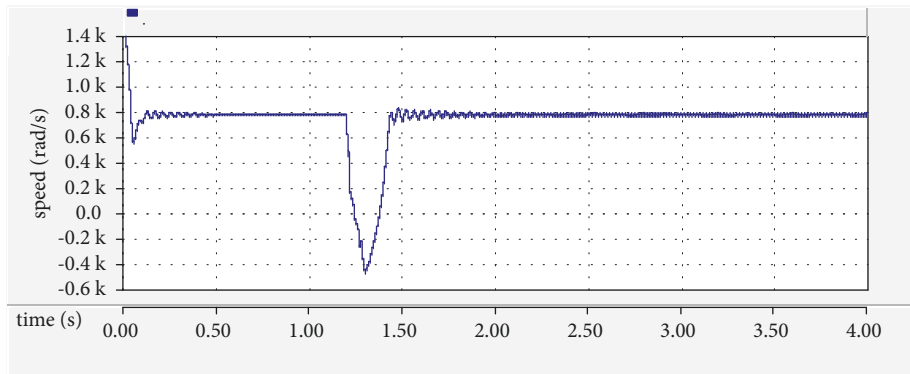
FIGURE 22: Synchronous generator speed of bus 3 during (a) three-phase fault, (b) single-phase-to-ground fault, (c) double-phase-to-ground fault, and (d) double-phase fault.

(a)

(b)

FIGURE 23: Synchronous generator speed of bus 3 during (a) stable power swing and (b) unstable power swing in presence of wind farm.
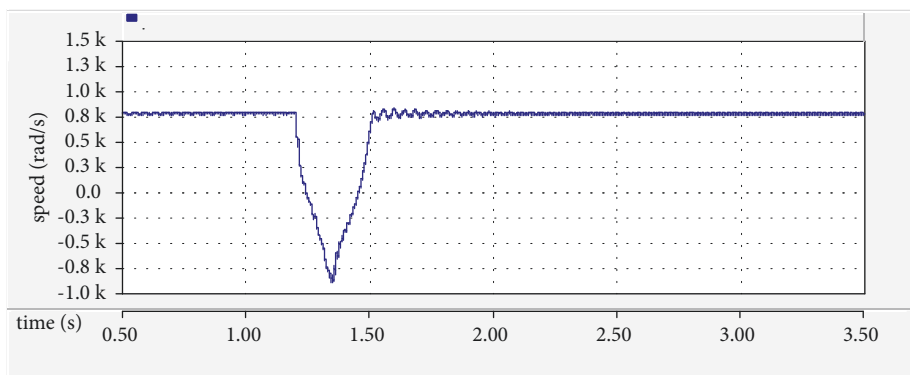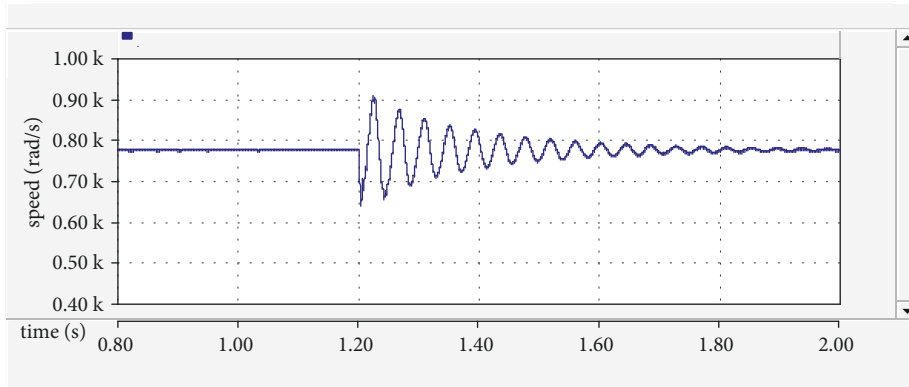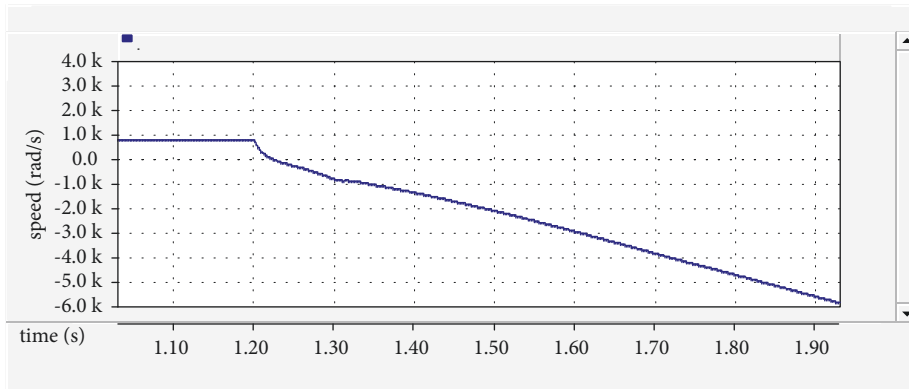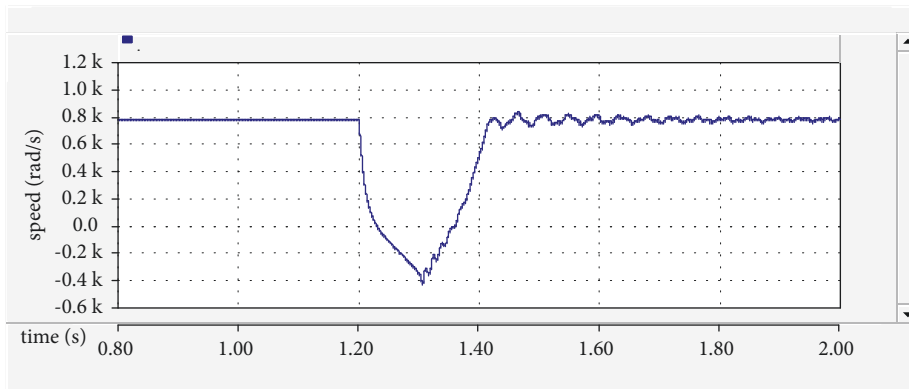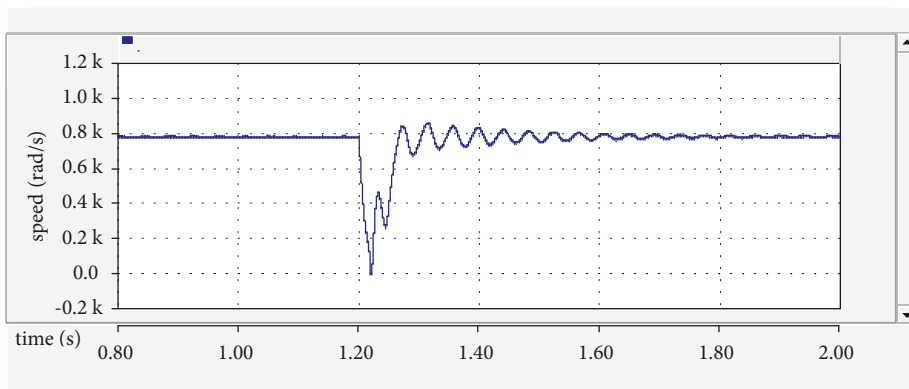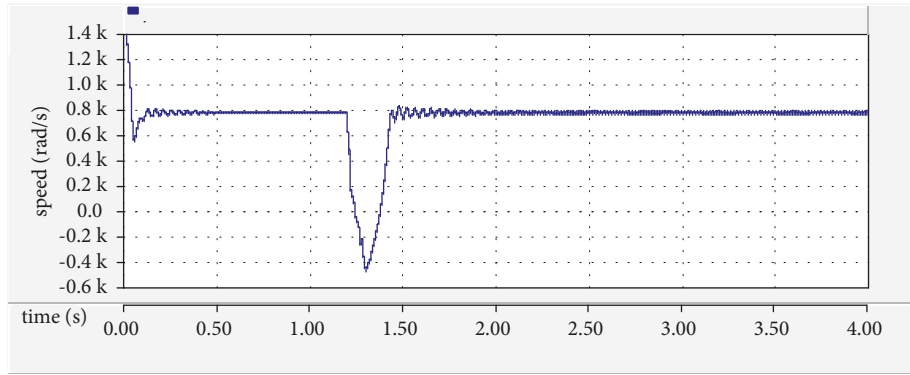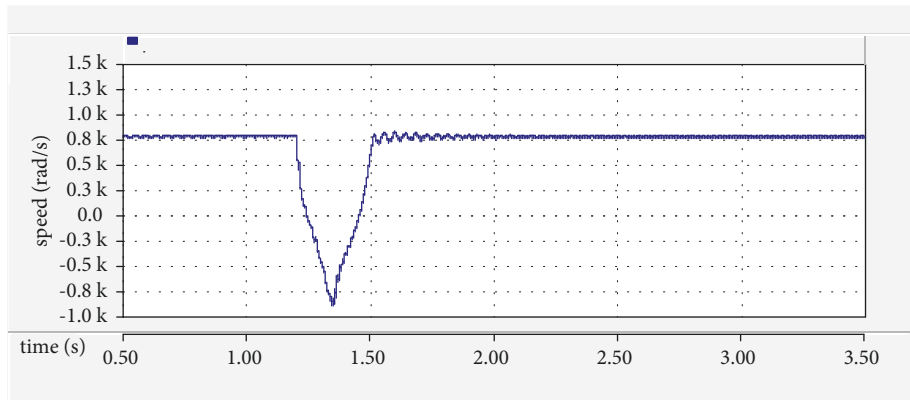

(a)

(b)

FIGURE 24: Continued.

(c)

(d)

FIGURE 24: Synchronous generator speed of bus 3 during (a) three-phase fault, (b) single-phase-to-ground fault, (c) double-phase-to-ground fault, and (d) double-phase fault in presence of wind farm.

TABLE 3: Comparison of the proposed method with previous methods.

Method	Symmetrical fault detection	Asymmetrical fault detection	Simple simulation	Simple implementation
Conventional blinder scheme [18]	N	Y	Y	Y
Wavelet transform [18]	Y	Y	Y	N
SCV tracer [18]	Y	N	Y	Y
Change of active/reactive power [18]	Y	N	Y	Y
Decrease resistance [18]	Y	N	Y	Y
Superimposed current [18]	N	Y	Y	Y
FFT [15]	Y	Y	Y	N
S transform [15]	Y	N	Y	Y
Prony [15]	Y	N	Y	Y
SVM [15]	Y	N	N	Y
GSZCM algorithm	Y	Y	Y	Y

used as an effective method in distance protection for proper operation in different conditions.

4. Conclusion

A new method was proposed to identify the power fluctuations based on the synchronous generator speed variations. In this method, all fault types with and without power swing, as well as the unstable power swing, are detected when the generator speed passes through zero. In other words, when the generator speed does not pass through zero, the power swing is detected as a stable type. The presented method has several advantages. First, it is independent of any of the line parameters. Second, it successfully detects the three-phase, double-phase, double-phase-to-ground, and single-phase-to-ground faults with high and low fault resistances in a short time. Third, the method has a simple implementation. Therefore, the proposed method can be used in the digital

distance relays for the protection of the interconnected power system with and without series compensators in the presence or absence of wind farms.

Data Availability

Data sharing is not applicable in this article because no data have been generated or analyzed during the current study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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