Improvement of Power Swing Detection Performance of a Distance Relay by using k-NN Algorithm

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Abstract

In this paper, power swing detection is studied in terms of blocking distance relay responses which lead to wrong breaker operation. A new power swing detection method based on k-NN algorithm is proposed which uses areas of triangles constituted by phase angles of instantaneous power phasors calculated by Discrete Fourier Transform (DFT). Triangles corresponding to harmonic components from 1st to 9th are processed for generating the learning database. The performance of the method is compared with four conventional power swing detection methods on a test system in 30 cases for only symmetrical faults. The results show that the proposed method has better performance than the four conventional methods in total for the cases created in this work.

1. Introduction

Today's power systems are in a large, complex and interconnected structure. Transmission lines are important parts of them which ensure energy suppliers and consumers meet reliably. Since the task is crucial, transmission lines are widely equipped with distance relays in order to be kept safe from short circuit faults. However, it is experimented in such cases like load encroachment, voltage instability or power swing that distance relays operate incorrectly and de-energize lines unnecessarily. It is an important issue since it may lead to some problems like cascading failures or blackouts.

There are various researches in literature which investigate this issue. Salient of them are focused on incorrect distance relay operation caused by power swings. This topic is investigated from the viewpoint of both power swing blocking and power swing de-blocking (when there is a fault identification during power swing) [1, 2]. Power swing blocking and de-blocking are generally dealed together [3, 4]. Because a reliable protection scheme must cope with both of them.

Today's distance relays use some conventional methods for power swing detection [5, 6]. But they seem to be insufficient in such cases like fast power swings, high resistance faults or symmetrical faults during power swing. So as to overcome those drawbacks, novel power swing detection approaches are proposed in literature.

In some of the studies, power system variables are used for the solution. The change of power [7], rate of change of voltage and current magnitudes [8], admittance trajectory [9] are used. Equal area criterion is adapted for solution of the problem [10].

In some of the studies, mathematical processes or transforms are applied for the solution. Wavelet [3], Discrete Fourier Transform (DFT) [11], Fast Fourier Transform (FFT) [12], signal processing [13] or mathematical morphology [14] methods are experimented as a solution of incorrect distance relay operation associated with power swing phenomena.

In some other studies, machine learning or fuzzy logic based methods are used. Probabilistic neural networks [15], support vector machines [16], neuro-fuzzy [4] and fuzzy-logic methods [17] are proposed as a solution of the same problem.

It seems that novel methods are more reliable and have better performance than the conventional methods in general, although some of them also have some drawbacks like computational burdens or system-dependences.

In this study, a distance protection scheme considering power swing detection by using k-NN algorithm is proposed. Fault and power swing cases are examined individually for testing, faults during power swing cases are not considered. The paper is organized as follows: Distance protection and conventional power swing detection methods are explained in Section 2. Test system, k-NN algorithm and the proposed distance protection scheme is revealed in Section 3. Results of the analyses are given in Section 4. Conclusions are released in Section 5.

2. Background

2.1. Distance Protection

Distance protection is widely used for protection of transmission lines and performed by distance relays. It is defined by zones for main and remote protection. The main operation is to measure fault impedance by using the measured short circuit voltage and current at the relay location and then compare it with the known line impedance [18]. If there is a fault on the line, the impedance value gets low values and it indicates an internal fault. If the impedance gets lower values than another predefined value, it indicates a fault in the adjacent line. The first impedance value determines Zone 1, which is defined by 80%-95% of impedance value of the transmission line being protected. The second impedance value determines Zone 2 (remote protection) and is commonly defined as 120%-150% of the line impedance with 0.3 seconds time delay.

2.2. Power Swing Blocking

When there is a sudden load change, loss of a big generation unit or opening of a critical line, then the phenomena called power swing happens. The oscillation is damped if it is a stable swing but it grows if it is an unstable one. During a power swing, distance relay may calculate lower impedance values than normal operating conditions falling in any of the zones. Since it means an incorrect breaker operation, it must be blocked by using some methods.

2.3. Conventional Power Swing Detection Methods

In order to block unnecessary tripping action during a power swing, today's industrial distance relays use some conventional methods [5, 6]. They calculate some parameters and compare it with a predefined value for that purpose.

According to the experiments, it is known that the duration of time (Δt) which takes impedance value for crossing Zone 2 is high for power swing cases when compared with fault cases. Using this assumption, it is possible to decide for a case if it is a fault or a power swing. It is called "the decreased impedance method" (named as "method 1" in this work).

Investigating the change of Vcosφ value may also indicate a difference between fault and power swing. The speed of change of Vcosφ is higher for fault and lower for power swing. Comparing a predefined threshold with Vcosφ calculated during operation, it may be possible to distinguish between fault and power swing. This method is called "the Vcosφ algorithm" (named as "method 2" in this work).

Another conventional power swing detection method is "the superimposed method" (named as "method 3" in this work). Since it is known that the superimposed current value is higher for fault and lower for power swing, the relay continuously calculates the superimposed current and compares it with a predefined threshold when necessary in this method. The superimposed current is defined as follows:

$$I_{k,si} = I_k - I_{k-N} \tag{1}$$

where $I_{k,si}$ denotes the superimposed current, k denotes the present sample number, N shows the number of samples per cycle. $I_{k,si}$ is defined as the difference of the present sample of current and the sample of current one cycle before.

Tracking only the real part of impedance value is also a key for discrimination of fault and power swing. "The decreased resistance method" (named as "method 4" in this work) uses this property. The speed of change of resistance is higher for fault and lower for power swing. So, it is possible to decide whether it is a fault or a power swing by comparing with a threshold.

3. Methodology

In this study, power swing detection is made by using k-NN algorithm which is a simple machine learning method. Learning database is created by using voltage and current samples. For this purpose, 12 fault and 12 power swing conditions are created in a test system shown in Figure 1 and after the signals are processed, they are used to distinguish power swing from fault.

The test system is used for power swing detection analyses in some studies before [3]. It is connected to an infinite bus and has a power signal which has a 50 Hz frequency and 22 kV voltage level. The distance relay (R) is protecting line 1 positioned on bus A side of the line. Protection zone 1 is set as 200 ohm, which is approximately 80% of the impedance value of the line.

The test system is simulated in PSCAD/EMTDC software and the results are used for both obtaining learning (24 cases) and testing (30 cases) databases. The performance analyses are carried out in MATLAB.

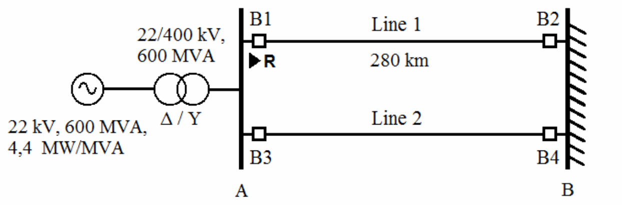

Fig. 1. Test system used for creating fault and swing cases which are involved either in learning or test databases

3.1. k-NN Algorithm

Machine learning is a broad set of methods which is widely used for various classification and regression problems in literature. k-NN algorithm is one of the simplest machine learning methods [19]. It is used as a classification tool in this study. For classification, the learning database is ready to be used directly for making a decision in this algorithm. Let L_1 and L_2 be the learning sets containing N numbers of points with n dimensions for a two class problem. They form the learning database together and must be stored in memory during the process. When a new point is detected, the algorithm checks the Euclidean distance of the new point to the points defined in L_1 and L_2. After the nearest k points are determined, it is clear that:

$$p_1 + p_2 = k \tag{2}$$

where p_1 and p_2 are defined as the number of the points belong to class 1 and class 2, respectively. Decision is made like that:

$$\begin{array}{l}\text{the new point belongs to class 1, if } p_1>p_2\\ \text{the new point belongs to class 2, if } p_2>p_1\end{array} \tag{3}$$

k is chosen as an odd number (like 3, 5, 7, ...etc.) in order to prevent any equality case which means a dilemma (no decision).

3.2. Generating the Learning Database

During a power system operation, the learning database must be already formed which contains fault and swing sets as reference. In this study, 12 fault and 12 power swing cases are created in test system shown in Figure 1. Criteria used as basis for that purpose are the location of the fault (2 cases - on Line 1 or Line 2), the distance of the fault (3 cases - on 25%, 50% or 75% of the line length) and fault inception angle (4 cases - on 0°, 45°, 90° or 135° phase angles). Total 2 × 3 × 4 = 24 cases are created in this way. Duration of the simulation carried out in PSCAD is 3 seconds for all of the analyses. In all of the 24 cases, symmetrical (three-phase) faults with a 10 mΩ fault resistance which are cleared after 100 ms by operation of circuit breakers are created. The fault is located on Line 1 in 12 of the cases and on Line 2 in 12 of others, representing fault and power swing cases, respectively.

The voltage and current signals are being tracked with a 1 kHz sampling frequency by distance relay (20 samples per cycle). As a part of the proposed method in this work, when the absolute value of the impedance enters Zone 2 (which is set as region of impedance values less than 375 ohm), the phase angles of instantaneous powers are calculated for three consecutive sampling windows right after the entrance. The phase angles are determined by DFT and it is repeated for harmonic components form 1st to 9th, synchronously. It can be shown by the formula:

$$Pe^{j\alpha} = \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} p(k\Delta t)e^{-\frac{jk2\pi}{N}} \quad (4)$$

where P is the instantaneous power phasor defined by calculating DFT of instantaneous voltage and current values' product, α is the phase angle, N is the number of samples per cycle, k is the sample number, p is the instantaneous power value for any sample. In order to obtain a learning set, the three angles are reduced to a single parameter for 9 harmonic components. It is the area of triangle which is formed by three consecutive angles and defined on the unit circle. Since there are 9 harmonic components dealed with, there are 9 triangles (and area values) for a fault or a swing case. The area of the triangles can be defined as follows:

$$A_h = \frac{1}{2}\det\left(\begin{bmatrix} \cos(\alpha_1) & \sin(\alpha_1) & 1 \\ \cos(\alpha_2) & \sin(\alpha_2) & 1 \\ \cos(\alpha_3) & \sin(\alpha_3) & 1 \end{bmatrix}\right), (h = 1...9) \quad (5)$$

where h is the number of harmonic component; α_1, α_2, and α_3 are phase angles of three consecutive instantaneous power phasors.

Since the area is calculated by determinant operation, it can have negative values also, depending on sequence of the consecutive angles. It is an advantageous result from the point of reflecting the changing regime better. The learning database (for either fault or swing sets) contain points defined by 9 areas of triangles for corresponding harmonic components. For instance, triangles constituted when Zone 2 is entered for the case when the three-phase fault with a 90° inception angle is created on 50% of Line 1 (a fault case) and on Line 2 (a power swing case), are shown in Figure 2 together.

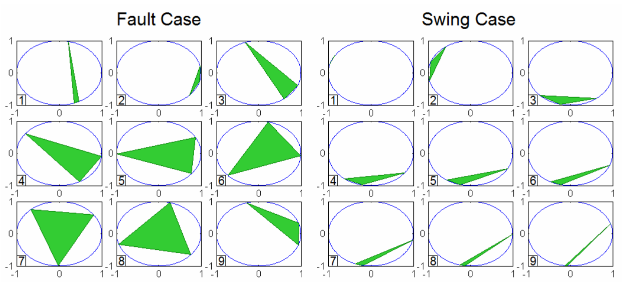

Fig. 2. Triangles constituted for harmonic components from 1st to 9th (for a fault and a power swing case)

When 9 couples of triangles in Figure 2 are compared with each other, the key idea behind selection of this feature for generating the learning database can be understood better. The areas of triangles for a certain harmonic component differ from each other for fault and power swing cases. By using this feature, learning sets L_1 and L_2 are formed which are matrices with 12×9 dimensions, both. By using this approach, all of the three consecutive angle parameters are valued and the memory size is reduced by calculating a single parameter (area of triangle). The overall structures of the learning sets (fault and swing databases) are shown in Figure 3.

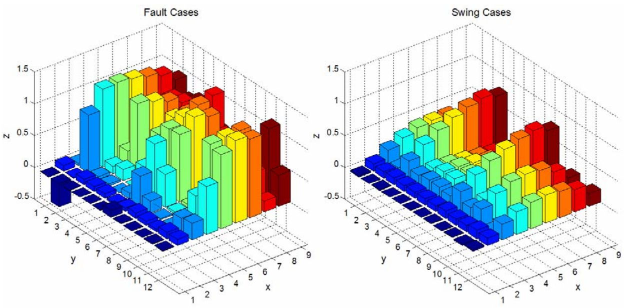

Fig. 3. Demonstration of fault and power swing databases (x denotes the number of harmonic component, y denotes the case number, z denotes the area of triangle)

3.3. Proposed Distance Protection Scheme with Power Swing Detection

Distance relay must perform proper action with the proposed power swing detection method, either for a fault or a power swing case. In order to carry out a correct operation, the protection scheme shown in Figure 4 is established.

According to the protection methodology, when there is a warning that Zone 2 is entered, the algorithm calculates the triangle areas and determines parameters p_1 and p_2 by using k-NN algorithm which represents number of fault and swing neighbors, respectively. These parameters are stored as long as Zone 2 is not left. If $p_1>p_2$ then it means there is a fault condition, but if Zone 1 is not entered yet, there won't be a tripping action. If $p_2>p_1$ then it means there is a swing condition and if Zone 1 is entered, power swing blocking action is taken. If Zone 2 is left before Zone 1 is visited, parameters p_1 and p_2 will be ruled out. When Zone 2 is visited again, parameters p_1 and p_2 will also be calculated again.

4. Analyses and Results

In this section, the proposed protection scheme with power swing detection is tested for various conditions and the performances of the proposed and the four conventional methods are compared. The same test system used for generating the learning database for k-NN algorithm is used again (Figure 1). Total 30 (15 fault and 15 power swing) cases are generated.

The distance and duration of the fault are all created randomly (with a uniform distribution) this time in contrast to the process of learning set creation. Criteria used for generation of test cases are: the location of the fault (15 cases on Line 1, 15 cases on Line 2), the distance of the fault (random between 0% and 80% of the line length - so as to fall in Zone 1), fault inception angle (random between 0° and 180° phase angles) and duration of fault (random between 80-320 ms for 23 cases, between 10-80 ms for 7 cases). Although the duration of fault is constant at 100 ms in learning cases, it has random values for test cases. In all of them, symmetrical (three-phase) faults with a 10 mΩ fault resistance are created as such in the learning cases. Faults are cleared after a circuit breaker operation except 7 of the power swing cases in which the duration of faults is less than 80 ms and the fault is cleared before any action.

The threshold parameters set for the conventional methods are listed in Table 1. They are left unchanged during the whole process of testing.

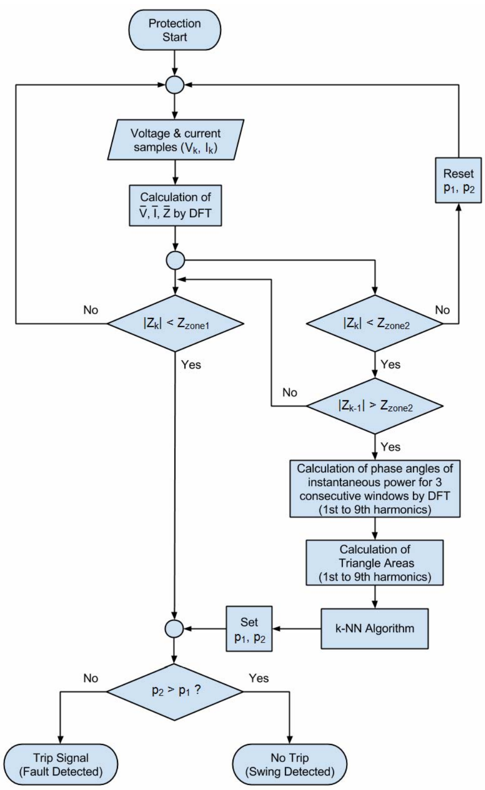

Fig. 4. The flowchart of the proposed protection scheme (k denotes the instantaneous sample number)

Table 1. Parameters of the conventional methods and the threshold values of them used during the analyses

Method	Parameter Being Tracked	Swing Threshold
1	Δt	> 10 ms
2	d(Vcosφ)/dt	< 6000 kV/s
3*	I_k-I_{k-N}	< 0.8 kA
4	dR/dt	< 20 kΩ/s

*N=20, number of samples per cycle

Parameter k for k-NN algorithm is 3. After setting all of the parameters, analyses of the 30 test cases are repeated for each of the methods in order to obtain the switching responses. It is ideally expected for any of the methods that there must be a breaker operation (switch must be on) for all of the fault cases and there must not be any breaker operations (switch must stay off) for all of the swing cases. So, this criterion is used for performance comparison and the methods are tested in existence of any incorrect operation.

For example, the fault is on Line 2, the distance of the fault is 22.38% of the line length, inception angle is 102.6° and the duration of the fault is 221.7 ms for one of the swing cases (case 25). Current of phase 1 versus time during a power swing is shown in Figure 5, for this case.

Distance protection is carried out in forward direction. Switching responses for distance relay operation solely, operation with method 1, method 2, method 3, method 4 and with the proposed method are given in Figure 6 together for this case. Since the symmetrical fault is investigated, impedance of only phase 1 is considered during analyses.

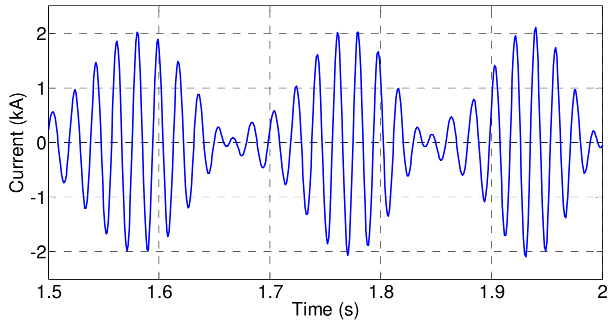

Fig. 5. The current signal during power swing for case 25

It can be seen from Figure 6 that, breakers are operated unnecessarily in distance relay operation without using any swing detection methods. When the conventional methods are used, it is not possible to prevent wrong breaker operation similarly. However, breakers are not operated when the proposed method is used. It is seen that, only the proposed method is successful at detecting power swing properly and at blocking unnecessary breaker operation for this case.

The same results are valid in 5 of the 15 swing cases. Only the proposed method is successful at blocking breaker operation correctly in these 5 cases. All of the methods are successful at blocking wrong operation in 7 of the cases. None of the methods are successful at power swing detection in 3 of the cases. The performances of the methods are summarized in Table 2.

Table 2. Performances of Conventional Methods and the Proposed Method in Operation (%)

	Conv. Method 1	Conv. Method 2	Conv. Method 3	Conv. Method 4	Prop. Method
Fault	86.7	**100.0**	93.3	80.0	86.7
Swing	46.7	46.7	46.7	46.7	**80.0**
Total	66.7	73.3	70.0	63.3	**83.3**

It can be clearly seen from Table 2 that, the proposed method has quite better performance than the conventional methods regarding both the power swing cases and all of the total 30 cases. It is also good at correct fault operation but it causes wrong swing blocking in 2 of 15 fault cases. Compared with the other methods it has a sufficient performance, but a worse performance than method 2 and 3 in fault cases.

5. Conclusions

In this study, a power swing detection method which uses k-NN algorithm is proposed and performance of the method is compared with some conventional methods. In this method, the feature extracted for fault and power swing discrimination is the area of triangles constituted by angles of three consecutive sampling windows of instantaneous power phasors for harmonic components from 1st to 9th.

30 test cases are created for performance comparison. It is observed that conventional methods are strongly dependent on the threshold parameter chosen, leading to serious incorrect breaker operations during some fault or power swing conditions.

The swing detection performance of the proposed method is the best of the whole methods. But the drawback is the wrong

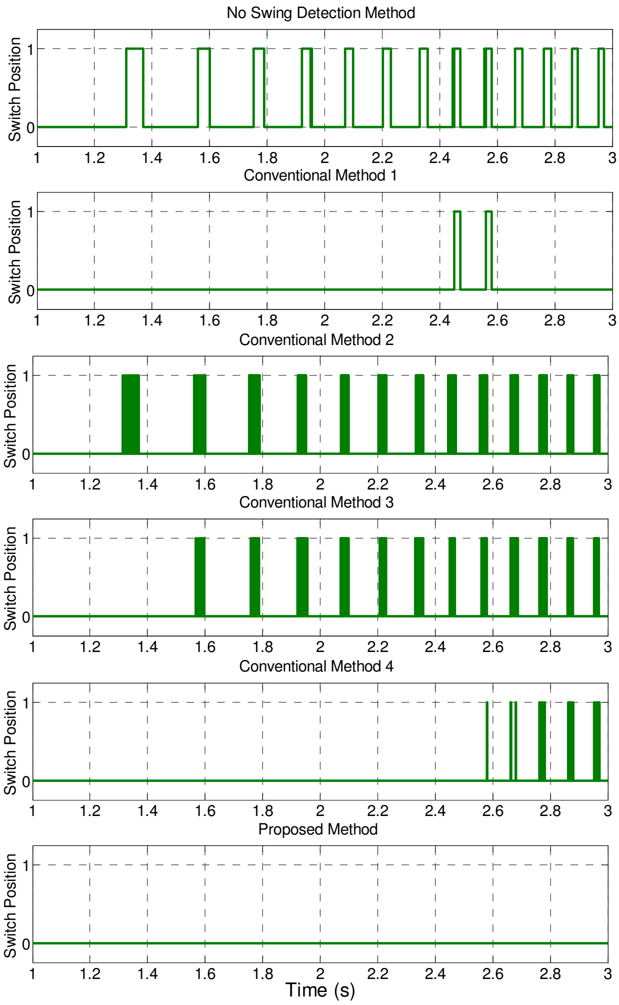

Fig. 6. Responses of distance relay with the proposed, conventional methods and without any of them

breaker operation happened in 2 fault cases. Although it has the best operation performance in this study, it is still unsuccessful at correct operation in some fault and swing cases.

It can be concluded that the proposed method is more successful than the four conventional methods. Besides that, since the analyses are done for only symmetrical short circuit faults and for a single test system in this work, the studies must be extended to other types of faults and to different test systems in future work. Creation of optimum learning databases may also be focused on in order to get better performance.

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