Identification of Fault and Load Increase to Prevent Distance Relay Mal-Operation

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Abstract—**Distance relay mal-operation has been identified as one of the factors of blackouts in the world. One of the causes that lead to this problem is distance relay cannot differentiate between fault occurrence and load increase in transmission lines. This paper presents a proposed method to identify fault occurrence and load increase in transmission line to prevent distance relay mal-operation. The analysis of instantaneous voltage and root mean square (RMS) voltage signal waveform measured at the corresponding buses are used to differentiate the characteristics between two of them. The proposed technique is designed and validated through simulations of IEEE 9 bus test system in PSCAD and the plots of the voltage waveform using Microsoft Excel. The results show that there are different characteristic of voltage waveform that can clearly indicates fault occurrence and load increase.**

Keywords: Distance relay mal-operation, Fault, Load increase, Transmission line, Instantaneous voltage, Root mean square (RMS) voltage.

I. INTRODUCTION

The function of distance relays in transmission line is to discriminate between the normal operations and fault conditions. It operates on the basis of voltage to current ratio (impedance, Z) at the point of measurement. A relay initiates a trip signal to the associated circuit breaker when a fault occurs within its operating zone. However, it has been observed that unwanted tripping signal caused by unexpected loading conditions have often contributed to the mal-operation of distance relay and lead to cascading blackouts.

On 14 August, 2003, the largest North American blackout has occurred about 4:10 p.m. Eastern Daylight Time (EDT) [1-3]. It resulted in more than 70,000 megawatts (MW) of electrical load loss in parts of Ohio, Michigan, New York, Pennsylvania, New Jersey, Connecticut, Massachusetts, Vermont, and the Canadian provinces of Ontario and Quebec. The number of people that have been affected is predicted about 50 million. According to the report, there are many different factors that caused the wide area system collapse. One of them is many of the key lines that tripped operated on Zone 3 impedance (distance) relays (or Zone 2 relays set to operate like Zone 3s), which responded more to overloads than faults on the protected facilities.

Another analysis of most recent blackouts; such as on September 23, 2003 that is blackout in Sweden and Denmark; and on September 28, 2003 in Italy [4]; indicates a common theme and points to similar causes and outcomes. One of the theme in the referenced cases is the blackouts occurred when the power system was extremely stressed, such as during times of heavy power demand (overloading).

To improve the reliability of distance relay performance, it is important for us to find an indicator that can differentiate between fault occurrence and load increase. This can be done by identifying the characteristics that can clearly differentiate between two of them. Instantaneous voltage and root mean square (RMS) voltage signal has been used to achieve this goal.

This paper is organized as follows. In section II, a general overview of distance relay tripping zone is presented. Section III presents the methodology used in order to identify the fault occurrence and load increase. Results and discussion of the proposed method are presented in section IV. Finally a conclusion is presented in section V.

II. DISTANCE RELAY TRIPPING ZONES

For a typical transmission line in an electric utility's transmission system, there are three zones of distance relay protection. The first zone, designated as Zone 1 (Z_1) distance relay is used to provide primary high speed protection for a significant portion of the transmission line. To avoid unnecessary operation for faults outside the remote terminal, Zone 1 is set to reach for approximately 80-90% of the transmission line impedance. The second zone, known as Zone 2 (Z_2) is used to cover the rest of the protected line and provide some backup for the remote end bus. It is set to cover 100% of the line plus 20% of the adjacent line. The third zone, which is Zone 3 (Z_3), is the backup protection for all the lines connected to the remote end bus. Its reach is set for 100% of the line plus 120% of the adjacent line. Figure 1 shows the reach of distance relay protection zones.

The relays' time of operation for each zones are different. Zone 1 distance relay protection is designated with no intentional time delay. It means, Zone 1 distance relay will operate instantaneously right after the fault occurs. Zone 2 relays have to be time delayed to coordinate with relays at the remote bus which is to allow Zone 1 relays operate first. Typical Zone 2 time delays are of the order of 15 to 30 cycles or about 0.25 second to 0.5 second. Originally, Zone 3 was applied as a remote backup to Zone 1 and Zone 2 of an adjacent line in the case that a relay or breaker failure. Zone 3 times allows the relays closer to the fault to operate first. Therefore, Zone 3 operations must be in longer time delayed to coordinate with Zone 1 and Zone 2 delays. There are no standards in Zone 3 operation, but 90 cycles is a usually used timer setting. It is about 1.5 seconds. The purpose of different time setting for each zone is to allow the relays closest to the fault to operate first.

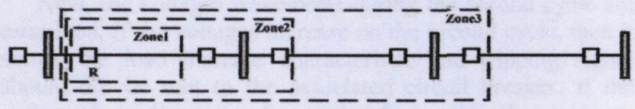


Figure 1: Distance relay protection zones

The R-X diagram shows the distance relay tripping zones characteristic. The R-axis indicates the value the real part of impedance, Z, while the X-axis indicates the imaginary part of impedance, Z. The adjustable setting of distance relay operating zones is obtained from the line impedance parameter, Z_L. The value of apparent impedance, Z_a is calculated from the measured voltage and current at the remote buses. Figure 2 shows the R-X diagram of the three zones of distance relay protection.

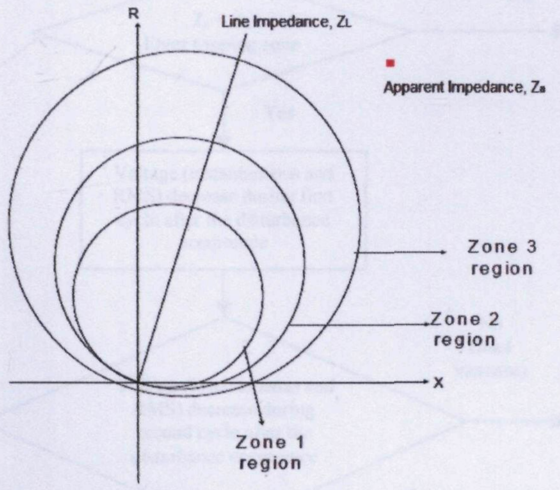


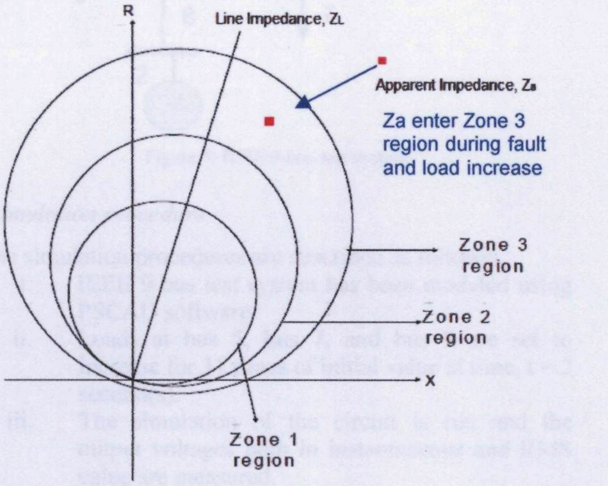
Figure 2: R-X diagram for three zones of distance relay protection

The setting of distance relays is based on the line impedance, Z_L while the relay operating zones is based on the measured impedance calculated from the monitored voltage and current signals that is apparent impedance, Z_a.

When a fault occurs in a power system, voltage will decrease while current will increase. Thus, the value of voltage over current ratio, Z_a will decrease. If Z_a is smaller than Z_L, it will enter the tripping zone and causes the distance relay to send tripping signal to associated circuit breaker.

The same thing occurs when there is load increase in the power system. Voltage will decrease while current will increase. Thus, the value of voltage over current ratio, Z_a will decrease. If Z_a is smaller than Z_L, it will enter the tripping zone and causes the distance relay to send tripping signal to associated circuit breaker. However, it should not send the tripping signal when there is load increase.

The setting of distance relays should ensure that they are not going to operate when not required (security) and will operate to trip when necessary (dependability). The behavior of distance relays during several recent major blackouts combined with the significant pressure on utilities to increase the loading of their transmission systems is the reason why discrimination between fault and load increase is really important. It is to avoid the distance relay sending false tripping signal to the circuit breaker and causes the unintended blackouts.



Za enter Zone 3 region during fault and load increase

Figure 3: Z_a entering the operating region

III. METHODOLOGY

This is the proposed method that used to distinguish between the characteristic of fault occurrence and load increase. In order to achieve this goal, the instantaneous voltage and root mean square (RMS) voltage signal waveform are used.

Firstly, apparent impedance, Z_a is monitored. The value of Z_a is obtained from the measured voltage and current at the remote bus. It is calculated using the following equation,

$$Z_a = V_i / I_{ij} \tag{1}$$

where,

V_i = Voltage at bus i
I_{ij} = Current flow from bus i to bus j

The value of Z_L which is the adjustable setting of distance relay tripping zones is obtained from the line impedance parameter.

Under normal operation, Z_a must be greater than Z_L and it makes Z_a lies outside the tripping zones. If the monitored value of Z_a is less than Z_L, it will enter the tripping zone of distance relay.

When Z_a enters the tripping zone, it means fault has occurred. But, there is also a possibility that Z_a enters tripping zone during load increase. Then, both of instantaneous voltage and RMS voltage waveform are examined. During first cycle after the disturbance occurrence, both of the voltages are decreased.

Next, the voltages waveforms during the second cycle are examined. If the voltages increase on the second cycle, then it shows the load increase characteristic and tripping signal should not be sent to the associated circuit breaker. If the voltages keep decreasing for another few cycles, then it shows fault is occurs. Only then the tripping signal should be sent to the associated circuit breaker.

The proposed technique is summarized in the flow chart shown in Figure 4.

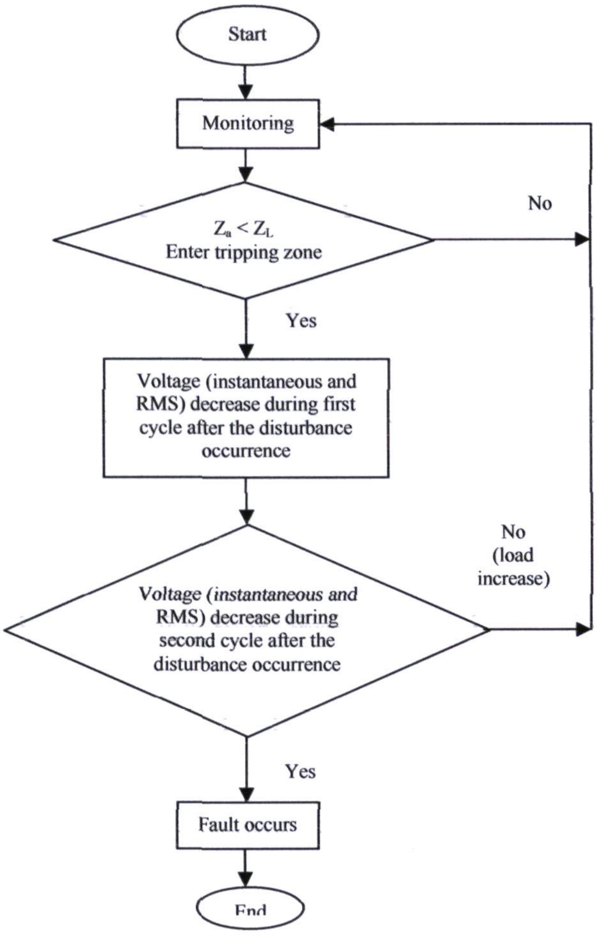


Figure 4: Flow chart of the proposed method for differentiating fault occurrence and load increase

IV. RESULT AND DISCUSSION

A. Test system

IEEE 9-bus test system has been used as the test system. It consists of three generators, nine transmission lines, and three loads. The voltage is at 13.8 kV. Bus 1, bus 2, and bus 3 are noted as the generation buses; and the loads are located at bus 5, bus 7, and bus 9.

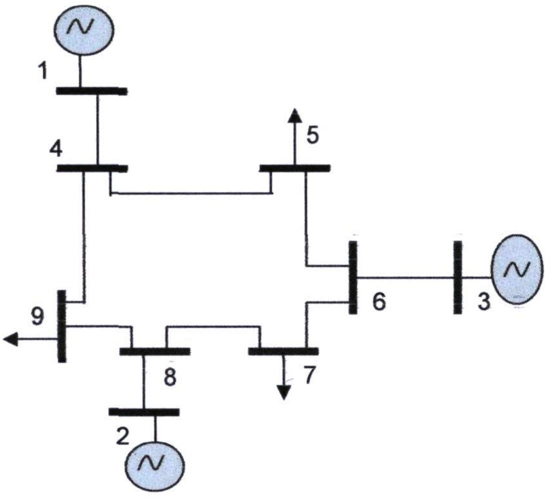


Figure 5: IEEE 9-bus test system

B. Simulation procedure

The simulation procedures are described as follows:

i. IEEE 9-bus test system has been modeled using PSCAD software.
ii. Loads at bus 5, bus 7, and bus 9 are set to increase for 11 times of initial value at time, t = 2 second(s).
iii. The simulation of the circuit is run and the output voltages both in instantaneous and RMS value are measured.
iv. Another IEEE 9-bus test system is constructed in other file using PSCAD software.
v. Relays are assumed to be located near bus 5 (remote bus is bus 5). Fault is created at line 9-4 which is located in Zone 3 reach of the set relay, at t = 2s, and the duration of fault is 0.1s.
vi. The simulation of the circuit is run and the output voltage at the corresponding bus both in instantaneous and RMS value are measured.
vii. The data of instantaneous voltage and RMS voltage signal waveform at the corresponding bus for both fault occurrence and load increase are collected and the waveform of the voltages against time are plotted in Microsoft Excel.
viii. The voltage waveforms are analyzed to find the major difference between fault occurrence and load increase.
ix. Step V-VIII is repeated by creating faults at various locations those are in Zone 3 reach of the set relay.

Relays are assumed to be located near bus 5 that is the remote bus is bus 5. Faults are set to occur in various locations considering the Zone 3 reach of the relays. Various cases are considered. Those are:

a) Case 1: Fault occurs at line 9-4
b) Case 2: Fault occurs at line 9-8
c) Case 3: Fault occurs at line 7-6
d) Case 4: Fault occurs at line 7-8
e) Case 5: Fault occurs at line 1-4
f) Case 6: Fault occurs at line 3-6

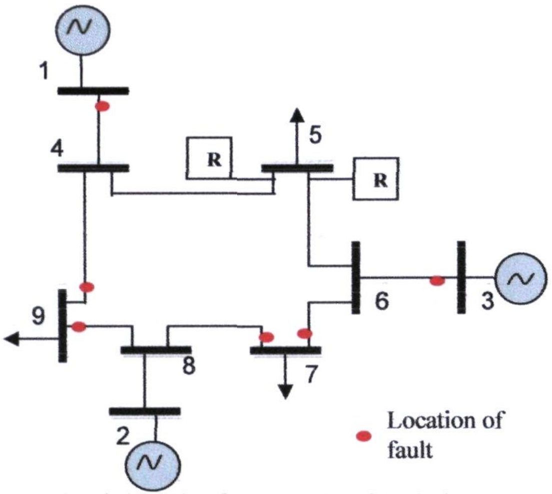


Figure 6: Various fault locations for Zone 3 reach of Bus 5 relays

The results of instantaneous voltage,V and RMS voltage,V_{RMS} signal waveform for both fault occurrence and load increase are plotted in Microsoft Excel and observed as shown as follows.

C. Result for comparison of instantaneous voltage, V waveform

Figure 7 (a) shows the waveform of instantaneous voltage, V against time, t (V versus t) measured at bus 5 for Case 1.

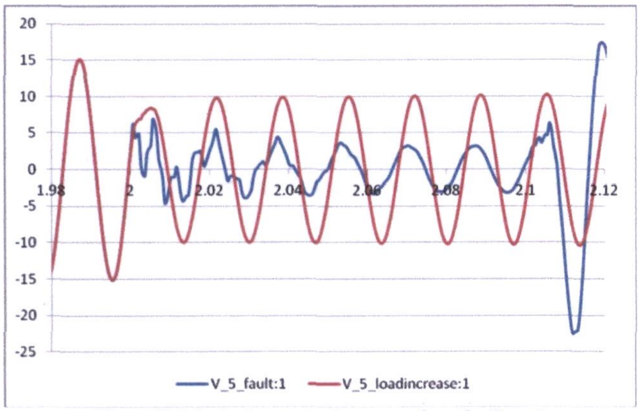


Figure 7(a): Instantaneous voltage waveform for Case 1

From the figure, it can be seen that the instantaneous voltage, V for both of fault occurrence and load increase decreased at the first cycle after time, t = 2 second, s (the time when the disturbances are set to occur). On the second cycle, V for fault occurrence is still decreasing; but for load increase V is increased. Therefore, the difference between two of them can be identified during the second cycle. During fault occurrence, V decreased on the first cycle after the occurrence and it keep decreasing for a few cycles forward; but during load increase, V decreased only for the first cycle and it will increase during the second cycle.

There are five other cases of fault occurrence at different locations are tested in this condition. All the cases tested have resulted in the same characteristic as described in Case 1. It is been proven in Figure 7 (b, c, d, e, f) below.

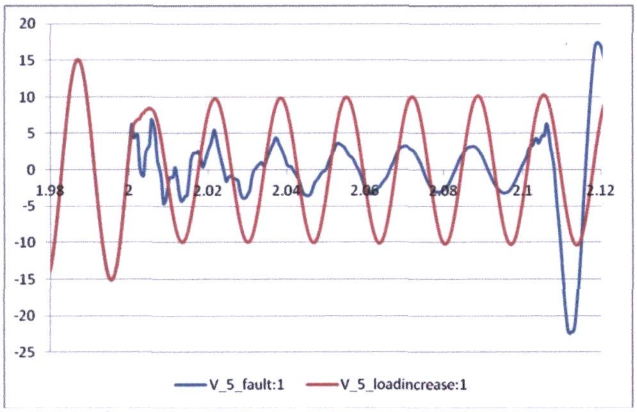


Figure 7(b): Instantaneous voltage waveform for Case 2

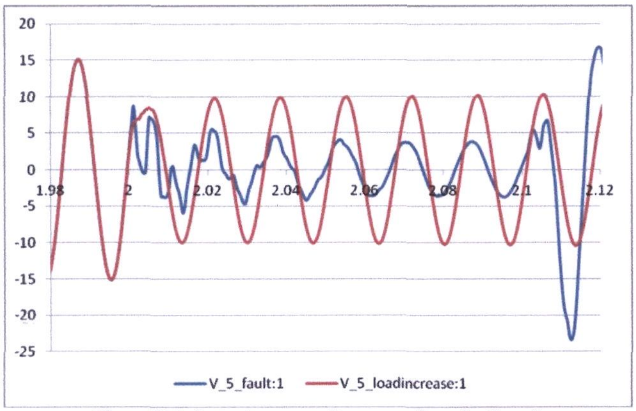


Figure 7(c): Instantaneous voltage waveform for Case 3

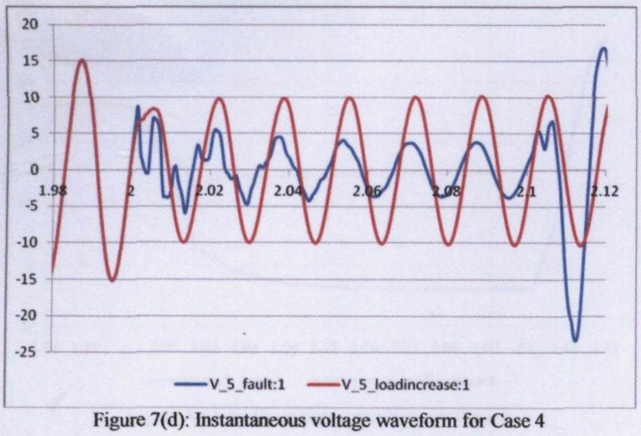


Figure 7(d): Instantaneous voltage waveform for Case 4

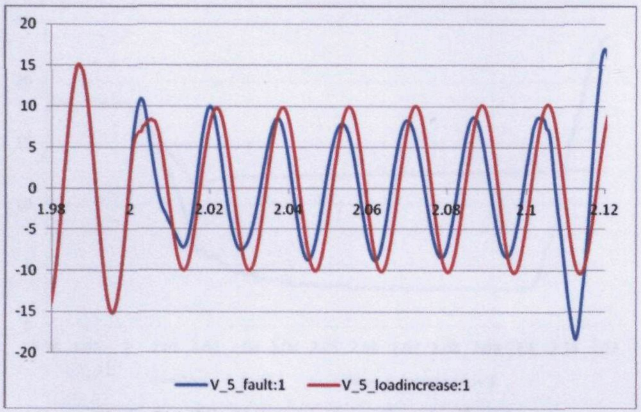


Figure 7(e): Instantaneous voltage waveform for Case 5

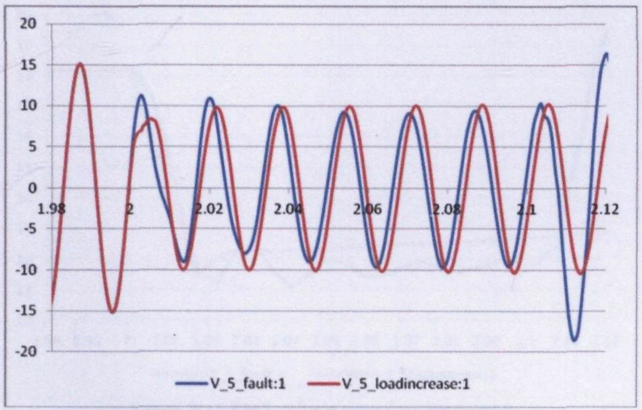


Figure 7(f): Instantaneous voltage waveform for Case 6

After analyzing all of the instantaneous voltage waveforms, it is proved that all the cases tested will result in the same pattern of waveform as described in Case 1. During fault occurrence, V decreased for the first cycle after the disturbance and it will keep decreasing for a few cycles forward; but during load increase, V decreased only for the first cycle after the disturbance and it will increase during the second cycle.

D. *Result for comparison of RMS voltage, V_{RMS} waveform*

Figure 8 (a) shows the plot of RMS voltage, V_{RMS} against time, t (V_{RMS} versus t) for RMS voltage measured at bus 5 for Case 1.

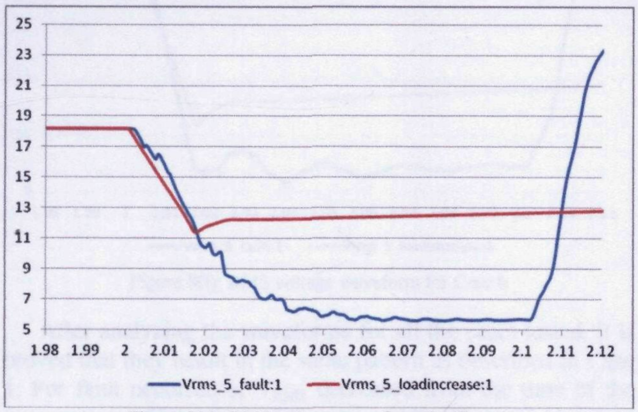


Figure 8(a): RMS voltage waveform for Case 1

From the figure, it can be observed that the similar pattern between instantaneous voltage and RMS voltage signal waveforms are shown. The RMS voltage, V_{RMS} for both of fault occurrence and load increase decreased after time, t = 2 second, s (the time when the disturbances are set to occur). Note that for frequency used is 60 Hz, the time taken for 1 cycle is 0.016s. Therefore, the time for 1 cycle after t = 2s is t = 2.016s. After t = 2.016s, V_{RMS} for fault occurrence is still decreasing; but for load increase V_{RMS} is increased. Therefore, the difference between two of them can be identified after the time of 1 cycle. For fault occurrence, V_{RMS} decreased from the time of the occurrence until the time of 1 cycle, and it will keep decreasing for a few seconds forward; but during load increase, V_{RMS} decreased only from the time of the occurrence and it will increase after the time of 1 cycle.

There are five other cases of fault occurrence at different locations are tested in this condition. All the cases tested have resulted in the same characteristic as described in Case 1. It is been proven in Figure 8 (b, c, d, e, f) below.

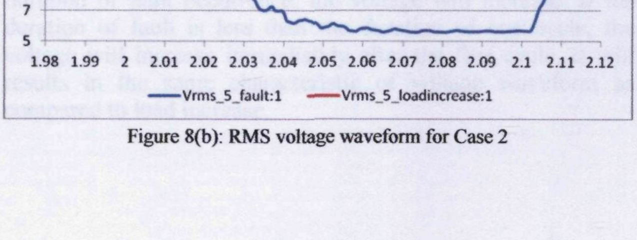


Figure 8(b): RMS voltage waveform for Case 2

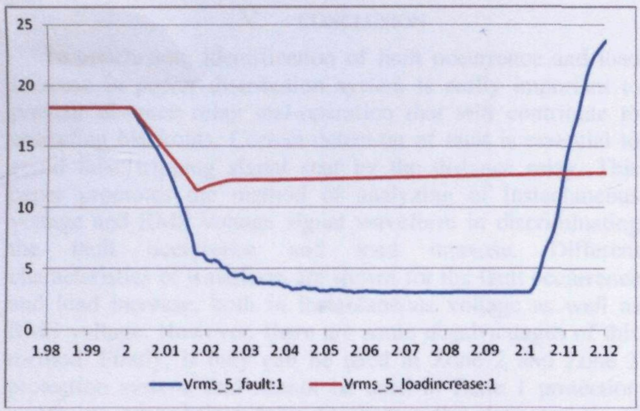


Figure 8(c): RMS voltage waveform for Case 3

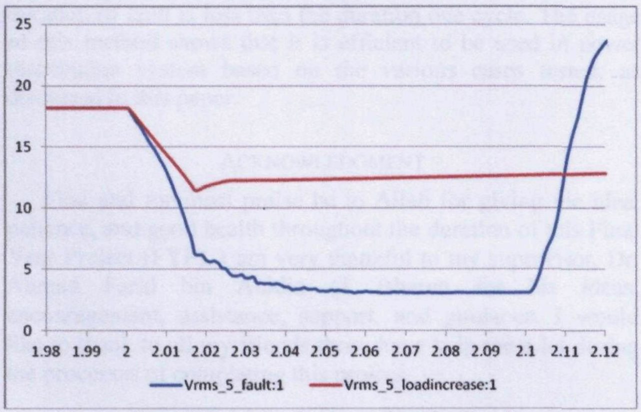


Figure 8(d): RMS voltage waveform for Case 4

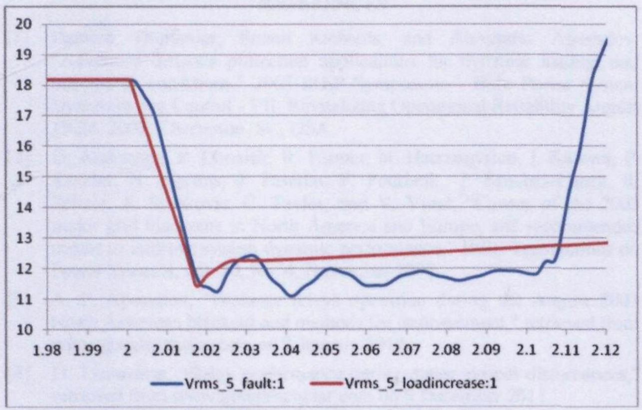


Figure 8(e): RMS voltage waveform for Case 5

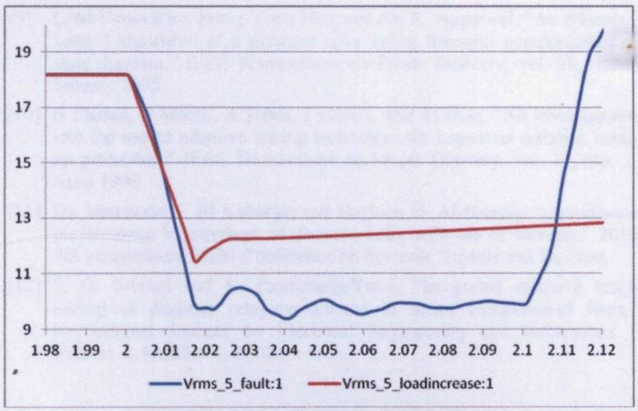


Figure 8(f): RMS voltage waveform for Case 6

After analyzing the waveforms for all the cases tested, it is proved that they result in the same pattern as described in Case 1. For fault occurrence, V_{RMS} decreased from the time of the occurrence until the time of 1 cycle, and it will remain constant or keep decreasing for a few seconds forward; but during load increase, V_{RMS} decreased only from the time of the occurrence and it will increase after the time of 1 cycle.

Based on all the results obtained, they show that, if either fault occurs or load increase, the instantaneous voltage, V and also RMS voltage, V_{RMS} are decreased during the first cycle after the occurrence of disturbance.

Different characteristic between two of them has been clearly seen during the second cycle. When fault occurs, V will keep decreasing for a few cycles; but if load is increased, V will decrease only for the first cycle and it will increase during the second cycle.

Similar pattern is observed for RMS voltage signal waveform. For load increase, the magnitude is decreasing for certain time that is the duration for one cycle. After the duration of one cycle, it will increase. Different characteristic is shown for fault occurrence. The magnitude is also decrease in time of one cycle, but after that time, it will continue decreasing for another few seconds.

From the observation, it shows that the difference between fault occurrence and load increase can only be classified on the second cycle. That is why this method is valid for Zone 3 operation as the operation of the zone has time delay that is of the order of 90 cycles or 1.5 seconds. It is not valid for Zone 1 because its operation is designated to trip with no intentional time delay.

This method also cannot be used if the duration of fault is less than the duration of one cycle. It is because, after the duration of fault occurrence, the voltage will increase. If the duration of fault is less than the duration of one cycle, the voltage will increase immediately after the first cycle. It will results in the same characteristic of voltage waveform as compared to load increase.

V. CONCLUSION

In conclusion, identification of fault occurrence and load increase in power distribution system is really important to prevent distance relay mal-operation that will contribute to cascading blackouts. Correct detection of fault is essential to avoid false tripping signal sent by the distance relay. This paper promotes the method of analyzing of instantaneous voltage and RMS voltage signal waveform in discriminating the fault occurrence and load increase. Different characteristics of waveform are shown for the fault occurrence and load increase, both in instantaneous voltage as well as RMS voltage. However, there are some disadvantages of this method. Firstly, it only can be used in Zone 2 and Zone 3 protection system, and cannot be used in Zone 1 protection system as it need time delay to observe the characteristic of the voltage waveform. Secondly, it cannot be used if the duration of fault is less than the duration one cycle. The usage of this method shows that it is efficient to be used in power distribution system based on the various cases tested, as discussed in this paper.

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