Blocking of Distance Relays Zone3 under Load Encroachment Conditions- A New Approach Using Phasor Measurements Technique

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Abstract - Cascaded tripping of power lines due to mal-operation of zone 3 distance relays was one of the main causes of many previous blackouts worldwide. Encroachment of load into the zone 3 characteristics is one of the main cause for the mal-operation of the relays. By improving the operation of zone 3 of distance relays it is possible to prevent such mal-operations so that cascaded line tripping can be avoided.

This paper proposes a new algorithm that utilizes Synchronized Phasor Measurements (SPM) to control the operation of distance protection zone 3. Based on the proposed algorithm, several improvements in operation of zone 3 can be achieved. For instance, the relay can differentiate between actual system faults and load encroachment. In addition to this, the tripping decision is not affected by the value of fault resistances from zero to High Impedance Faults (HIF). These improvements would in turn help prevent blackouts due to mal-operation of distance relay zone3.

Keywords- Distance Relay Zone3; Mal-Operation of Zone 3; Cascade Tripping; Fault Resistance; N-x criterion

I. INTRODUCTION

The mal-operation of zone 3 impedance relays with mho-characteristics is a factor for causing cascading failures as seen in several previous large scale blackouts. This mal-operation could be due to the increase of the load level to the limit that the relay interprets the system voltage and current into an impedance that its value appears to the relay as if it is a fault while it is not, e.g. load encroachment, Fig.1 [1]. Although the line characteristics are far from the load characteristics, it is not possible to set zone 3 setting to take into account only the line characteristics because it has to accommodate for the existence of fault resistance.

There are also other causes for the mal-operation of zone 3 like power swings and voltage instability. The change of voltages and currents in these cases causes the measured impedance by the relay to seem as if it is a fault. In this paper we use the term ”virtual faults” to refer to phenomena (i.e. load encroachment, power swing, voltage instability) that can appear to the relay as if there is a fault while in reality there is not.

Some of the techniques proposed to detect virtual faults prefer not to use communication links to design the relaying algorithms and to base its decision on values of current and voltage at the relay location [2-4] while on the other hand some other techniques [6, 7] use new technologies based on remotely measured data like Synchronized Phasor Measurements (SPM) and fiber optic communications.

Figure 1. Encroachment of Load into Zone 3 [1]
is not always assured that voltage instability would occur when the load level is increasing.

Reference [4] proposes to block the zone 3 operation based on comparing a predetermined value of power flow of the line and the actual measured value of the power flow. The decision to block zone 3 holds when the estimated and the measured value of power are identical. However, the estimation of the value of power flow of the line is not always guaranteed to be right due to the loop-flows described in [5] which caused some previous blackouts. In this case the method described in [4] could cause problems.

For the time being, the use of Synchronized Phasor Measurements (SPM) has a great attention and the applications of SPM in the area of Power System Protection is increasing and getting improved. In [6], two measures (one to discover power swing and block the relay and another to calculate fault location and allow the relay to trip) are used to differentiate between a fault and a power swing case. The use of two measures could be a reason for the relay operation to be unsatisfactory especially when a combination between an actual fault and a virtual fault occurs (e.g. a fault during a power swing).

The methods in [3-6] are not verified to which limit they are capable to withstand the existence of high impedance faults (HIF) which might lead the relay not to differentiate between fault and non-fault case correctly or even not to estimate the fault location correctly.

The methodology proposed in this paper overcomes some problems that arose in references [2-4, 6] and suggests a simpler and reliable method that discriminates the real fault cases from the virtual fault cases. The technique to improve the operation of zone 3 proposed here uses only one measure to distinguish between an actual and a virtual fault and makes the relay decisions independent of fault resistances (low or HIF). Applying this technique would solve problems that face the setting of differential relays (e.g. setting the biasing current) leading to more sensitivity of the relaying system.

The paper is organized to first introduce the idea of the technique and its flow chart; section II. Simulation and verification of the proposed method is given in III. Then section IV presents how to apply this technique in more complex power systems.

II. THE PROPOSED TECHNIQUE

A. The Idea

Fig. 2a shows a faulty transmission line in a power system. The value of fault resistance can range between zero (bolted faults) to few tens of kOhms (HIF) [8].

![Figure 2](image_url)

**Figure 2.** Transmission line with and without fault

Fig. 2b shows a healthy power line where we can imagine that it is having a fault resistance with a very high value that is outside its practical range from 0 to few tens of kOhms (theoretically infinity).

During normal system operation or during system virtual faults (e.g. load encroachment) the system looks as shown in Fig. 2b (i.e. with \( R_f \) very high). The values of voltages and currents could be changing at the buses of the shown system in Fig. 2b (e.g. due to load increase or power swings) but Kirchhoff’s current and voltage laws are still holding and the value of the calculated fault resistance \( R_f \) will be very high. When a fault occurs (Fig. 2a), the value of \( R_f \) will attain its practical range (from 0 to few tens of kOhms). This change of \( R_f \) from very high value (theoretically infinity) to a relatively low value (0 to around 10 kOhms) is an indication of the occurrence of a fault between the terminals of the monitored line section as shown in Fig. 3.

![Figure 3](image_url)

**Figure 3.** Change of \( R_f \)

Changing the tripping decision of zone 3 from being based on the value of the measured impedance to fault to be based directly on the value of the fault resistance \( R_f \) improves the operation of the protection performance in two main aspects. The first one is the use of a single measure (\( R_f \)) to discriminate between actual and virtual- or no- fault condition. The second one is the recognition of the value of the fault resistance regardless of being low or high and so HIF or normal values of \( R_f \) can not influence the protection operation even when it occurs during a virtual fault. Normal differential protection can be affected by the existence of \( R_f \) [9] due to the settings of the operating and restraining currents. Using \( R_f \) to design zone 3 doesn’t depend on any biasing or restraining current configuration and does not depend on the system topology.

The given formula of \( R_f \) as in (4) in the next section uses the value of the fault current \( I_f \) but in a way that translates this value to an equivalent impedance (\( R_f \)). Because \( R_f \) has known deterministic and practical values, then it is more reasonable to use it in the judgment of occurring of a fault or not (virtual fault). The results will be more accurate than using \( I_f \) (i.e. in case of conventional differential protection) which is not
accurate enough in case of HIF and requires the setting of biasing current which is dependent on the system configuration and other estimations. The detection of virtual fault in this paper or the judgment of occurrence of an actual fault is based on only one measure \( R_f \) so there will be no need to use two different measures to differentiate between a fault and a virtual fault.

Because impedance operating relaying is more preferable than current operating relaying due to their better selectivity, sensitivity and independence of the value of the fault current, the algorithm presented here resembles this change from using current operating relaying to use impedance operating relaying but applied on the differential form and so we would like to call this algorithm Differential-like Impedance-Algorithm (DIA). The use of the word differential here doesn’t refer to the impedance (i.e. not differential impedance) but it means that the algorithm is like the differential relaying in the perspective that the tripping decision is dependent on the state of each unit in the system.

The value of \( R_f \) can be used to correct the apparent impedance measured by the distance relay to overcome the error of measurements due to the existence of fault resistances. In this case the relay will not face the under-reach problem.

Because load encroachment (or other virtual faults) appears to the relay as if it is a three phase fault, the simulation in this paper will consider only three phase faults. Single phase faults are anticipated to be detected by using negative sequence currents. The algorithm proposed here will be used in the software module responsible for handling three phase faults.

The paper is intended to show only the basic concept of DIA. The simulation will also set focus on the case of increase of the load current (e.g. load encroachment).

B. Flow Chart

Fig. 4 depicts a simple transmission system upon which the new algorithm could be applied.

![Figure 4. Protection scheme for two transmission lines](image)

The flow chart in Fig.5 shows how the protection of the system shown in Fig. 4 operates using the new algorithm. First the values of voltage and currents at the terminals of all transmission lines are measured using any devices capable of making synchronized phasor measurements like Phasor Measurement Units (PMU). After the measurement process the PMU’s send their data to a central computer using a flexible communication structure. At the central computer the values of \( R_f \) for all transmission lines on the system will be calculated.

![Figure 5. The new algorithm in a block and monitor scheme](image)

To illustrate the operation of the algorithm TL2 of Fig.4 will be used. The fault resistance \( R_{f2} \) of TL2 will be calculated (the calculation method is given in the next section) and if it is found to be outside of its practical range then blocking of zone 3 (Relay 1) should take place otherwise zone 3 is unblocked. Because there is a possibility for zone 3 not to trip due to the existence of a fault resistance, the new algorithm will still monitor the operation of zone 3 and if the circuit breaker CB1 is not opened after the allotted time of 1 to 1.5 seconds has passed (e.g. due to HIF) then the algorithm will open CB1. The same algorithm will be applied for TL1.

For systems with more transmission lines, the values of \( R_f \) for all transmission lines will be checked and as long as the measured value of \( R_f \) of each line is very high then it is indication that all zone 3 in the substation don’t need to operate and will be blocked. Once any of the measured \( R_f \)’s of any transmission line drops to be within its practical range then the designated zone 3 of that line will be unblocked and monitored.

C. Calculation of Fault Resistance

From Fig. 6, the voltages and currents at terminal A and B during a fault with fault resistance \( R_f \) can be described by the following equations:

![Figure 6. System for calculation of \( R_f \)](image)
By adding (1) and (2) we get:

\[ \frac{\bar{V}_A}{I_A} + \frac{\bar{V}_B}{I_B} = \frac{Z_A}{I_A} + \frac{Z_B}{I_B} + R_f \left( \frac{I_f}{I_A I_B} \right)^2 \]

Where \( \frac{Z_A}{I_A} + \frac{Z_B}{I_B} \) is equivalent to the total impedance of the protected transmission line (\( Z_{T,L} \)).

From (3), the fault resistance is equivalent to:

\[ R_f = \frac{\left( \frac{\bar{V}_A}{I_A} + \frac{\bar{V}_B}{I_B} - Z_{T,L} \right)}{I_f} \left( \frac{I_f}{I_f^2} \right) \]

Where \( I_f = I_A + I_B \)

Fig. 7 depicts the change of \( R_f \) during no fault (or virtual fault) and during an actual fault according to (4).

### TABLE I.  System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volt Level</td>
<td>345 kV</td>
</tr>
<tr>
<td>ZG1 (Ohm)</td>
<td>4+j25</td>
</tr>
<tr>
<td>ZG2 (Ohm)</td>
<td>4+j50</td>
</tr>
<tr>
<td>Z T.L.(Ohm/km)</td>
<td>0.037+j0.3</td>
</tr>
<tr>
<td>Y T.L.(µs/km)</td>
<td>3.76</td>
</tr>
<tr>
<td>Line Length</td>
<td>160 km</td>
</tr>
</tbody>
</table>

**A. Test 1**

1) **No- or Virtual- Fault**

Table 2 shows the calculated value of \( R_f \) in case the system is experiencing no- or virtual- fault. The values of \( R_f \) in this case are calculated using (4) at different power angles corresponding to load increase.

### TABLE II.  Calculated \( R_f \) When in Virtual- or No- Fault

<table>
<thead>
<tr>
<th>Delta</th>
<th>( R_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3*10^6</td>
</tr>
<tr>
<td>30</td>
<td>2.2*10^6</td>
</tr>
<tr>
<td>60</td>
<td>1.8*10^6</td>
</tr>
<tr>
<td>90</td>
<td>1.9*10^6</td>
</tr>
</tbody>
</table>

The values of \( R_f \) in this case are very high because under no- or virtual- fault no actual \( R_f \) exists. So long the system is in normal state or experiencing a virtual fault, the value of \( R_f \) is expected to keep so high indicating that there is no need for zone 3 distance relay to trip.

2) **Load Encroachment as a case of virtual fault**

The system shown in Fig. 9 was used to test the relay performance under load encroachment. The two transmission lines have the same parameters as in Table.1. Fig. 10 traces the change of the measured impedance by the relay at Bus1 when the load is increasing. Under this load increase, normal zone 3 distance relays at Bus1 are expected to mal-trip. On the other hand, the value of the calculated \( R_f \) (between A and B) keeps very high (in Mega Ohms) indicating that the distance relay zone 3 at Bus1 (which is supposed to protect TL2 by its zone 3) is not required to trip due to the non existence of a fault at the TL2; Fig. 11.
B. Test 2: Fault Case

Once a fault occurs in the system, the value of $R_f$ will have a change from very high values as given in Table 2 to very low values representing the value of the fault resistance ($R_f$). In Test 2, the value of $R_f$ has been changed in the simulation from 0 to 10 kOhms then formula (4) has been used to retrieve back the value of $R_f$ from the measured currents and voltages.

Fig. 12 to Fig. 14 show the calculated values of $R_f$ when a fault occurs at different locations and different power angles. At high power angles (e.g. delta=60°) the deviation between the actual and the calculated value of $R_f$ increases for faults near the line ends (e.g. 10%). At faults near the middle of the line the calculated values of $R_f$ are enhanced. Regardless of how much exactly $R_f$ is, the value of the calculated $R_f$ has dropped from its very high value (e.g. during normal load increase or no fault condition as in Table 2) into the range that is indicating that a fault has occurred between the monitored line terminals.
IV. APPLICATION ON MORE COMPLEX POWER SYSTEMS

The Power system in Fig. 15 shows an application of the proposed algorithm. The relay at G is supposed to protect lines 1 and 2 by zone 3. The required measurements to calculate $R_f$ at both lines using (4) (e.g. $I_{A1}, I_{B1}$, etc.) could be sent to a central computer using a flexible communication network [5] or it might be possible to send the data directly to the relay at G using fiber optic cables in between the substations themselves. Based on the value of $R_f$ (in the practical range) activation of zone 3 timer at the central computer (or unblocking of the relay at G) will take place and result in tripping of the circuit breaker at G if none of the relays at line 1 or line 2 has not operated while $R_f$ is in its practical range. If the algorithm at the central computer (or the relay at G) finds that the calculated value of $R_f$ is very high and outside the practical range then the timer of zone 3 will not be activated (or blocking of zone 3 of relay at G).

![Figure 15. Application on a more complex system](image)

The new algorithm presents a form of isolation between the location of the fault or the value of the load and the relay. The relay decision at G is only dependent on the value of $R_f$ (i.e. load encroachment can’t affect the relay decision). The system configuration will not affect the reach of zone 3 [1] in this case because if line 1 or line 2 is disconnected (i.e. for maintenance) the tripping decision is still based on $R_f$, and not on the measured impedance between the G to the fault location. This in turn results in more freedom choosing the reach of zone 3.

V. CONCLUSIONS

This paper presents a new protection algorithm (DIA) that uses the value of the fault resistance to differentiate between virtual and real faults. The detection of virtual faults leads to the enhancement of the operation of zone3. During normal faults with or without fault resistance the algorithm is capable of detecting the fault in a differential-like form but with the help of calculation of the value of the fault resistance instead of the differential current. This resembles the transfer from using the current value (in current-operating relays) to impedance value (in impedance-operating relays).

The algorithm –using only the value of $R_f$– has basically the following advantages:

1) Discrimination between virtual- (or no-) fault case and actual system fault.
2) The algorithm is like the differential relaying in the sense that each equipment or transmission line has its protection that is using the fault resistance information instead of the differential current information. This leads to a tripping decision that is not affected by the complete range of $R_f$ from 0 through normal fault resistances until HIF and
3) Easier protection system designs because there is no need for setting a biasing or restraining current. The sensitivity of the system is completely reserved.
4) The relay selectivity and tripping time delay will be always as required with no possibility for under-reach.
5) Enables extending the reach of zone 3 without intersection with the load characteristics which will make it of ease to design the third zone reach in case of N-x contingency.

The algorithm is not intended to discover other types of faults like single phase to ground or correct the measured impedance in case of single phase to ground fault because the main objective proposed here is to prevent the relay tripping in case of virtual faults that appear to the relay as if it is a three phase short circuit.

REFERENCES


