Investigating Performance of Symmetrical Component Distance Relay

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Abstract— Symmetrical component distance relay (SCDR) was introduced by A.G Phadke, M. Ibrahim and T. Hilbka in order to reduce the computational burden in conventional numerical distance relay (CNDR) where all the six elements, each represented by one equation simultaneously estimates the positive sequence impedance of the protected line for all kinds of faults. SCDR uses only one equation to estimate the fault location (FL) for all kinds of faults. Even though the field tests are successful, the performance equation of SCDR fails to survive as an algorithm in relay industry. This paper investigates the performance of SCDR for different fault types, location, source to line reach impedance (SIR) and for different loading conditions. The results obtained are compared with CNDR (non-switched type).

Keywords- symmetrical component distance relay; discrete Fourier transform; source to line reach impedance ratio.

I. INTRODUCTION

Long transmission lines are in general protected by distance protection where it inherently provides a backup protection as an additional feature. Even though the distance protection philosophy is old, distance relay has seen a drastic development, particularly after entering the digital domain where the algorithm is implemented digitally. Full scheme non-switched numerical distance protection utilizes six separate elements [1] (3 ground elements and 3 phase elements) to estimate the positive sequence impedance and to decide whether to trip or not. All the six elements simultaneously estimates the positive sequence impedance of the line from the received 3 phase voltage and current samples, which are delivered from capacitive voltage transformers (CVT) and current transformers (CT) via analog anti-aliasing filter, sample and hold circuits and after quantization. The main drawback of this non-switched scheme is that all the six elements i.e., six equations, simultaneously estimates the positive sequence impedance of the protected line e.g. SIEMENS 7SA6, 7SA522 relays [2] and to make a decision before the next sample arrives, which increases the computational requirement and demands for processor with high processing speed [3] and thereby increasing the relay cost. In 1970’s an attempt was made to overcome the computation burden by using SCDR, where only one equation is used to estimate the FL [4] instead of six equations. There seems to be a similarity between switched numerical distance protection and SCDR, since both of them uses only one equation to estimate the positive sequence impedance and FL of the protected line respectively, but the main difference arises from the fact that SCDR does not receive the selected voltage and current phasor pairs as done in switched numerical distance protection, where these phasors are selected and delivered to the impedance estimation algorithm by fault classification algorithms e.g. SIEMENS 7SA511 distance relay [2]. Even though field tests on 765 KV line [5], [6] show satisfactory results from algorithm point of view when SCDR is digitally implemented, relay manufacturers have not incorporated this SCDR algorithm in numerical distance relay.

II. INTRODUCTION

A. Operating Principle Of CNDR (non-switched)
CNDR (non-switched) extracts the required fundamental frequency information from voltage and current samples using full cycle discrete Fourier transform (FCDFT). The 3 phase current and voltage phasors obtained from the FCDFT are used as inputs to main algorithm which has six separate elements [1] as listed in Table I.

TABLE I: GROUND AND PHASE ELEMENTS USED TO ESTIMATE POSITIVE SEQUENCE IMPEDANCE

<table>
<thead>
<tr>
<th>Phase</th>
<th>Impedance estimated by</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>$V_r / (I_r + k_e \cdot 3I_b)$</td>
</tr>
<tr>
<td>Y</td>
<td>$V_y / (I_y + k_e \cdot 3I_b)$</td>
</tr>
<tr>
<td>B</td>
<td>$V_b / (I_b + k_e \cdot 3I_b)$</td>
</tr>
<tr>
<td>RY</td>
<td>$V_r - V_y / (I_r - I_y)$</td>
</tr>
<tr>
<td>YB</td>
<td>$V_y - V_b / (I_y - I_b)$</td>
</tr>
<tr>
<td>BR</td>
<td>$V_b - V_r / (I_b - I_r)$</td>
</tr>
</tbody>
</table>
where,

\[ k_E = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}} \]  

(1)

- \( k_E \) residual compensation factor
- \( Z_{L0} \) zero sequence impedance of the protected line
- \( Z_{L1} \) positive sequence impedance of the protected line
- \( V_{r,y,b} \) voltage phasors
- \( I_{r,y,b} \) current phasors
- \( I_0 \) zero sequence current phasor

These six elements estimates the positive sequence impedance of the protected line simultaneously and the tripping decision is made based on the angle criterion [7] as shown in Figure 1 and Figure 2 where, \( Z_R \angle \theta \) is the impedance of the protected transmission line referred to secondary of CT and CVT and \( Z_e \angle \theta_r \) is the estimated positive sequence impedance.

**B. Operating Principle Of SCDR**

SCDR uses only one performance equation, using which it estimates the FL in per unit for all fault types [4]. The performance equation is given by equation (3), if the fault resistance \( R_f \) is assumed to be zero.

\[ k = \frac{k_1 + k_2 k_3 + k_4 k_0}{1 + k_0 + k_2 + k_4} \]  

(3)

where,

\[ k_x = \frac{E_x}{\Delta E_x} \]  

(4)

\[ k_0 = \frac{\Delta E_0}{\Delta E_1} e^{-j(\theta_1 - \hat{\theta})} \]  

(5)

\[ k_2 = 1 \text{ if } |\Delta E_0| \geq |\Delta E_1| \]  

(6)

\[ k_4 = \frac{Z_1 I_1}{\Delta E_1} \]  

(7)

where,

- \( x = 0 \) zero sequence
- \( x = 1 \) positive sequence
- \( x = 2 \) negative sequence

The trip command gets asserted when the value of k falls below the threshold setting, for e.g. if zone 1 has 80% reach setting, trip command will be issued when value of k falls below 0.8 and similar thresholds can be fixed for other zones.

The paper is organized as follows, section III deals with the test system and test method, followed by Section IV which analyzes performance analysis of CNDR (non-switched) and SCDR and finally Section V with conclusion.

**III. TEST SYSTEM**

In order to analyze the performance of SCDR, 400KV test system (Appendix A) [8], shown in Figure 3 is used. Basic requirements for a protective relay i.e. speed, selectivity, reliability [9] are considered for performance analysis and obtained results are compared by taking CNDR (non-switched) as reference. CNDR and SCDR are digitally modeled and the simulation is carried out in an on-line way.

\[ -90^\circ \leq \text{ang}(S_1) - \text{ang}(S_2) \leq 90^\circ \]  

(2)
Power system shown in Figure 3 is subject to 600 different conditions like,

- $\delta_s = 0,10,20,30$
- 10 different kinds of faults
  - single phase to ground fault (SPGF)
  - phase to phase fault (PPF)
  - phase to phase and ground fault (PPGF)
  - 3 phase fault (3PF)
- SIR = 1,5,10,20,30
- FL = 50km, 100km, 200km

The manner in which the simulation is carried out to investigate the performance of SCDR is shown in Figure 4.

IV. PERFORMANCE ANALYSIS

A. Speed

Speed is one of the prime requirements for any protection device. An increase in relay operating time may lead to equipment or plant damage, raises safety issues and it may lead to an unstable system. SCDR and CNDR operating time for different types of faults at 50km and 100km are obtained by using the test method as shown in Figure 4 of previous section. Since the fault location lies within the zone 1 reach setting of both SCDR and CNDR, zone 1 element of both the relays are expected to assert trip signal. Figure 5, Figure 6, Figure 7 and Figure 8 show the actual operating times of SCDR and CNDR for SPGF, PPF, PPGF and 3PF respectively.

Figure 5. Relay operating time for SPGF

Figure 6. Relay operating time for PPF

The current and voltage samples obtained from sampling unit are delivered to both CNDR (non-switched) and SCDR. CNDR estimates the positive sequence impedance of the protected line with voltage and current phasors obtained from discrete Fourier transform, whereas SCDR estimates FL in pu with positive, negative and zero sequence voltage and current phasors. The reach setting of SCDR for zone 1, zone 2, zone 3 are kept as 0.8, 1.2 and 1.5 respectively and the same reach settings are used for CNDR also. CNDR is modeled with six elements having 3 zones each. Trip command will be issued by CNDR if angle criteria is satisfied and SCDR issues the trip command if the estimated value of $k$ is less than the threshold setting. The trip command for zone 2 and zone 3 is delayed by 200ms and 400ms respectively for both SCDR and CNDR. Relay operating times for both SCDR and CNDR are obtained when the trip signal gets asserted by the respective relays and after delay time.
Figure 5 and Figure 7 shows maloperation by zone 1 element of SCDR and maloperation of SCDR respectively. These will be handled separately latter in the reliability subsection. In order to analyze the impact on relay operating speed for SCDR, change in relay operating time is calculated by using equation (8).

$$\Delta t = t_{SCDR} - t_{CNDR}$$

where,

- $t_{SCDR}$ operating time of SCDR
- $t_{CNDR}$ operating time of CNDR

Figure 9 shows the impact on relay operating speed when CNDR is replaced with SCDR. Test results shows that for about 45% and for about 65% of the test cases, the operating time increases for SPGF and 3PF respectively. Relay operating time for 3PF and SPGF are concentrated here, since in the latter case, the fault current exceeds the maximum fault current for a 3PF for solidly earthed systems and in the former case, it is considered to be the most severe type [10].

B. Selectivity

In order to analyze the selectivity requirement, faults outside zone 1 reach setting are considered i.e. faults at 200km. For faults outside zone 1 reach, trip signal should not be asserted by zone 1 elements. In order to avoid overreaching due to dc offset in CNDR which may result in operation of zone 1 element, digital mimic filtering [11] is incorporated in simulation where the current samples are fed to the digital mimic filter before it is fed to full cycle discrete Fourier transform. Table II shows the mal-operation rate for both relays.

<table>
<thead>
<tr>
<th>Relay</th>
<th>Maloperation (%)</th>
</tr>
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<tbody>
<tr>
<td>CNDR</td>
<td>54</td>
</tr>
<tr>
<td>SCDR</td>
<td>46.5</td>
</tr>
</tbody>
</table>

Even though mal-operation rate of conventional distance relay is high, it is to be noted that the test method utilized here does not involves any bi-quad filter [12] in voltage signal path. Moreover, this problem is successfully handled during practical implementation by different techniques used by relay manufacturers as mentioned in Table III.

<table>
<thead>
<tr>
<th>Relay Manufacturer</th>
<th>Technique used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay A</td>
<td>double zone 1</td>
</tr>
<tr>
<td>Relay B</td>
<td>tracks SIR and adapts reach setting for zone 1</td>
</tr>
<tr>
<td>Relay C</td>
<td>reduced zone 1 reach</td>
</tr>
<tr>
<td>Relay D</td>
<td>reduced zone 1 reach setting</td>
</tr>
<tr>
<td>Relay E</td>
<td>loss of load accelerated tripping</td>
</tr>
</tbody>
</table>
Investigation shows that, mal-operation occurs only during high SIR conditions and this can be tackled in CNDR by using a security counter to assist the trip decision to increase selectivity.

C. Reliability

1) Security: The trip signal should not be asserted by the relays when there is no fault in the system. Test results simulated for 20 cases shows that both the relays fulfill the security requirement.

2) Dependability: The trip signal should be asserted by the relay when there is a fault within its zone of protection. It is found from test results that CNDR satisfies the dependability requirement, whereas for SCDR, it was 96% i.e. for 4% of the cases, the relay was not asserting the trip signal when faults are applied on the system, which is clear from Figure 5 and Figure 7, where in the latter case SCDR fails to operate and in the former case zone 1 element of SCDR fails to operate. It is also found that both these issues occur only at high SIR (SIR = 30) and faults involving zero sequence components. Figure 10 to Figure 17 are included to aid the above investigation i.e. the reason why SCDR fails to operate. Figure 10 to Figure 17 are self explanatory.

![Figure 10. Estimated FL by SCDR for SLGF at 25% of line length](image1)

![Figure 11. Estimated FL by SCDR for PPF at 25% of line length](image2)

![Figure 12. Estimated FL by SCDR for PPGF at 25% of line length](image3)

![Figure 13. Estimated FL by SCDR for 3PF at 25% of line length](image4)

![Figure 14. Estimated FL by SCDR for SLGF at 50% of line length](image5)
V. CONCLUSION

- Investigation on reliability shows that SCDR fails to meet the performance requirement since it fails to meet the dependability requirement. It is also observed that this occurs only at high SIR i.e. when SIR is 30.

- Investigation on speed requirement, particularly for SPGF and 3PF shows that SCDR relay operating times is relatively high for most cases.

- Investigation on selectivity requirement shows that SCDR performs better than CNDR.

On the whole, CNDR outperforms SCDR, since it is necessary for any protective relay algorithm to fulfill all the basic requirements to penetrate the relay industry. Even though this investigation has highlighted the problem of SCDR mal-operation during high SIR, future paper will be devoted to analyze the reason behind this.

APPENDIX A

<table>
<thead>
<tr>
<th>TABLE IV: TRANSMISSION LINE PARAMETERS</th>
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<tbody>
<tr>
<td>line parameters</td>
</tr>
<tr>
<td>Positive sequence</td>
</tr>
<tr>
<td>negative sequence</td>
</tr>
<tr>
<td>zero sequence</td>
</tr>
</tbody>
</table>

REFERENCES

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