Calculation of Apparent Impedance and Distance Relay Tripping Characteristics in EHV/UHV Transmission Line with and Without Capacitance

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Abstract—EHV/UHV long transmission lines have large distributed capacitance which has significant effect on the operation of a distance relay. To set the distance relay without considering the distributed capacitance will cause serious overreaching or underreaching. This paper analyzes the effect of distributed capacitance on the relay tripping characteristics and the setting principal of distance relay for EHV/UHV long transmission line is discussed.

Keywords—EHV/UHV long transmission line, distance relay, distributed capacitance, relay tripping characteristics.

I. INTRODUCTION

Distance relays are widely used as primary or backup protection for UHV/EHV lines, as they are independent of communication channels, and their reaches are insensitive to system condition[1]. A distance relay operates by measuring the electrical circuit distance between the relay location and the point of fault (apparent impedance) to determine if a fault is in its protection zone. It is apparent that the protection zones need to be set accurately to avoid overreaching or underreaching, and ensure the reliability and selectivity. Normally the protection zones can be set without considering the distributed capacitance, as the impedance of the distributed capacitance is too big compared with the line impedance. With the transmission distance increasing, however, the distributed capacitance of the whole line increases correspondingly. Meanwhile, to improve the economical and transmission efficiency over long distance, higher voltage levels are adopted, which brings higher distributed capacitance per unit of transmission lines[8]. The impedance of the distributed capacitance is comparable with the line impedance, thus its effects on the distance relay need to be considered, to ensure the distance relay’s reliable operation [2].

II. APPARENT IMPEDANCE WITHOUT CONSIDERATION OF LINE CAPACITANCE

In the case of zero fault resistance, the measured impedance by distance relay is the exact impedance of the line section between the fault and the relaying points.

III. APPARENT IMPEDANCE WITH CONSIDERATION OF LINE CAPACITANCE

From Fig.1., this impedance is equal to dZ1L, where d is per unit length of the line section between the fault and the relaying points and Z1L is the line positive sequence impedance in ohms. For a non-zero fault resistance, the measured impedance at the relaying point is not equal to the mentioned magnitude. In this case, the structural and operational conditions of the power system affect the measured impedance. The operational conditions prior to the fault instances can be represented by the load angle of the line ‘δ’ and the voltage magnitude ratio at the line ends ‘h’ or in general EN / EM= he-jδ. The structural conditions are evaluated by the short circuit levels at the line ends.
For zero fault resistance, the apparent impedance at the relaying point is equal to the impedance of the line section located between the relaying point and the fault point. From equation (12) it is observed that, in the presence of fault resistance the apparent impedance is affected by power system conditions only.

III. APPARENT IMPEDANCE WITH CONSIDERATION OF LINE CAPACITANCE

Long EHV/UHV transmission lines are highly affected by the line capacitance. If the effect of line capacitance for a fault with considerable value of fault resistance is ignored, then there is a substantial error in the impedance seen by a relay. Transmission line model including the line capacitance is shown in fig.2. In this proposed method double π model is utilized for considering the transmission line capacitance with fault resistance as shown in fig.3. The system of fig.3 includes four additional shunt branches. compared to fig.3 the fault point divides the line into two π sections. Each line section is modeled by a π model[8],[5].

\[
I_{0MF} = C_o I_{of} = C_o \frac{V_{PRE}}{Z_+ + 3R_F} 
\]

\[
I_{AM} = I_{PRE} + (I_{1MF} + I_{2MF} + I_{0MF}) 
\]

\[
Z_{AM} = \frac{V_{AM}}{I_{AM} + K_{ot} I_{of}} 
\]

\[
Z_{AM} = dZ_{ot} + \frac{3R_F}{(Z_+ + 3R_F)K_0 + 2C_r + C_o (1 + K_{ot})} 
\]

\[
K_0 = \frac{1 - he^{j\delta}}{Z_{in} + Z_{1m}he^{j\delta}} 
\]

Fig.2. Transmission line model including shunt capacitance

Fig.3. Line diagram for phase-to-ground fault with consideration of line capacitance

\[
I_{1SM} = \left[ \frac{(Z_{1SN} + Z_{1CN})(Z_{1SN} + Z_{1CM} + Z_{1SM})}{((Z_{1SN} + Z_{1CN})(Z_{1SN} + Z_{1CM}) + Z_{1SM})} \right] 
\]

\[
I_{1LM} = \frac{Z_{1CM} (Z_{1SN} + Z_{1CN})}{((Z_{1IL} + Z_{1CM})(Z_{1SN} + Z_{1CN}) + Z_{1SM})} 
\]

\[
I_{1SN} = \left[ \frac{(Z_{1SM} + Z_{1CM})(Z_{1SN} + Z_{1CM}) + Z_{1SM}}{((Z_{1SM} + Z_{1CM})(Z_{1SN} + Z_{1CM}) + Z_{1SM})} \right] 
\]

\[
I_{1LN} = \frac{Z_{1CM}}{(Z_{1CM} + Z_{1SM})} 
\]

\[
I_{PRE} = I_{1SM} - I_{1NM} 
\]

\[
I_{1IL} = I_{1LN} 
\]
It can be seen from equation (30) that the fault resistance is not only the factor causing the measured impedance deviation, but also the line capacitance. The ZAPP is also dependent on power system conditions and line length.

IV. THE IDEAL TRIPPING CHARACTERISTICS

Knowing the structural and operational conditions, i.e. the short circuit levels, the load angle, and the voltage magnitude ratio, the distance relay ideal tripping characteristic can be defined. This characteristic has four boundaries. First boundary is the measured impedance for zero fault resistance; fault location varies from near end up to the far end of the line. In the second boundary, the fault point is at the far end; fault resistance varies between 0 and 200 ohms. Third boundary is the result of the fault point variation along the line for the fault resistance of 200 ohms. Forth is achieved by variation of the fault resistance between 0 and 200 ohms for the faults on the near end of the line[6],[7].

V. FLOW CHART TO OBTAIN THE IDEAL TRIPPING CHARACTERISTICS.

Fig.4 shows the flow chart for ideal tripping characteristics for with considering line capacitance and explains the procedure for R-X plot with considering line capacitance.

<table>
<thead>
<tr>
<th>Source Impedance</th>
<th>Bus M</th>
<th>Bus N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive and negative, sequence</td>
<td>1.7431+j</td>
<td>0.0871+j0.99</td>
</tr>
<tr>
<td>Impedance</td>
<td>19.9238</td>
<td>61</td>
</tr>
<tr>
<td>Zero sequence impedance</td>
<td>2.6146+j</td>
<td>0.1307+j1.49</td>
</tr>
<tr>
<td>Impedance</td>
<td>29.8858</td>
<td>42</td>
</tr>
</tbody>
</table>
Table B: Line parameters

<table>
<thead>
<tr>
<th>Line parameters</th>
<th>R (Ω/Km)</th>
<th>L (mH/Km)</th>
<th>C (µF/Km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive and negative sequence impedance</td>
<td>0.0301</td>
<td>1.0</td>
<td>0.011</td>
</tr>
<tr>
<td>Zero sequence impedance</td>
<td>0.2269</td>
<td>2.2</td>
<td>0.009</td>
</tr>
</tbody>
</table>

The distance relay tripping characteristic at h=0.96 and load angle is 160 shown in Fig.5. (I) first boundary line is for zero fault resistance and fault location varies from relay point to reach point (II) in the second boundary-line, the fault is at reach point with fault resistance varying from 0 to 200 Ohm (III) third one refers to fault resistance of 200 Ohm with fault position varying from relay to reach point and (IV) fourth line is for relay location with fault resistance varying from zero to 200 Ohm.

The characteristic without considering the line capacitance is also in the dotted form for comparison. In the Fig.5 the other important thing observed in this plot is that there is significant difference in trip characteristic while considering line capacitance.

Fig.5. Distance relay tripping characteristic at h=0.96, δ=160

The percentage Relative error with and without consideration of line capacitance is defined as

\[
\text{Error}\% = \left| \frac{Z_{\text{APP}} - Z_{\text{APP'C}}}{Z_{\text{APP'C}}} \right| \times 100
\]

(31)

Table C: Percentage error in R, X and ZAPP in transmission line at 95% distance with h=0.96, δ=160

<table>
<thead>
<tr>
<th>R0 (Ω)</th>
<th>Without Capacitance</th>
<th>With Capacitance</th>
<th>% error in Resistance</th>
<th>% error in Reactance</th>
<th>% error in Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8.71 +j90.55</td>
<td>9.62 +j95.24</td>
<td>9.45</td>
<td>4.92</td>
<td>4.9</td>
</tr>
<tr>
<td>200</td>
<td>361.35 +j60.84</td>
<td>374.54 +j1.951</td>
<td>3.52</td>
<td>3018.8</td>
<td>16.11</td>
</tr>
</tbody>
</table>

Fig 6 shows the amount of increase in the measured impedance for the various fault points, in the case of zero fault resistance. Here, the increase in the measured resistance, reactance, and impedance magnitude are shown by dotted, dashed, and full curves, respectively. It can be seen that the impedance deviation is a function of fault location. Because of different deviation of the measured resistance and reactance, the angle of the measured impedance varies as well as its magnitude.

Fig.6. Increase in measured resistance, reactance, and impedance magnitude

VI. APPARENT IMPEDANCE VARIATION

Fig.7. Tripping characteristic variations with changes in power system conditions
In Fig.7, curve (1) is the tripping characteristic of Fig.5. When the load angle increases from 160 to 220 and the voltage ratio decreases from 0.96 to 0.94, curve (2) would be resulted. On the other hand, when load decreases, curve (3) is resulted for $\delta = 100$ and $h = 0.98$.

![Tripping characteristic variations with changes in power system operational conditions for $h=0.96$ and $\delta=-10^\circ$ & $h=0.9$ and $\delta=-30^\circ$](image1)

Fig.8. Tripping characteristic variations with changes in power system operational conditions for $h=0.96$ and $\delta=-10^\circ$ & $h=0.9$ and $\delta=-30^\circ$

It can be seen that as the load angles varies, the tripping characteristic changes considerably. In the case of negative load angles, the tripping characteristic is in crescent shape.

![Tripping characteristic variations with changes in load angle.](image2)

Fig.10. Tripping characteristic variations with changes in load angle.

A. Load Angle Variation

Once the load level of a transmission line increases, the load angle also increases, and vice versa. If power flow direction in a transmission line reversed, the sign of load angle is inversed. Fig.10 shows the effect of the load angle variation on the tripping characteristic. Here, load angle takes the values 250, 150, 50, -50, -150 and -250.

![Variation in amount of increase in measured resistance, reactance and impedance magnitude, with changes in power system conditions.](image3)

Fig.9. Variation in amount of increase in measured resistance, reactance and impedance magnitude, with changes in power system conditions

![Increase in measured resistance, reactance, and impedance magnitude as load angle changes.](image4)

Fig.11. Increase in measured resistance, reactance, and impedance magnitude as load angle changes.

B. Voltage Ratio Variation

Variation of the voltage ratio of transmission line affects the reactive power flow through the line. The amount of reactive power flowing through the line increases as this factor decreases (for ratios lower than 1).
If the ratio is higher than 1, it means that the reactive power flow direction is inversed. Fig.12 shows the impact of voltage ratio, the magnitudes of 0.95, 1.00 and 1.05 are considered for this factor, while the other parameters are the same as Fig. 5.

![Tripping characteristic variation, with change in voltage ratio](image)

**Fig. 12.** Tripping characteristic variation, with change in voltage ratio

Fig.13 shows the amount of increase in the measured resistance, reactance, and impedance magnitude for voltage ratios of 0.95, 1.00, and 1.05.

![Increase in measured resistance, reactance, and impedance magnitude](image)

**Fig. 13.** Increase in measured resistance, reactance, and impedance magnitude.

**C. Line Length Variation**

Fig.14 shows the tripping characteristic for the line lengths of 100, 200, 300, and 400 km. It can be that as the line length increases, the covered region by tripping characteristic also increases in both resistance and reactance axis. Fig.15 shows the amount of increase in the measured resistance, reactance, and impedance magnitude for the mentioned line lengths.

![Tripping characteristic variation as line length changes](image)

**Fig. 14.** Tripping characteristic variation as line length changes

![Increase in measured resistance, reactance, and impedance magnitude, line length changes](image)

**Fig. 15.** Increase in measured resistance, reactance, and impedance magnitude, line length changes

**VII. ADAPTIVE DISTANCE RELAY SETTING**

**A. Effect Of $Z_{1SN}$ & $Z_{0SN}$ Trip Boundary**

From the equation, (31), it is clear that the change in trip boundary is due to $\text{VPRE}$, $\text{IPRE}$. Further the $\text{VPRE}$, $\text{IPRE}$, are function of factors $\delta$, $h$, $\text{Z1L}$ etc. The variation of apparent impedance with change in $Z_{1SN}$ with zero fault resistance is given in table D.

<table>
<thead>
<tr>
<th>$Z_{1SN}$</th>
<th>Apparent Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>5∠85°</td>
<td>95.79∠84.220°</td>
</tr>
<tr>
<td>2.5∠85°</td>
<td>95.78∠84.224°</td>
</tr>
</tbody>
</table>
From Table D, it is observed that the effect of remote source impedance on apparent impedance is quite negligible.

\[
S = h e^{-j\delta} = 1 - Z_{1L} \left( \frac{I_{\text{relay}}}{V_{\text{relay}}} \right)
\]

(32)

Fig.16 shows trip boundaries with change in Z1SN & Z0SN. From Fig.16 it is seen that even if we decrease the Z1SN and Z0SN to half of its case-1 values, there is no effect on boundaries of the trip characteristics. Hence, the remote end side impedance values are kept fixed to estimate the h and \( \delta \) from the local information only. From the voltage and current equations the following relation can be obtained

\[
S = h e^{-j\delta} = 1 - Z_{1L} \left( \frac{I_{\text{relay}}}{V_{\text{relay}}} \right)
\]

(32)

The h and \( \delta \) values are estimated using equation (32). The voltage and current phasors are estimated using Matlab simulink model.

B. Proposed Adaptive Technique

The proposed scheme and see the validity of the approach for Relay setting, a simulation study is carried out for line-to-ground fault. With the same system data as time-domain simulations were carried out by creating line to ground faults at different locations and conditions. Phasors are estimated using three phase voltage and current samples from equation (32).

VIII. RESULTS AND DISCUSSION

Simulations are performed for a 400 kV sub transmission system that contains an overhead line of 300 km length. The line parameters of the source and transmission line are given in table A and table B.
