Impedance seen by Distance Relays on Lines Fed from Fixed Speed Wind Turbines

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Abstract—This paper deals with line protection challenges experienced in system having substantial wind generation penetration. Two types of generations: Thermal Synchronous Generators and Fixed Speed Wind Turbines based on Squirrel Cage Induction Generators (SCIG) are simulated as thevenin equivalent model, connected to grid with single circuit transmission line. The paper gives comparative discussion and summarizes analytical investigations carried out on the impedance seen by distance relays by varying fault resistances and grid short circuit MVA, for the protection of such transmission lines during faults.

Keywords—Wind Generation, Distance Relays, Fault Resistance, Short Circuit MVA, DFIG, WTGU, SCIG

ABBREVIATIONS
Z_{BC} BC loop impedance
Z_{AG} AG loop impedance
R_{t} Fault resistance
Z_{0A} Source impedance at bus A
Z_{0B} Grid equivalent impedance at bus B
R_{c} General representation for fault loop impedance
K Complex factor for fault resistance
K_{m} Zero Sequence current compensation factor
m Fault point on line from Bus A
a Complex number (1∟120°)
Z_{f} Fault impedance
R' +jX' Transient impedance of Induction machine
P, Q Pre fault active and reactive power
Vr, Ir Relay measured voltage and current
V_{L}, I_{L} Load Voltage and current
I_{1f}, I_{1g}, I_{0} Positive, negative & zero sequence fault point current
V_{f}, V_{g}, V_{0} Positive, negative & zero sequence fault point voltage
V_{a}, V_{b}, V_{c} Phase ground voltage at relay point
I_{a}, I_{b}, I_{c} Line currents at relay location
I_{a1}, I_{b1}, I_{g1} Positive, negative & zero sequence relay current at bus A
V_{a0}, V_{b0}, V_{g0} Positive, negative & zero sequence relay voltage at bus A
C_{1}, C_{2}, C_{0} Positive, negative & zero sequence current distribution factor
Z_{f0}, Z_{a2}, Z_{b0} Positive, negative & zero sequence line impedance
Z_{a1}, Z_{b1}, Z_{g0} Positive, negative & zero sequence source side impedance
Z_{a1}, Z_{b1}, Z_{g0} Positive, negative & zero sequence grid side impedance

I. INTRODUCTION

With the recent development of technologies, environment concerns and continuously decreasing fossil fuels, wind generation is an inevitable solution and the power grids throughout the world are going with more and more wind penetration. For new format of power transfer where power can be transferred bidirectional i.e. from EHV to LV and from LV to EHV, a proper review of the protection philosophy is needed. These wind generators are primarily squirrel cage induction generators (SCIG) and known as type-1 wind generators due to their rugged performance and low maintenance. They are used widely when there is relatively constant wind speed. Modern types of wind generators are doubly fed induction generators (DFIG) which use power electronic controllers to make wound rotor induction machines (WRIM) work on unity power factor.

Line protection at HV/EHV/UHV level is primarily provided with distance protection or impedance protection due to required requirements of better security and dependability. Reference [3] describes that current contribution from induction machines will be changed with the slip of the machine. Such a property is different from the conventional synchronous machines, which maintain the constant voltage with the help of independent excitation and Automatic Voltage Regulator (AVR) system. Thus there is a need to investigate the effect of these SCIG currents on the impedance seen by the distance relays with wind farm connected to the grid. Reference [4] presents an investigation of trip characteristic of distance relay for phase to earth (Ph-G) fault with change in wind farm loading levels and for different small system perturbations. The theoretical analysis of dynamic behavior of Wind Turbine Generating Units (WTGU) during three phase and asymmetrical voltage dips is explained in [7, 8]. A study is done using DIGISILENT program with manually applying the waveforms to a distance relay through secondary injection kit and the results are presented in the paper concludes that behavior of distance relay is not as desired [6]. A MATLAB SIMULINK based study for behavior of distance protection loops has been carried out and reported in [12]. This paper presents a Thevenin equivalent model based analytical study to estimate theforesaid effect on the impedance seen by distance relays fed by fixed speed wind turbines.

II. IMPEDANCE PRESENTED TO MEASUREMENT LOOP

Impedance measurement by the distance relay depends on the type of fault and the selection of the measurement loop. Simultaneous measurement in three phases to earth loops AG, BG, CG and three phase to phase loops AB, BC, CA is well
documented in the literature [1,2] and reported in IEC and IEEE standards. For phase to phase fault (B-C fault) and for phase to earth fault (A-G), impedance seen by the relay is given by expressions,

\[
Z_{BC} = \frac{V_B - V_C}{I_B - I_C} \quad \text{and} \quad Z_{AG} = \frac{V_A}{I_A + K_0 I_0}
\]

where \(K_0 = (Z_{L0} - Z_{L1})/3Z_{L1}\). Effect of fault resistance and pre fault load flow on loop impedance been discussed in following sections.

A. No Load Condition

The effect of fault resistance in the measured loop impedance \(Z_{Fnl(loop)}\) is given by following equation as explained in Appendix A (for 3 different loops)

\[
Z_{Fnl(loop)} = mZ_{L1} + K_r R_F \quad (1)
\]

The complex factor \(K_r\) is based on the current contribution factors from each end as explained in the literature [1]

\[
K_r = 1/C_1 \quad \text{(Three phase fault case)} \quad (2)
\]

\[
K_r = 1/(C_1 + C_2) \quad \text{(Ph-Ph fault case)} \quad (3)
\]

\[
K_r = 3/C' \quad \text{(Ph-earth fault case)} \quad (4)
\]

where, \(C' = C_1 + C_2 + C_0 Z_{L0}/Z_{L1}\) \( (5)\)

\(C_1, C_2, C_0\) are the complex current distribution factors of the fault current for positive, negative and zero sequence networks respectively as shown in Figure 1. Thus complex factor \(K_r\) make the fault resistance as inductive or capacitive impedance and the distance relay may over reach or under reach depending on the current contribution from the remote end Infeed.

The complex current distribution factors depend on the sources at both the ends of the line. In wind generation systems, the source impedance varies with the speed of the wind and the number of wind turbines contribution to the grid.

B. Load Condition

Distance relay voltage \((V_r)\) and current \((I_r)\) in terms of pre-fault load voltage \((V_L)\) and load current \((I_L)\) from [1] can be written as

\[
V_r = A_r V_L + B_r I_L
\]

\[
I_r = C_r V_L + D_r I_L \quad (6)
\]

\(A_r, B_r, C_r, D_r\) are the complex impedance plane parameters\([1]\). These parameters are calculated for different fault loops and for different type of faults. From (5), the impedance seen by the relay can be given as

\[
Z_r = \frac{A_r(Z_{L1} + B_r/A_r)}{C_r(Z_{L1} + D_r/C_r)} \quad \text{Where} \quad Z_{L1} = \frac{V_L}{I_L}
\]

The \(A_r, B_r, C_r, D_r\) parameters as mentioned in [1], is obtained by superposition theorem for different type of faults. Comprehensive Table (Table 1) for these parameters is given for particular type of fault.

<table>
<thead>
<tr>
<th>Loop</th>
<th>(A_r, B_r, C_r, D_r) parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 Ph-Gnd Fault</td>
<td>(A_r = \frac{Z_F}{Z_F + Z_{S1}})</td>
</tr>
<tr>
<td>A-G loop</td>
<td>(C_r = \frac{1}{Z_F + Z_{S1}})</td>
</tr>
<tr>
<td>Ph-Ph Fault BC loop</td>
<td>(A_r = \frac{(a^2 - a) Z_F}{Z_F + Z_{S1}})</td>
</tr>
<tr>
<td></td>
<td>(C_r = \frac{a^2 - a}{Z_F + Z_{S1}})</td>
</tr>
<tr>
<td>Ph-Gnd Fault AG loop</td>
<td>(A_r = \frac{Z_T}{Z_T + Z_{S0}})</td>
</tr>
<tr>
<td></td>
<td>(C_r = \frac{Z_T}{Z_T + Z_{S0}})</td>
</tr>
</tbody>
</table>

where \(Z_T = C' Z_F + (C_1 + C_2) Z_F + C_0 Z_{S0}\) and \(C' = -C_1 + C_0 Z_{S0}/Z_{S1}\)

Where \(Z_F\) is \(Z_{Fnl(loop)}\) as given in (1)

Figure 1: Positive negative and zero sequence circuits for Ph-G, Ph-Ph and 3 Ph faults [1]
III. SYSTEM MODELLING

The above analysis of distance protection as explained in (1) and (4) is carried out for the following systems.

A. Fixed Speed Wind Farms

System modeled for study is shown in Figure 2. WTGU farm of 10.5 MW installed capacity is modeled with fixed speed squirrel cage induction generators (SCIG).

![Figure 2 WTGU farm connected to 132 kV grid](image)

Note: $Z_a$ and $Z_b$ are the distance relays at two ends.

The data used for the system of Fig 2 is as follows.

Squirrel cage induction machine (for 1 machine)

- $P_g = 1.5 \text{ MW}$ ; $V_n = 0.4 \text{ kV}$ ; $R_s = 0.01379 \text{ pu}$ ; $X_s = 0.04775 \text{ pu}$ ; $R_e = 0.007728 \text{ pu}$ ; $X_e = 0.04775 \text{ pu}$ ; $X_m = 2.416 \text{ pu}$; $Q_e = -670e3$; $s_{nl} = -0.0001$; (slip on wind speed $< 8 \text{ m/s}$); $s_{nl} = -0.006$; (slip on average wind speed $= 12 \text{ m/s}$)

132kV System Data

$X_f = 0.12 \text{ pu}$; $Z_L = 0.29 \Omega/\text{km}$ with $X/R = 5$

$Z_f$; different SCMVCA, at 132 kV with $X/R = 8$; $Z_{L0} = 4Z_{L1}$

The farm contains a cluster of induction machines of 1.5 MW. Each machine is connected in series with small distribution transformer of 0.44/33kV, 2 MVA and a 33 kV cable of approximate 1 km length as seen in Figure 3. Fixed shunt compensation of 627 kVAR at each machine is provided to reduce the reactive power absorption from the grid.

![Figure 3: Squirrel Cage Induction Generator Wind Farm](image)

The WTGU farm interconnecting transformer is studied for Delta Star grounded (DYn) connection. Line is modeled as pi section with standard parameter of $X$ and $R$, at 132 kV level with $X/R$ ratio considered as 8. Grid is modeled as ideal voltage source with series impedance. Grid Impedance is varied as per the Grid SCMVCA capacity. Tests have been performed for 3 types of Grids (229 MVA, 690 MVA and 2800 MVA having maximum 3 ph short circuit current of 1.0 kA, 3.0 kA and 12.0 kA at Grid bus B respectively). Different fault resistances are modeled as for different type of faults. Line to Ground fault has fault resistances from 0 to 5 Ω. Line to line fault has been simulated till maximum arc fault resistances for particular grid SCMVCA calculated by Warrington formulae (5 Ω for 229 MVA grid, 1 Ω for 700 MVA grid and 0.2 Ω for 2800 MVA).

A.1 Thevenin Equivalent Model of single cage SCIG

The thevenin Equivalent model for Induction machine is taken from reference [3], which states positive sequence impedance for the machine is calculated at unity slip, while negative sequence equivalent impedance is calculated at rated slip from the following Fig. 4. The voltage behind the positive sequence impedance ($E_m$) at the instant of fault is calculated from (8).

$$E_m' = V_1 + \frac{(p-q)}{V_1} \cdot (R' + jX')$$

Since this voltage depends on load flow which in turn on the wind speed hence at different wind speeds different voltage need to be modeled for induction machine. This equivalent model of each SCIG machine is used in Figure 1. Sequence networks offigure 1 are used to analyze the apparent impedance seen by distance relays $Z_a$ and $Z_b$ for all the types of faults. It is not necessary to consider zero sequence model for Induction machine as the neutral of machine is normally isolated to limit the currents during internal faults.

![Figure 4: Positive and negative sequence equivalent of SCIG](image)

B. Synchronous Machine

A synchronous machine is modeled as $X_s$ of 0.12 pu with constant voltage source of 1.0 pu in place of WTGU farm of fig 2. A separate excitation system controlled with AVR and other auxiliaries are assumed to be in place, which help to maintain the constant voltage. Figure 5 shows the system considered for analysis.
Positive, negative and zero sequence parameters are assumed to be same for generator, transformer and grid. Line will have same impedance for positive and negative sequence network but different zero sequence impedance. Similar to wind farm case, thevenin equivalent model analysis is performed on the system of Figure 5 using pre fault load flow conditions and apparent impedance equations of Table 1.

### IV. CASE STUDIES

In Thevenin Equivalent Model (TEM) analysis the pre fault load flow is found taking magnitude of the Bus A and Bus B voltage as constant, 1.0 pu. Power flow angle is calculated for three loading conditions i) no load ii) 50% load iii) full rated load. Current flow is calculated from Bus A to Bus B based on system parameters. Based on the equivalent model as explained in Sec. III, current distribution factors \( C_1, C_2 \) and \( C_0 \) parameters are determined for both sides distance relays. Complex Resistance factor \( K_r \) and distance relay load dependent constants \( A_Z, B_Z, C_Z \) and \( D_Z \) are determined for different type of faults. The R-X diagram have been plotted to see the effect of different wind speeds (different load flow conditions) on the apparent impedances seen by both sides relays.

#### A. Fixed Speed WTGU Farm

For a WTGU Farm the variation in \( K_r \) factor can be seen in following Table 2.

<table>
<thead>
<tr>
<th>Grid SCMVA</th>
<th>( K_r ) for ( Z_A ) Relay Grid Side</th>
<th>( K_r ) for ( Z_B ) Relay WTGU side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ph-E Flt</td>
<td>Ph-ph Flt</td>
<td>3-Ph Flt</td>
</tr>
<tr>
<td>229</td>
<td>0.717</td>
<td>0.582</td>
</tr>
<tr>
<td>690</td>
<td>0.611</td>
<td>0.532</td>
</tr>
<tr>
<td>2800</td>
<td>0.571</td>
<td>0.513</td>
</tr>
</tbody>
</table>

Angle of \( K_r \) is approximately near to zero in all the cases since the system considered is homogeneous with respect to X/R ratio. The plots in Figure 6, Figure 7 and Figure 8 show the effect of \( K_r \) factor (Table 2) for 690 MVA case. The fault is created at 50% of line \( Z = 7.25 \Omega \) for different fault resistances as mentioned in system modeling.

Observations: Grid side distance relay can see the correct impedance in all the three fault types with minimal effect of fault resistance. Wind farm side distance relay can see the correct values of impedances for bolted fault of all types. However, with higher resistances, a fault resistance of 5 \( \Omega \) in Ph-G, the fault resistance appear as 15 \( \Omega \). Similarly, for a fault
resistance of 1Ω in Ph-Ph and 3-Ph fault appear as 9 Ω and 19Ω respectively at high wind speed.

B. Synchronous Machine

Similar to WTGU Farm case the variation in $K_r$ factor for a synchronous machine case is tabulated as follows. Angle of $K_r$ is approximately near to zero in all the cases since the system is considered homogeneous with respect to X/R ratio. The plots in Figure.9,Figure.10 and Figure.11 show the effect of $K_r$ factor (Table 3) for 690 MVA case. The fault is created at 50% of line ($Z=7.25 \, \Omega$) for different fault resistances as mentioned in system modeling.

Table 3: $K_r$ FACTOR FOR SYNCHRONOUS MACHINE CASE

<table>
<thead>
<tr>
<th>Grid SCMVA</th>
<th>$K_r$ for $Z_A$ Relay</th>
<th>$K_r$ for $Z_B$ Relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ph-E Flt</td>
<td>Ph-ph Flt</td>
<td>3-Ph Flt</td>
</tr>
<tr>
<td>229</td>
<td>0.735</td>
<td>0.617</td>
</tr>
<tr>
<td>690</td>
<td>0.618</td>
<td>0.546</td>
</tr>
<tr>
<td>2800</td>
<td>0.574</td>
<td>0.519</td>
</tr>
</tbody>
</table>

Observations: Grid side distance relay can see the correct impedance in all the three fault types with minimal effect of fault resistance. Wind farm side distance relay can see the correct values of impedances for bolted fault of all types. However, with higher resistances, a fault resistance of 5Ω in Ph-G fault appear as 1Ω similarly, for a fault resistance of 1Ω in Ph-Ph and 3-Ph fault appear as 6Ω and 13Ω respectively at rated load.

V. DISCUSSION

It is observed from Figure 6 to Figure.11, that apparent impedance seen by distance relays $Z_A$ are similar in behavior. But the adverse effect of $R_f$ and infed is worse in WTGU case. Based on the above study percentage (%) change in apparent impedances can be studied by analyzing the effect on $K_r$ factor. The % change for $K_r$ factor for different grid SCMVA is mentioned in Table 4

Table 4: % change in $K_r$ factor for WTGU and Synchronous Machine

<table>
<thead>
<tr>
<th>Grid SCMVA</th>
<th>% change in $K_r$ for $Z_A$ Relay (Grid Side)</th>
<th>% change in $K_r$ for $Z_B$ Relay (WTGU side)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ph-E Flt</td>
<td>Ph-ph Flt</td>
<td>3-Ph Flt</td>
</tr>
<tr>
<td>229</td>
<td>-2.38</td>
<td>-5.77</td>
</tr>
<tr>
<td>690</td>
<td>-1.12</td>
<td>-2.55</td>
</tr>
<tr>
<td>2800</td>
<td>-0.42</td>
<td>-1.12</td>
</tr>
</tbody>
</table>

VI. CONCLUSIONS

Based on the above observation, following conclusions can be derived from the studies:

i. Availability of zero sequence current for the relay in DYn connection of the ICT gives distance relay a better operating condition during Ph-G fault. Thus it is recommended to have DYn connection.

ii. Distance protection will operate with high reliability and selectivity for solid phase to earth as well as multi phase faults.
iii. For higher resistance Ph-G faults additional earth fault protections such as communication added directional earth fault schemes, are recommended in addition to distance protection.

iv. For high resistive ph-ph and 3ph faults transfer tripping schemes are recommended to supplement distance protection.

APPENDIX A

(APPEARANT LOOP IMPEDANCE WITH FAULT RESISTANCE)

With reference to sequence network of Figure 1,

\[ V_{a1} = V_{F1} + C_1 I_1 \cdot mZ_{L1} \]  \hspace{1cm} (9)

\[ V_{a2} = V_{F2} + C_2 I_2 \cdot mZ_{L2} \]  \hspace{1cm} (10)

\[ V_{a0} = V_{F0} + C_0 I_0 \cdot mZ_{L0} \]  \hspace{1cm} (11)

Also \( I_{a0} = C_1 I_1, I_{a2} = C_2 I_2, I_{a0} = C_0 I_0 \)

where \( V_{F1}, V_{F2}, V_{F0} \) are the fault point voltage for positive and negative sequence networks and \( C_1, C_2, C_0 \) are distribution factors defined in [1] by current division theorem.

\[
C_1 = \left( Z_{g1} + (1 - m)Z_{L1} \right) / \left( Z_{g1} + Z_{L1} + Z_{s1} \right)
\]

\[
C_2 = \left( Z_{g2} + (1 - m)Z_{L2} \right) / \left( Z_{g2} + Z_{L2} + Z_{s2} \right)
\]

\[
C_0 = \left( Z_{g0} + (1 - m)Z_{L0} \right) / \left( Z_{g0} + Z_{L0} + Z_{s0} \right)
\]  \hspace{1cm} (12)

Phase to phase fault:

For a B-C fault in system of Figure 2, BC loop measurement will be given by

\[ Z_{BC} = (V_B - V_C) / (I_B - I_C) \]  \hspace{1cm} (13)

Where,

\[ V_B - V_C = (a^2 - a)(V_{a1} - V_{a2}) \]  \hspace{1cm} (14)

and, \( I_B - I_C = (a^2 - a)(I_{a1} - I_{a2}) \)

From Figure 1, in ph-ph fault case,

\[ V_{F1} = I_1 R_f + V_{F2} \quad I_1 = -I_2 \]  \hspace{1cm} (15)

Using equation (9), (10), (11), (12), (14), (15) in Eq(13),

\[ Z_{BC} = mZ_L + R_f / (C_1 + C_2) \]  \hspace{1cm} (16)

Three phase fault:

For 3Ph fault in Figure 2 and its equivalent sequence component network of Figure 1,

\[ V_{F1} = I_1 R_f \quad I_2 = I_0 = 0 \]  \hspace{1cm} (17)

Ph-Ph loops will see the impedance as

\[ Z_{BC} = mZ_L + R_f / C_1 \]  \hspace{1cm} (18)

Ph-Gnd loops will see the impedance as

\[ Z_{AG} = mZ_L + R_f / C_1 \]  \hspace{1cm} (19)

Single phase to ground fault

For a AG fault in system of Figure 2, A-G loop measurement will be given by,

\[ Z_{AG} = V_{AG} / (I_A + K_0 I_0) \]  \hspace{1cm} (20)

And from sequence component network of Figure 1,

\[ V_{F1} + V_{F2} + V_{F0} = 3I_1 R_f \quad I_2 = I_0 = I_1 \]  \hspace{1cm} (21)

\[ Z_{AG} = (V_{a1} + V_{a2} + V_{a0}) / (I_{a1} + I_{a2} + K_0 I_{a0}) \]  \hspace{1cm} (22)

Using equations (9), (10), (11), (12), (20), (21) in (22), the A-G loop impedance will be given by,

\[ Z_{AG} = nZ_L + 3R_f / C \]  \hspace{1cm} (23)

Where \( C = C_1 + C_2 + C_0(Z_{L0} / Z_L) \)

REFERENCES