NEW CRITERION FOR STATOR INTER TURN FAULT DETECTION OF SYNCHRONOUS GENERATOR

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Abstract—Generator is an important component of power system which plays a vital role in the whole system for security and stability. The conventional protection systems will not detect inter turn faults. Longitudinal differential protection detects only inter phase and ground faults. Some large capacity generators are provided with split phase windings to enable transverse differential relay to detect inter turn faults. But this system cannot be retrofit to existing generators. The inter-turn fault protection for stator windings of generators is an important and effective measure to ensure the safe operation of the generator because the inter turn fault may finally lead to ground fault. Therefore, early detection of inter-turn faults would eliminate subsequent damage to adjacent coils and stator core, reducing repair cost and generator outage time. The new Criterion discussed in this paper for detection of inter turn fault is based on the fact that the inter turn fault causes unbalance in the generator phase voltages. The resulting generator internal negative sequence voltage is used as fault indicator for inter-turn fault detection. The new protection technique has been studied using MATLAB. In addition, it is ensured that this protection won’t incorrectly operate for external fault and unbalanced load as long as generator windings are healthy.

Keywords- Inter Turn fault, Internal Negative Sequence Generator Voltage

I. INTRODUCTION

The stator inter turn faults in the synchronous generator are taken to be rare and so are not taken into serious consideration while designing the protection system. However there is enough data to indicate that inter turn short circuit can exist in stator windings of generators. The synchronous generator is exposed to variety of operating conditions resulting in varying electrical, thermal and mechanical stresses. The operating conditions coupled with aging lead to weakening of insulation. This process may finally lead to inter turn fault in the winding. Recent methods to protect a Synchronous Generator have been proposed in the application guide [1]. In order to protect the machine against turn-to-turn faults for the turbo-generator with only three lead-out terminals in the neutral side, using negative sequence impedance directional protection of asymmetrical fault is explained in [2]. A fuzzy neural network (FNN) based inter-turn short circuit fault detection scheme for generator using second harmonic magnitude of field current and the negative sequence components of voltages and currents is proposed in [3]. The most popular feature extraction approaches for the stator inter-turn fault in electrical machines using symmetrical component method is discussed in [4]. Negative Sequence Power directional protection for stator internal asymmetrical fault is proposed in [5]. Performance analysis of the above protection methods using Negative sequence quantities shows poor sensitivity to detect inter turn faults, the new criterion for inter turn fault detection discussed in the following sections is superior to other existing protections in the aspect of sensitivity and protection range.

The symmetrical component technique is being preferred over traditional methods for fault diagnosis of synchronous generators. Each Power system element can be represented by three decoupled sequence networks pertaining to positive, negative and zero sequences respectively. Under balanced winding condition the generator voltage has only the positive sequence EMF, the negative sequence & zero sequence equivalent circuits contain no EMFs induced in it. The stator winding inter-turn short circuit fault produces the unbalance in the generator phase voltages. Figure 1 shows the Negative sequence network of Synchronous Generator for balanced and unbalanced winding conditions respectively.

From the negative sequence network, the negative sequence terminal voltage is

\[ V_2 = E_2 - jX_2^* I_2 \]  

(1)

The internal negative sequence voltage is

\[ E_2 = V_2 + jX_2^* I_2 \]  

(2)

The above equation shows the presence of internal negative sequence voltage when there is an unbalance in the
phase windings of the machine which is caused by inter turn fault.

II. MODELLING OF SYNCHRONOUS GENERATOR

In this section the state-space model for a Synchronous Generator is described that will be used for Negative Sequence Reactance estimation for Inter turn fault analysis. In order to formulate the state estimation equation for a synchronous generator, it is necessary to employ a mathematical model [7] which represents the synchronous generator in the conditions under study. This model will comprise three stator windings, one field winding and two damper windings as shown in Fig. 2. The magnetic coupling between the windings is a function of the rotor position. Thus, the flux linkage of the windings is also a function of the rotor position.

The equations for the flux linkages of the stator and rotor windings can be expressed as

$$\Psi_s = L_{ss} I_s + L_{sr} I_r$$

$$\Psi_r = L_{sr} I_s + L_{rr} I_r$$

where $L_{ss}$, $L_{sr}$ and $L_{rr}$ correspond to stator-stator, rotor-rotor and stator-rotor inductances respectively.

$$I_w = \begin{bmatrix}
L_{ss} + L_A + L_q \cos 20 & -\frac{L_A}{2} + L_A \cos(20 - 120) & -\frac{L_A}{2} + L_A \cos(20 + 120) \\
-\frac{L_A}{2} + L_A \cos(20 - 120) & L_A + L_A \cos 2(0 - 120) & -\frac{L_A}{2} + L_A \cos 20 \\
-\frac{L_A}{2} + L_A \cos(20 + 120) & -\frac{L_A}{2} + L_A \cos 2(0 + 120) & L_A + L_A \cos 2(0 + 120)
\end{bmatrix}$$

$$L_{tr} = \begin{bmatrix}
L_{trd} & L_{tmd} & 0 \\
L_{tmd} & L_{tqr} & 0 \\
0 & 0 & L_{tkd}
\end{bmatrix}$$

$$L_{sr} = \begin{bmatrix}
L_{msd} \cos(\theta) & L_{msd} \cos(\theta - 120) & L_{msd} \cos(\theta + 120) \\
L_{msd} \cos(\theta - 120) & L_{msd} \cos(\theta - 120) & L_{msd} \cos(\theta + 120) \\
L_{msd} \cos(\theta + 120) & L_{msd} \cos(\theta + 120) & L_{msd} \cos(\theta + 120)
\end{bmatrix}$$

It is important to note that the inductances are time varying since $\theta$ is a function of time i.e., $\theta = \omega t + \theta_0$. The time-varying inductances can be simplified by referring all quantities to a rotor frame of reference through Park’s Transformation. The new transformed voltages, currents and flux linkages can be obtained from the following relationship:

$$V_{dq0} = T_{dq0} V_{abc}$$

$$\Psi_{dq0} = T_{dq0} \Psi_{abc}$$

Where the vectors $V_{dq0} = [V_d \ V_q \ V_0]^T$

$$I_{dq0} = [I_d \ I_q \ I_0]^T$$

and the Park’s transformation matrix is:

$$T_{dq0} = \frac{2}{3} \begin{bmatrix}
\cos(\theta) & \cos(\theta - 120) & \cos(\theta + 120) \\
-\sin(\theta) & -\sin(\theta - 120) & -\sin(\theta + 120)
\end{bmatrix}$$

Machine modelling, calculation of Machine Parameters and Steady state operation is explained in [8].

Dq0 voltage equations of synchronous machine are

$$E_d = -I_d R_d - \omega \psi_q + P \psi_d$$

$$E_q = -I_q R_q + \omega \psi_d + P \psi_q$$

$$E_0 = -I_0 R_d + P \psi_0$$

$$E_{fd} = I_{fd} R_{fd} + P \psi_{fd}$$

$$E_{kd} = I_{kd} R_{kd} + P \psi_{kd} = 0$$

$$E_{kq} = I_{kq} R_{kq} + P \psi_{kq} = 0$$

The expression for the stator dq0 flux linkages are

$$\Psi_d = \frac{3}{2} (L_A + L_q) I_{fd} + \frac{3}{2} (L_A - L_q) I_{kd} - (L_{ls} + \frac{3}{2} (L_A + L_q)) I_d$$

$$\Psi_q = \frac{3}{2} (L_A - L_q) I_{kq} - (L_{ls} + \frac{3}{2} (L_A - L_q)) I_q$$

$$\Psi_0 = -L_{ld} I_0$$

The expression for the rotor windings flux linkages are

$$\psi_{fd} = L_{fkd} I_{kd} + L_{md} I_{ld} - L_{md} I_{d}$$

$$\psi_{kd} = L_{kdd} I_{kd} + L_{md} I_{fd} - L_{md} I_{d}$$

$$\psi_{kq} = L_{kqd} I_{kq} - L_{mq} I_q$$

The actual voltage $E$ of the windings can be written in the following form

$$[E] = [R][I] + [L][I]$$

Where
Defining voltage components as system control inputs and currents as measurable state variables, the state equation is

\[
\dot{I} = [A][I] + [B][E]
\]

(12)

where \([A] = -[L]^{-1}[R]\) and \([B] = [L]^{-1}\)

To analyze the protection sensitivity, a typical synchronous generator is taken for example in this paper, for which the major data is listed in Table I.

<table>
<thead>
<tr>
<th>TABLE I. GENERATOR RATINGS AND PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power (S_{rated})</td>
</tr>
<tr>
<td>Rated Voltage (V_{rated})</td>
</tr>
<tr>
<td>Rated Frequency (f)</td>
</tr>
<tr>
<td>Stator resistance (R_s)</td>
</tr>
<tr>
<td>Stator leakage reactance (X_{ls})</td>
</tr>
<tr>
<td>D-axis Reactance (X_d)</td>
</tr>
<tr>
<td>Q-axis Reactance (X_q)</td>
</tr>
<tr>
<td>D-axis Transient Reactance (X_{d1})</td>
</tr>
<tr>
<td>Q-axis Transient Reactance (X_{q1})</td>
</tr>
<tr>
<td>D-axis Sub-transient Reactance (X_{d1})</td>
</tr>
<tr>
<td>Q-axis Sub-transient Reactance (X_{q1})</td>
</tr>
<tr>
<td>Field resistance (R_f)</td>
</tr>
<tr>
<td>Field leakage reactance (X_{lf})</td>
</tr>
</tbody>
</table>

III. NEGATIVE SEQUENCE REACTANCE

Steps involved for calculation of negative sequence reactance \(X_2\) of Synchronous generator [8] are as follows:

1. Let the unexcited field structure be rotated forward at synchronous speed with all rotor circuits closed with the balanced negative sequence voltage applied to the stator of synchronous generator.

2. The negative sequence currents produce an mmf rotating backward at synchronous speed with respect to the armature and hence backward at twice the synchronous speed with respect to rotor.

3. Currents of twice rated frequency are induced in all the rotor circuits.

4. The d-axis and q-axis reactances are then the ratio of impressed transformed voltages and currents.

5. Negative sequence reactance \(X_2\) is the arithmetic mean of the two computed axis reactances.

\[
X_2 = \frac{X_d + X_q}{2}
\]

(13)

The State Space Model of the machine is formed with \(E_{fd} = 0, E_{kd} = 0, E_{kq} = 0\) and \(V_d, V_q, V_0\) corresponding to negative sequence voltages \(V_a, V_c\) and \(V_b\) applied shown in Fig. 3 as control inputs. The obtained second harmonic D and Q-axis currents are as shown in Fig. 4

![Figure 3. Negative Sequence Voltages](image-url)

![Figure 4. Negative Sequence D and Q-axis currents](image-url)

This gives the D and Q-axis sub transient reactance

\[
X_d = 0.052 \Omega, \quad X_q = 0.069 \Omega
\]

Negative Sequence Reactance, \(X_2 = 0.060 \Omega\)

IV. INTERNAL NEGATIVE SEQUENCE VOLTAGE

Consider the test system Synchronous Generator connected to a three phase RL load as shown in the Fig.5

![Figure 5. System Configuration](image-url)
The actual terminal voltage $V$ of the windings of the Synchronous Generator can be written in the following form

$$v = r i + p [l][i]$$  \hspace{1cm} (14)

Where $v = [v_a \ v_b \ v_c \ E_{fd} \ E_{kd} \ E_{kq}]^T$

$[l] = \begin{bmatrix} L_{ss} & L_{se} \
-L_{es} & -L_{ee} \end{bmatrix}$ and $[r] = \text{diag}[-r_a \ -r_b \ -r_c \ r_{fd} \ r_{kd} \ r_{kq}]$

The matrix $[l]$ has time varying elements.

The load voltage equation is

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} r_{la} & 0 & 0 \\ 0 & r_{lb} & 0 \\ 0 & 0 & r_{lc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + p \begin{bmatrix} l_{la} & 0 & 0 \\ 0 & l_{lb} & 0 \\ 0 & 0 & l_{lc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$  \hspace{1cm} (15)

Equation (14) and (15) are combined and solved for terminal voltages and currents. In order to calculate negative sequence current and voltage from the phase quantities using (16) & (17), the phase quantities must be of vectors but not instantaneous quantities.

$$V_2 = \frac{1}{3}(V_a + \alpha^2 V_b + \alpha V_c)$$  \hspace{1cm} (16)

$$I_2 = \frac{1}{3}(I_a + \alpha^2 I_b + \alpha I_c)$$  \hspace{1cm} (17)

where $\alpha = -0.5 + j0.866$

So to extract Negative sequence voltage and current D-Q transformation is used considering that the reference frame is rotating in clockwise direction. For the positive sequence phase quantities the transformed D and Q axis quantities will be second order quantities. For the negative sequence phase quantities the transformed D and Q axis voltages and currents will be dc quantities. From the phase quantities obtain the D- and Q- components which comprises of dc quantity due to Negative sequence components and second order quantities due to Positive sequence components. Filtering out the higher order quantities using a Low Pass filter gives the dc quantity alone which represents negative sequence components.

Negative sequence voltage, $V_2 = V_q + jV_d$  \hspace{1cm} (18)

Negative sequence current, $I_2 = I_q + jI_d$  \hspace{1cm} (19)

Negative sequence Impedance, $Z_2 = jX_2$

Internal Negative Sequence Voltage $E_2 = V_2 + I_2 Z_2$  \hspace{1cm} (20)

V. RESULTS

In order to investigate the sensitivity of the proposed protection scheme, it is essential to analyze the synchronous generator under various external asymmetrical conditions and inter-turn faults. The waveforms of phase voltages and currents measured at the terminals of generator are as shown in Fig 6, Fig 7 and Fig 8.
External faults at the load terminals and the Inter Turn in the phase- a winding of stator are applied at \( t = 2.5 \) sec. The Negative Sequence Voltage and Negative sequence current is obtained using (18) and (19) respectively. Then the corresponding Internal Negative sequence generator voltage obtained from (20) for various faults are as shown in the Fig 10 - Fig 14.

### Table 1: Inter Turn Fault

<table>
<thead>
<tr>
<th>External fault</th>
<th>All phases Healthy</th>
<th>1% turns shorted in phase-A</th>
<th>5% turns shorted in phase-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Through Fault</td>
<td>( E_1 ) (V)</td>
<td>( I_1 ) (A)</td>
<td>( E_2 ) (V)</td>
</tr>
<tr>
<td>0</td>
<td>0.6</td>
<td>58.09</td>
<td>137</td>
</tr>
<tr>
<td>Unbalanced Load</td>
<td>320.6</td>
<td>5.619</td>
<td>265.5</td>
</tr>
<tr>
<td>LG</td>
<td>217.1</td>
<td>11.940</td>
<td>271.2</td>
</tr>
<tr>
<td>LLG</td>
<td>338.2</td>
<td>10,450</td>
<td>307.5</td>
</tr>
<tr>
<td>LLLG</td>
<td>56.7</td>
<td>179</td>
<td>84.78</td>
</tr>
</tbody>
</table>

Figure 9. Voltage and Current waveforms for Line to ground fault without inter turn fault

Figure 10. Unbalanced load without inter turn fault

Figure 11. Line to Ground fault without inter turn fault

Figure 12. 7% of turns shorted in phase-A

Figure 13. LG fault and Inter turn fault

Figure 14. Unbalanced load and Inter turn fault
It is noticed form the waveforms that the Internal Negative Sequence Generator Voltage is zero under balanced operating condition.

### Table II. INTERNAL NEGATIVE SEQUENCE GENERATOR VOLTAGE AND CURRENT FOR DIFFERENT FAULT CONDITIONS

<table>
<thead>
<tr>
<th>% of Turns shorted in phase-A</th>
<th>E2 (V)</th>
<th>I2 (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0</td>
<td>0.6</td>
</tr>
<tr>
<td>1%</td>
<td>58.09</td>
<td>137</td>
</tr>
<tr>
<td>2%</td>
<td>92.6</td>
<td>231.8</td>
</tr>
<tr>
<td>3%</td>
<td>153.6</td>
<td>350.8</td>
</tr>
<tr>
<td>4%</td>
<td>220.1</td>
<td>475.4</td>
</tr>
<tr>
<td>5%</td>
<td>283.8</td>
<td>661.5</td>
</tr>
<tr>
<td>6%</td>
<td>339.3</td>
<td>806.4</td>
</tr>
<tr>
<td>7%</td>
<td>401.7</td>
<td>943</td>
</tr>
<tr>
<td>8%</td>
<td>442.9</td>
<td>1013.2</td>
</tr>
<tr>
<td>9%</td>
<td>499.6</td>
<td>1190</td>
</tr>
<tr>
<td>10%</td>
<td>547.2</td>
<td>1346</td>
</tr>
</tbody>
</table>

The logic has to be such that the relay should operate only for inter turn fault and it should not operate for external faults or load unbalance. The maximum internal negative sequence generator voltage for all external faults is selected as the set voltage. From Table II and Table III, the set voltage is 400V.

Plot of Internal Negative Sequence Voltage for few turns shorted in phase-A winding of Generator is shown in Fig 15.

VI. CONCLUSION

In this paper a new method for Inter-turn fault protection of Large Generator is presented. The performance of the proposed method was evaluated for both internal and external faults. This method uses the internal negative sequence voltage of the Generator and can detect minor turn-to-turn faults very efficiently. Also it can differentiate between internal and external faults. No additional sensors are required to implement the scheme since it only needs the terminal voltage and current data of Generator. The scheme can be very easily implemented to ensure rapid tripping of the faulty machine at a cheaper cost.

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