Verification of Synchronous Generator Model

The simulation of the internal fault of the synchronous generator is verified experimentally by applying numerous internal fault types at different locations, inception time and pre-fault loading. These types include: single phase to ground fault, phase to phase fault, double phase to ground fault, and three phase fault. These faults were applied using the following laboratory systems.

1. Hardware Components

A three-phase synchronous machine was physically modeled in the Lab to represent a large system; an overall schematic diagram of the experimental system setup is shown in Fig. 1.

The power system current signals are obtained through current transformer. The data acquisition board receives the analog signals through an Analog Input Card. The analog filtered signal is then transferred to a personal computer, and is then converted to a digital one by internal Analog to Digital (A/D) converter. Details of these blocks are presented in the following subsections.

![Schematic diagram of lab work system](image)

**Figure 1: Schematic diagram of lab work system**

1.1 Synchronous Generator

The synchronous lab machine is a three-phase 2 kVA, 220 V universal laboratory machine driven by a separately excited dc machine and is connected to a three-phase load bank.

**General Description Laboratory Machine**

- The B.K.B. universal laboratory machine set, shown in Fig. 2 consists of a two-pole uniform air gap universal machine coupled to dc dynamometer.
- Nominal ratings of the universal machine are 2 kVA as a three phase 50 Hz, 3000 r.p.m.
- The dynamometer is rated at 3 kW, 220V, 2000/3000 r.p.m.

All winding connections are brought out to the large terminal panel and the stator connections are also terminated at a 24-way socket.
Table 1 Principal data of the machine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance/coil (R_s)</td>
<td>0.03</td>
</tr>
<tr>
<td>Rotor resistance/coil (R_f)</td>
<td>0.0057</td>
</tr>
<tr>
<td>Total moment of inertia of rotors plus coupling</td>
<td>$6.2 \times 10^{-2}$ kg.m$^2$</td>
</tr>
<tr>
<td>Self-inductance of stator winding (L_s)</td>
<td>2</td>
</tr>
<tr>
<td>Self-inductance of field winding (L_f)</td>
<td>1.37</td>
</tr>
<tr>
<td>Self-inductance of d-axis damper winding (L_D)</td>
<td>1.344</td>
</tr>
<tr>
<td>Self-inductance of q-axis damper winding (L_Q)</td>
<td>1.357</td>
</tr>
<tr>
<td>Mutual inductance between stator and field windings (L_sf)</td>
<td>1.34</td>
</tr>
<tr>
<td>Mutual inductance between stator and d-axis damper windings (L_sd)</td>
<td>1.264</td>
</tr>
<tr>
<td>Mutual inductance between stator and q-axis damper windings (L_sq)</td>
<td>1.264</td>
</tr>
<tr>
<td>Mutual inductance between field and d-axis damper windings (L_fd)</td>
<td>1.325</td>
</tr>
</tbody>
</table>

1.2 Current Transformer

The differential relay uses the line and neutral side currents input signals. The current signals are obtained by 100/5 A current transformer. The CT secondary’s are connected to shunt resistance to obtain an equivalent voltage signals. The low-level output voltage signals out from transformers are filtered then input to data acquisition card.

1.3 Analog Filter

A second-order Butterworth band-pass filter is used to attenuate the dc component and high frequency components. The Butterworth filter has a flat response in the passband. The filter is centered at the nominal system frequency and its pass band is chosen to be 80Hz. This value allows a considerable reduction of the high frequency and dc components with a small-time delay. The filter circuit used is shown in Fig. 3.

An array of six filter circuits simultaneously filters the current signals before being fed to the data acquisition system. For current signals, the filter unit circuit is preceded by an amplifier circuit.
1.4 Data Acquisition Board

The objective of the DAQ is to convert the analog signals into a digital form ready for use by the computer. A 1 kHz sampling rate implies 1ms time interval between samples which is needed for an appropriate software and hardware setup to accomplish protecting relay task within this time interval. The national instruments NI USB-6008 multifunction I/O device connected to the computer, and used to acquire voltage and current signals.

2. The Lab Work Procedure

The armature winding of each phase of the generator is splitting into four parts; the parts of each phase are connecting to three phase contactors. The outputs of each contactor are connecting to a ground through a selector, as shown in Fig.4. The location and type of fault will be changed by changing the connection of the selectors. In this way internal faults at 25%, 50%, 75% and 100% of the winding can be carried out. The type of the fault can be either a ground fault, phase to phase fault, phase to phase to ground fault, or three phase fault.

The following procedure is used practically to record the faults occurred in the synchronous machine:

1- Split each coil of the synchronous generator stator into many parts (in this work it will be split into four parts).
2- Connect each part of the windings to three phase contactors (Contactor A, B and C).
3- Connect the output of each contactor to the selector (Selector A, B, and C) to detect the type of fault.
4- Connect the dc motor (prime mover) and the rotor winding of the synchronous generator to dc supply through three phase contactor (Ks).
5- Start up the generator by energized the contactor Ks at the desired power.
6- Switch on the fault simulation switch to operate the contactors (A, B, and C) control circuit. This will cause an internal fault to occur for a specified fault type and location.
Figure 4: The connection diagram of the proposed lab work
3. Software structure

A graphical user interface (using LabVIEW program) is designed to illustrate the three phase currents at both sides of generator; neutral and grid side as shown in Fig. 6.

4. Results

Numerous internal fault types such as single phase to ground fault, phase to phase fault, double phase to ground fault, and three phase fault at different locations, inception time and pre-fault loading are applied using the prescribed laboratory system.

The laboratory results for two different internal single phase to ground faults at phase A are shown in Fig. 7 and Fig. 8. The first one is a single phase to ground at 25% of windings from the neutral point. The stator currents at both the neutral and terminal side of the synchronous generator is shown in Fig. 7. Twenty cycles of currents are recorded for test, ten cycles before fault and the other during fault. It is cleared from the figure that the neutral side current ($i_{a1}$) of phase A is increased due to the short circuit and the terminal side current ($i_{a2}$) is decreased by
25% approximately because the neutral point is moved toward the terminal side. The currents in the other two phases B and C at terminal side are the same at the neutral side and they decrease due to the short circuit in phase A.

The second fault is emulated at 75% of winding of phase A. The stator currents are shown in Fig.8. The current waveforms are similar to currents in the first case in shape. But the change of currents is more than the first case.

Figure 7: Recorded currents for an internal single phase to ground fault at 25% of phase A winding

Figure 8: Recorded currents for an internal single phase to ground fault at 75% of phase A winding

Figure 9 illustrates the stator currents of synchronous machine in case of phase to phase (A-B) faults at 50% of windings. It is cleared from the figure that the neutral side currents of phase A ($i_{a2}$) and B ($i_{b2}$) were increased due to the short circuit and the terminal side currents ($i_{a1}$ and $i_{b1}$) are decreased by 50% because the fault point in the middle of the stator windings of phase A and B. The neutral and terminal side currents of phase C was decreased.
Figure 10 illustrates double phase to ground fault (A-B-G) occurs at 50% of the windings, the current waveforms of the neutral and terminal side currents of the synchronous generator are shown in Fig. 10. The stator currents waveforms are similar to the waveforms in case of phase to phase faults in shape and different in magnitude due to the different in fault type.

As an example of three phase internal faults, Fig. 11 shows the stator currents at both ends of the generator when a three-phase fault occurs at 50% of windings. The figure illustrates that the neutral side current of the three phases are increased due to the short circuit and the terminal side current are decreased, because the fault divides the winding of each phase into two parts and the neutral point is moved. The experimental lab work is done for many fault cases.

**Figure 9: Recorded currents for an internal phase to phase fault at 50% of phase A and B windings**

**Figure 10: Recorded currents for an internal double phase to ground fault at 50% of phase A and B windings**
Figure 1: Recorded currents for an internal three phase fault at 50% windings

5. Comparison between laboratory and simulation results

Comparisons between laboratory and simulation results for internal single phase to ground faults are shown in Fig. 12. The fault currents shown in Fig. 12a are the results of an internal single phase to ground fault at 50% and obtained from simulations of the proposed model of SG. Figure 12b shows the measured fault currents for a single phase to ground fault at the same location of windings (50%).

It can be observed that the current waveforms of the simulated and laboratory are very close in shape and magnitude. There is a small difference in the curves of simulated cases with respect to the experimental ones. These differences are due to the operating environment of physical system, which is not ideal due to the existence of noise, CT mismatches and CT saturation.
a) Computed stator currents for an internal single phase to ground fault at 50% of phase A winding, the load power before fault is 1pu

b) Measured currents for an internal single phase to ground fault at 50% of phase A winding, the load power before fault is 1pu

Figure 12: Comparisons between laboratory and simulation results for internal single phase to ground faults

6. Reference