Effects of Types of Faults on Generator Vibration Signatures

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Abstract – Generators are frequently subjected to high currents and voltages caused by electrical disturbances in the power system. Faults in particular subject the generator to stresses beyond its design limits and cause high temperature increase, amplify and distort air gap torques, and create unbalanced flux densities. Even more stressful as a consequence of faults are sudden loss of load, fault clearance and reclosing.

Mechanically, the abnormal forces that are generated excite the rotor and as a result, amplify the shaft’s normal mode of oscillation. The objective of this paper is to present the results on the experiment conducted regarding the effects of selected types of electrical faults on generators vibration signatures. It aims to examine the generated vibration frequencies, changes in rotor shaft orbits and increase in vibration magnitudes as a result of faults.

I. INTRODUCTION

Generators are frequently subjected to high currents and voltages caused by electrical disturbances in the power system and these significantly contribute to the reduction of the machine operating life.

The most affected group by these disturbances are small-scale grid-connected power plants (<20MW), such as mini-hydro, micro-turbines fueled by natural gas or landfill gas, and wind turbines because of their low-inertias. In general, they have lower plant availabilities as compared with the larger plants connected to high voltage transmission lines.

Faults in particular, although transient in nature, subject the generator to stresses beyond its design limits and cause high temperature increase that weakens the machine’s mechanical strength and insulation, amplify and distort air gap torques and create unbalance flux densities in the air gap [1-5]. Even more stressful as a consequence of faults are sudden loss of load, fault clearance and reclosing. The cumulative effect of these abnormalities leads to material fatigue, insulation and structural failure and eventually to equipment breakdown. Mechanically, the abnormal forces generated excite and amplify the rotor oscillatory motion and result in severe machine vibration.

Generator vibration is normally monitored by the plant’s condition monitoring system that serves as back up to its electrical protection system. Vibration is defined as continuous, repetitive or periodic oscillations relative to a certain fixed reference. The physical motion of rotating machines generates vibration, which gives a physical indication of the health of equipment (“what is happening to the machine”) and the generated vibration frequencies and magnitudes represent the machine vibration signature [6, 7].

In this paper, the results on the experiment conducted regarding the effects of selected types of electrical faults on generator vibration signatures are presented. It aims to examine the generated vibration frequencies, changes in rotor shaft orbits and increase in vibration magnitudes due to three-phase fault (3PF), line-to-line fault (LLF), line-to-ground fault (LGF) and double-line-to-ground fault (LLGF). In the experiment, the above conditions were applied to the terminals of a loaded 5KVA three phase synchronous generator. The vibration responses for each condition were examined, analyzed and compared.

II. TYPES OF FAULTS

Electrical faults are the most damaging among the disturbances that could possibly happen in the power system. Although faults are transient in nature that occur in just a few cycles, they subject the generator to mechanical and temperature stresses beyond its operating limits. The more frequent the occurrences of these events in the power network, the faster will be the rate of deterioration or wear of the machine.

The system parameters that can influence the effect of electrical faults to the generator are generator inertia, generator and line damping, line and fault impedance, transient reactance and fault critical clearing time or CCT [8]. Smaller machines are more susceptible to damage or fatigue and more unstable during faults therefore will have lower CCTs. This means that the lighter the machine, the less will be its tolerance against electrical disturbances thus making it more unstable compared with heavier machines. Heavier machines have higher tolerance against faults primarily because of the flywheel effect of inertia. The higher damping ability provided by the generator damper windings and the line resistance, provides higher generator stability as unbalanced currents or voltages are, to some
extent absorbed by the damper windings and the system. Large fault impedances provide more stability while for large line reactances, the effect is the opposite as the magnitude of the fault is higher.

There are three interrelated factors considered that excite the rotor’s normal mode of oscillation during electrical faults: (i) sudden loss of load, (ii) distorted and amplified air gap torques or magnetic fields, and (iii) unsymmetrical flux densities in the air gap.

The effect of sudden loss of load is the abrupt change in the electrical torque $T_e$ due to the change in the fundamental frequency of the armature current that induces impact torques on the shaft or torsional oscillations as in [1]. The magnitude of which is proportional to the change in $T_e$ in relation to mechanical torque $T_m$ (or $\Delta T$). The higher the change, the higher will be the machine vibration response. This happens in a few cycles prior to clearance and again after clearance.

At the instant of a fault, the power developed by the generator abruptly decreases to zero and its terminal voltage will drop to almost zero in magnitude. Since the prime mover is incapable of responding instantly, $T_m$ will be greater than $T_e$ resulting in the increase of engine speed [9, 10]. The generator over speed protection will normally operate once the frequency exceeds a certain level. The impact is analogous to a car towing another car when suddenly the chain connecting them breaks.

The large transient currents, at system or other frequencies particularly the positive, negative, zero sequence and unidirectional components in the armature windings alter or interact with the steady-state magnetic fields in the air gap [1, 11, 12]. A dc component on the armature for instance will induce an ac component on the rotor windings.

The currents including the dc component are attributed to the machine synchronous transient and subtransient reactances, which are in turn associated with the flux linkages between the rotor and stator windings [13]. The larger the fault currents in the stator windings, the greater the air gap torque distortion and amplification.

Under normal conditions, the electric and magnetic fields are circumferentially distributed periodically and evenly across the air gap. However during electrical disturbances, these fields change abruptly and become distorted. The unsymmetrical magnetic flux densities in the air gap create an unbalanced pull on the rotor [14, 15]. Healthy or loaded phase windings will have higher flux densities than the open-circuited phase or phases. This condition is most likely to exist as a result of unbalanced loading and single phasing conditions as well as prolonged or sustained unbalanced faults. The worst-case effect is when the rotor rubs on the stator coils.

The effect of the first two factors discussed above is sudden, excessive and pulsating electromagnetic torques in the air gap, which is impressed on the generator shaft. Mechanically, these are detected as severe vibration magnitudes that originate from the rotor shaft, transferred to the machine casing through the bearings and travel along the shaft train and to the prime mover.

As a consequence of faults, fault clearance and reclosing can be more severe than faults as they can produce even higher generator torques resulting in abrupt changes in the shaft mechanical torques [1-3, 11, 12, 16]. Automatic reclosing for instance produces abnormal torques similar to faulty synchronization as in [3, 17, 18]. Fault clearing time also has significant effect on air gap torques. According to [1], longer clearing times results in higher air gap torques and therefore could result in higher and longer abnormal machine vibration.

III. VIBRATION MEASUREMENT AND ANALYSIS

Vibration can be measured using displacement, velocity and acceleration transducers that convert machine motion to electrical signals. From these, the machine’s signature can be generated and analyzed.

Machines generate an array of vibration signals at different frequencies which can be seen and analyzed in the frequency spectrum of the signals. These are basically plots of amplitudes versus the various frequency components and represent machine motion as a function of frequency. On the other hand, a time plot of the signals is used to determine the resultant vibrations magnitudes of the various frequencies in the frequency spectrum and represent machine motion as a function of time.

In the experiment, a dual-axis accelerometer was used to measure the generator vibration response. The sensor output was fed to a data logger and finally to a personal computer. The transducer was mounted on the end-side of the stator casing adjacent to a bearing and in-line with the rotor shaft. The set-up allows two simultaneous vibration readings: horizontal (x-axis) and vertical (y-axis). From the two perpendicular signals, three plots were generated, which provides information on what is happening to the machine and can represent the machine vibration signature. The plots, which were generated by using Matlab and MS Excel are the: (1) Time plot, (2) Frequency Spectrum, and (3) XY plot, which is an approximate magnified picture of the shaft centerline of motion or generator (or shaft) deflection.

Generator vibration signals are principally caused by the inter-relationships of the (i) response of the stator core to the attractive forces in the air gap, (ii) electromagnetic forces in the air gap between the fixed stator and the rotating rotor as discussed above, (iii) response of the shaft
bearings to the forces transmitted to it by the rotor or its shaft, and (iv) dynamic behavior of the rotor [6].

Generator vibration is influenced by the machine’s stiffness, inertia, configuration (drive train), natural frequency and rotational speed among others. Any machine has a vibration response unique to its own hence the term “machine signature”. The machine health is normally diagnosed by comparing its signature with any deviation or change brought about by normal wear or by abnormal conditions. In the experiment, emphasis is on the change in machine vibration signature when the faults where applied.

IV. EXPERIMENTAL SETUP

Fig. 1 below shows the equipment setup. The generator is a Mawdsley 3-phase synchronous generator (5KVA, 2-pole, 3000RPM) mainly used for short-circuit testing. A PC data acquisition software exclusive for the accelerometer was used for data logging. Two computers were used, one to log the vibration and the other to record the transient fault voltages. The load is a resistor bank, set at 1600W per phase and the system configuration is three-phase four-wire, the neutral being grounded.

Twenty samples were taken per each condition, 80 samples total and each is 20 seconds in length. Logging commenced 10 seconds prior to the application of fault and terminated 10 seconds after the fault is cleared. The fault was therefore applied on the 10th second or in the middle of the logged data.

V. RESULTS

A. Time Plots

The effect on the generator vibration amplitude at the instant of fault are summarized on Table 1.

<table>
<thead>
<tr>
<th>Fault Type</th>
<th>g’s</th>
<th>% Increase</th>
<th>Axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>3PF</td>
<td>0.330</td>
<td>65</td>
<td>-x</td>
</tr>
<tr>
<td>LLF</td>
<td>0.334</td>
<td>67</td>
<td>+y</td>
</tr>
<tr>
<td>LLGF</td>
<td>0.314</td>
<td>57</td>
<td>+y</td>
</tr>
<tr>
<td>LGF</td>
<td>0.336</td>
<td>68</td>
<td>-y</td>
</tr>
</tbody>
</table>

The above values considered are the highest for all samples for each fault type.

Fig. 2 below is the time plot of sample numbered lgf-010 with the vibration gain of about 68% as seen in the middle or around the 10th second when the fault was applied.

Referring to Table 1, LGF caused the highest increase in vibration magnitude by about 68% followed by LLF. The reason could be that a LGF is unsymmetrical and causes the highest amplified and unbalanced air gap torques. On the other hand, LLGF caused the weakest response. This could mean that the addition of another faulted line, compared to LGF, must have lessened the torque imbalance.

However, taking the average of the five highest responses for each condition, 3PF had the highest amplitude gain. This reveals that although LGF or LLF could produce the strongest vibration magnitudes, a 3PF will most likely generate strong vibration responses.

B. Frequency Spectra

The time plot of sample lgf-010 in Fig. 2 above was divided into three parts, the 1st one-third is the “prefault”, the middle is the “during fault” and the last one-third is the “post fault”.

Fig. 3, 4 and 5 below are the “prefault”, “during fault” and “post fault” frequency spectrum respectively of Fig. 2 in the y-axis direction.

The fundamental mechanical frequency of the machine is 50Hz (3000RPM) and therefore this should be the dominant frequency. However, the dominant ones are below the 30Hz range. These frequencies are associated to the horizontal movement of the generator frame and the vertical motion of the flooring where the generator lays as the machine has no
foundation. Had there been a foundation, these should be negligible.

No pattern or significant change in terms of frequency contents and phase observed between the “prefault”, “during fault” and “post fault” spectra for both the x and y-axis directions. Overall however, the “during fault” amplitudes are higher than the “prefault”.

C. XY Plots

To obtain the plots, the acceleration data were converted to displacement to give a unit of measurement in mils. Two coordinate systems were used: the Cartesian to measure the displacement while the Polar to determine the direction of the displacement in terms of angle at the time of fault.

Below are the “prefault”, “during fault” and “post fault” XY plots of Figure 2 for the same sample.

Fig. 6 represents the normal shaft or generator displacement, Fig. 7 captures the displacement at the time of fault and Fig. 8 is again the displacement for normal condition.

The actual plot is the inner red lines and the blue peripheral lines represent the maximum generator motion for a set of shaft revolutions. Fig. 7 for instance is for 334 shaft revolutions equivalent to 761 data points which is the middle one-third of the time plot.

Fig. 7 above demonstrates the typical response of the generator when fault is applied. The “during fault” plots are larger in diameter (and distorted) than the “prefault” and “post fault”. From the same plot, at the time of fault, the generator was displaced by 1.5 x 10^{-3} mils towards 286° and by about 0.5 x 10^{-3} mils at 185°. The “post fault” plot is still distorted since the machine has not yet recovered from the effect of the fault since it has no foundation.

VI. RESULTS AND DISCUSSIONS

It is evident from the plots that the vibration frequencies are random, which means that the generator motion is not periodic. Random motion is associated with severe mechanical or structural looseness [7]. This is due to the fact that the generator has no foundation, situated on a second floor and lay only on concrete floor slab. Without foundation, there is a tendency that the generator motion could interact with the floor’s, nothing restricts the generator movement, there is no damping and the floor could act as a cushion when the machine abnormally vibrates such as during a fault.
In the experiment, it was observed that the actual sampling rate is much lower that the acquisition software’s 275 hertz (hz) speed and fluctuates from 107 to 118hz. Therefore the frequency spectra plots have to be verified and this is probably the reason why the plots did not provide sufficient information. Additionally, some critical points could have been missed.

Lastly, the amplitude gains during fault are much lower than what were anticipated and only a few displayed increases in vibration magnitudes when faults were applied. This is because that generators that are used for short circuit testing as in the case of the model generator are extremely robust in construction, over-designed [19]. Another possible reason could be that the generator is loaded only with real power with zero power factor. Therefore the magnitude of the fault current is lower since the X/R value is lower.

VII. CONCLUSIONS

The effect of 3-phase fault (3PF), line-to-line fault (LLF), line-to-ground fault (LLGF) and line-to-ground fault (LGF) on the 5KVA model generator vibration signature is evidently seen particularly on the time and XY plots. LGF appears to have caused the strongest magnitude gain followed by LLF. However, 3PF has the highest average gain. This reveals that although LGF and LLF could produce the strongest vibration magnitudes, a 3PF will most likely generate strong vibration responses.

LGF also exhibited the greatest effect on the generator shaft deflection by a wide margin against 3PF, which came in second. Additionally, LGF fault has the highest average shaft deflection, again by a wide margin. This means that a LGF has the greatest effect on the generator shaft deflection.

It is recommended however that the results should be validated since the model generator did not have a foundation, its motion is random; the results does not represent the response of commercially designed generator as the model generator is extremely robust in construction; the acquisition software sampling should be consistent and at least five times the generator’s mechanical frequency. Moreover, because of the above analyses, the frequency spectra were not a reliable source of information.

REFERENCES


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