Generator End-Winding Vibration Analysis - A Capstone Experience

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Abstract

The end-windings of large generators are exposed to some of the largest vibrations among all machines. The stability of these end windings has a major impact on the reliability of generators. A resonant vibration condition can lead to movement and forces that can compromise the stator bar insulation and possibly cause a complete failure of the generator. Currently, there is not a set of established industry standards or acceptance criterion for generator end winding vibration. There are many differing points of view within the power industry concerning the sources of vibration, methods of analysis, and solutions. This applied research paper investigates generator end winding vibration in order to establish a foundation to further the discussion among industry and academia in seeking to form a set of standards. This project relates directly to the problem of synchronous generator end-winding vibration at the J.H. Campbell power generating facility located in West Olive, Michigan. There were significant concerns that the end-windings for the A and B generators at the Unit-1 power plant were experiencing excessive levels of end-winding vibration and were at risk of a major failure. The objective of this capstone project was to perform an overall assessment including a determination of the cause of vibration, vibration testing, data acquisition, and analysis of the end-windings for each machine. It was concluded that the resonant vibration at a frequency equal to the fundamental electrical frequency as well as harmonic components of the fundamental frequency is the root cause of the end-winding vibration for each synchronous generator. Based on the analysis of test data a long term solution was established and executed successfully to reduce the vibration problem. This is an industry-university collaboration that is very important to enhance engineering education and research.

Introduction

The vibration of generator end windings has been a topic of concern since the beginning of power generation. Current flowing in the rotor and stator give rise to magnetic fields. The resulting forces lead to vibration within the stator core, but more seriously at the stator end windings and their support structures. The end winding structures have a high susceptibility to vibration damage on account of the complexity of their structure, the number of materials used in their construction, and the difficulty in supporting them properly [1]. Over the course of evolution of the synchronous generator there have been many changes that had an impact on the vibration of the system. The science of precise vibration monitoring and analysis is also a developing technology which until recently was not able to produce accurate and accepted data. The result has been a lack of consensus within the industry which has led to no accepted methods or standards on the subject. This paper will discuss the sources of vibration in the generator and the methods used to analyse them. The focal point of the discussion will be on stator end-windings.

History of Generator Vibrations

To gain a complete understanding of the lack of industry standards, a brief history review of the topic should be considered. Reviewing the progression of the problem, as explained below, can provide an improved overall understanding of this subject.

A. *Power Requirements*

The basic construction of the synchronous generator has remained very similar to the early design. The advancements within the industry have been in the design of the structure and components to allow for higher power ratings and efficiency. The growth in the power ratings of turbine-driven generators is shown in Figure 1.

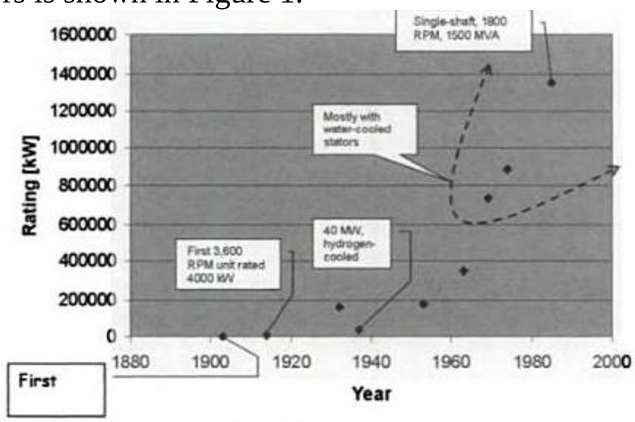

Figure 1 The growth of the power ratings of turbine-driven generators [2]

The excitation forces that cause vibration are a result from the rotating magnetic field in the generator. The force induced on a current carrying wire within a magnetic field is given by (1).

$$F = B \times l \times I \qquad (1)$$

where F = force induced on the conductor, B = magnetic flux density, l = length of the wire, and I = current in the wire. The rated apparent power of a generator is proportional to the flux and the armature reaction as shown (2).

$$MVA = KM_a \Phi P f \qquad (2)$$

where MVA = rated apparent power of the generator, K= proportionality constant, M_a = armature reaction, Φ = magnetic flux per pole at rated voltage, P = number of poles, and f = frequency of the stator voltage. Equations (1-2) demonstrate that the higher power requirements for a generator also increases the flux generated which in turn increases the forces of the vibration. In the early 1960s, improved stator winding cooling methods permitted large increases in generator power output capability. This improved cooling was accomplished by the flow of cooling media within the stator. The resulting much higher electromagnetic forces presented increasingly severe challenges for controlling stator winding vibration magnitudes. At this time, stator winding vibration became a major design and service issue, both vibrations in the slots and in the end-windings [3].

B. *Conductor Insulation*

The methods of conductor insulation have a long history of advancement due to necessity. The increased power levels that require higher magnetic flux also give rise to higher temperatures. The increase in flux requires an increase in current shown in (3).

$$\Phi = \frac{\mu N i A}{lc} \quad (3)$$

where, µ = permeability of the core, N = number of turns, i = current in the windings, A = cross sectional area of the core, and l_c = length of the conductor. The power loss due to heat in a conductor is expressed by (4) where R is conductor resistance. The ultimate result is a substantial

$$P = i^2 R \quad (4)$$

increase in heat as power requirements are raised. The increased heat levels within the end-winding conductors created a need for insulation materials to change over time. The type of insulation has an impact beyond just thermal resistance. The damping characteristics from one material to another can vary drastically which has an impact on vibration resistance. The early insulator materials used for generator stators were organic asphalt mica. In general, organic materials soften at a much lower temperature and have a much lower mechanical strength than copper or steel. Thus, the life of a stator winding is limited most often by the electrical insulation rather than by the conductors or the steel core [4**].** The result was positive for vibration dampening so the vibration problems did not arise as often. The change from organic materials to thermo-set resins which can withstand much higher temperatures also had an impact on the natural damping characteristics. The thermo-set resins are very rigid materials and also susceptible to vibration problems. The overall result was an increase in failures in insulation from vibration

Sources of Excitation of End-windings

Resonant frequency present near the natural frequency of the machine has already been established to be one of the problem [1-2]. A clear understanding of what other frequencies are considered as problem is the next question that must be answered. The 60 Hz excitation frequency of vibration is present in synchronous generator stator windings due to: (i) electromagnetic forces between current carrying conductors and ground, and (ii) system's mechanical vibration. The force between a single conductor and ground would be at 60 Hz which is the frequency of the induced current in the stator. When a force is generated from the magnetic field of the current carrying conductor then the ground structure will generate an equal force in the opposite direction. The final result will be an oscillating vibration signal at 60 Hz. The system mechanical vibration is due to the prime mover that is driving the generator. The prime mover is rotating at the fundamental frequency of the generator. As with the generator, every effort is made to eliminate all vibration from the prime mover but there will always be some amount of vibration present at 60 Hz for a 2 pole unit. Also, a 120 Hz excitation frequency of vibration is present in synchronous generator stator windings due to: (i) the periodic core deformation from the peaks of the electromagnetic force on to the stator core because of the revolving DC field, and (ii) electromagnetic forces between two conductors. This double frequency (2ω) force can be expressed as in (5).

$$F_1 = \frac{8\pi \times 10^{-7}}{w}\, i_m^2 [1 - \cos 2\omega t] \quad (5)$$

where i_m and w are current and slot-width of conductors, respectively.

Methods of testing and analysis

The analysis of end winding vibration requires the study of 4 integral methods that together should be reviewed to constitute a basis for a proper diagnosis of end-winding vibration.

A. *Expert Visual Inspection*
The consequence of continuous vibrations is fatigue which can be detected as dust inside a generator and/or cracks within the end-windings found by visual inspection [5]. The use of expert visual inspection must be included as a standard method for vibration analysis. Inspection of generators is not a trade that can be solely learned in the classroom. A combination of classroom learning with years of hands-on training, mainly while accompanying an experienced specialist, is what leads to the ability to decipher the root causes of conditions afflicting a generator [2]. Even though the availability of an expert for visual inspection is not always possible, there are publications and resources available to guide a user through an inspection if necessary.

B. *Online Vibration Sensors*
On-line monitoring of the actual vibration of the end-windings is critical to ensure reliability. There are numerous systems available from the OEMs and other companies for on-line monitoring of machine behaviour. All of them include monitoring of vibration levels by sensors installed throughout the machine. There are various system designs being used in the industry and all of them basically consist of a light source, fiber optic cable to transmit the light, an accelerometer to interrupt the light beam in a manner related to the measured motion, and a processor that receives the returning light pulses and converts them to electronic data using appropriate software. This system is usually referred to as a fiber optic vibration monitoring system or FOVM. In a typical application, the fiber optic accelerometer (FOA) rides on the coil ends and the processor converts the resulting light pulses into data that can be interpreted to describe the exact motion of the coil. More importantly, in addition to the amplitude of vibration in itself, the timeline and phase angle of the acceleration can be measured such that the motion of one coil with respect to other coils in the system can also be monitored. This means that the behavior of the entire end-winding can be mapped such that a coil moving independently or out of phase with respect to the rest of the structure can be detected and analyzed. Such a coil for example may have lost a support tie or blocking components and its motion could be erratic or out of control. Another typical finding may show that the entire structure is not moving in the expected oval shape (for a 2-pole unit) which would be indicative of a loose unconsolidated end winding. The online normal and maximum levels of vibration are subtle and impossible to monitor without an FOVM system. In the past most stator winding failures occurred because trends or sudden changes went undetected until the vibration resulted in fatigue of copper conductors, leading to meltdown, or abrasion of insulation, leading to ground fault failures. Most machines equipped with FOVMs today are avoiding such costly problems, while those not being monitored continue to experience unexplained failures or high maintenance problems. Due to the fact that most machines are not equipped with a FOVM system, it is not possible to require this method as a standard of analysis. It is a very useful tool that should be incorporated into all new designs and used whenever possible.

C. *The Impact Test*
It is very difficult to reproduce the exact operating conditions of a generator (the exact conditions of electromagnetic forces, temperatures and stator core vibration be present simultaneously and in the correct relationship to one another) without attaching the generator to a turbine of the same rating, and generating full load output. The impact test method involves striking the testing component with a special rubber tipped hammer. The hammer and its rubber tip are selected to

impart a broad flat spectrum of frequencies over the range of interest. When this occurs the component will begin to vibrate at its own natural frequency. This natural frequency response is detected by a small sensor temporarily attached to the component. The output of the sensor is fed to a structural dynamics analyser where the time response signals are filtered, averaged, and converted to frequency response signals using FFT. Each component may be tested in multiple locations along radial, tangential, or axial directions. However, this method has following limitations such as: (i) during impact testing the winding will be at ambient temperature, and the properties of all the non-metallic materials in the winding will be room temperature properties. Since these properties are temperature dependant, room temperature behaviour is only an approximation. (ii) the windings has not expanded and undergone any stress and shape changes due to operation, and (iii) the forces applied during impact testing are very small compared to those that will be experienced during operation. Therefore, the effects of any non-linearity in the response of the winding to a forcing function will tend to be lost. Despite these limitations, impact testing is the simplest way to evaluate the mechanical behaviour of the stator end-winding, and is capable of revealing a great deal of important information regarding the performance of the winding. Most of the concerns listed above as limitations can be accommodated by establishing a margin between the response measured during impact testing and the known forcing frequencies during operation.

It is worth noting that a liquid cooled generator has a significant mass of water in the winding during operation, and that this may have some effect on the winding response. If a suitable source of clean de-ionized water is available, then this mass can be introduced into the winding prior to impact testing, eliminating this source of uncertainty. Impact testing should be performed on the fully assembled, cured winding structure. The global behaviour of the winding, including natural frequencies, and mode shapes should be determined. Individual components such as series loops, phase connections and phase rings should be tested. If natural frequencies close to 60Hz and 120Hz in 60Hz machines are found, then mode shapes should be determined to aid in design of suitable blocking systems. The basic goal of the impact test is to provide the amplitude of vibration through a band of frequencies. The output of the impact test is to create a graphical representation for the frequency signature.

D. *The modal analysis test*

Modal analysis is the term used to describe the modelling of ‘patterns of vibration’ or mode shapes for a given structure. If a structure has a natural frequency of vibration at or near its driving frequency of vibration, this frequency can potentially be excited during operation, resulting in wear and/or cyclic fatigue of the components. In order to reduce the effects of vibration, structural analysis of equipment can be used to predict the mode shapes and make structural modifications as required. Modal testing is a technique by which actual structural responses relative to a measured excitation are recorded and used to create a modal model of the structural response. The measured excitation may take the form of a single impact, a harmonic shaker, or a reference signal representing the operational excitation. The general tendency of a typical 2-pole generator end winding structure is to be deformed into an oval shape by the polar forces of the generator rotor. The resulting vibration of the end-windings thus becomes that of a deforming and rotating oval pattern. Because of this global structure vibration tendency, the stator coils, and in particular the end of the stator coils in the area of their end connections, have a resulting vibration which has its biggest component in the radial direction, that is moving towards and away from the centre of the generator. It should be pointed out that the oval mode of an end winding is not the only mode that can be excited by forces within the generator. There are other modes such as, for example, cantilever modes (the whole cone bouncing up and down like a diving board) or breathing modes (the winding ring expanding and shrinking diametrically) that could become resonant if forces act on the winding in the critical directions and at the critical frequencies. The oval mode shape however is the most critical for global vibration analysis of the stator because they get naturally driven by the rotor forces if the resonant frequencies are close to the rotor forcing frequencies.

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Results and Acceptance Criteria

The acceptance criteria outcome of this paper is a two part foundation of accepted methods of analysis and the accepted metrics based on those methods.

a. Expert Visual Inspection Acceptance

The use of expert visual is recommended as part of the standard methods use for analysis. The obvious question arises of how to asses quantitative results that are consistent among inspectors. The desired solution would be to assign scaled numerical values based on condition assessment of the machine. Ratings scores would be developed to allow a final result to be determined. The construction of the ratings scale is not covered in this paper but is considered a necessity in the future of end-winding vibration analysis. A qualitative assessment can be made and thresholds for acceptance of vibration can be identified by individual inspectors on a case by case basis. The inspection results should be compared to the results of the other testing methods to make a final judgement.

b. The impact test acceptance

The impact test should not be considered a standalone test or a replacement to Modal Analysis Test. The acceptance criteria is based in the “Amplitude-Magnitude” of the deflection signal through the critical excitation bands which have been identified to be +/- 10 % of the target frequency. The threshold of acceptance is: 0.1 g/lbf in any plane (axial, radial, and tangential). This value is a reference and it is based in numerous tests and observations of generators successfully diagnosed. It is only appropriate that all locations of interest be tested. This represents the testing of all the series connections, and phase connections. A coincidence of natural frequency response signature peak within the excitation critical band may be indicative of a resonance condition. One of the many captured impact spectrum graph is shown in Figure 2.

Figure 2 A typical impact signature spectrum graph.

c. Modal analysis acceptance

The modal analysis test is considered an accepted method of vibration testing. The acceptance criterion for a resonant condition is diagnosed if the shapes of deflection match known resonance modes of deformation shown in Figure 3. Thus, a vibration condition is good if no match is identified and not good if a match is identified. The known resonance modes of deformation are: (i) 2 lobes, 180° apart. As the shape of two circles with offset centers at the first fundamental band. (ii) 4 Lobes, 90° apart. As the shape of two ellipses with their axes perpendicular to each other at the second fundamental band.

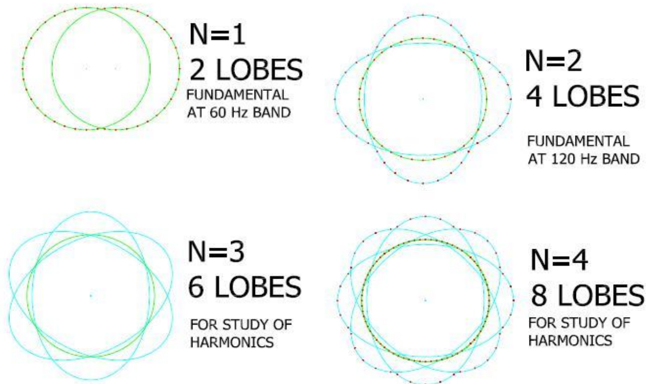

Figure 3 The mode shapes of the generator.

Conclusions

The performance and reliability of the stator end-winding system in a generator depends upon the physical design of the end-winding, its support system, and on the forces that the system is subjected to. There is no single method that can be used to diagnose a generator as having "excessive" vibration levels. The use of expert visual inspection, impact testing, and modal analysis should all be used together for a proper diagnosis. The use of online vibration sensors is recommended if available but not required. There are many factors beyond the scope of this paper that can be applied to the analysis of end-winding vibration. The overall intent of this capstone project to provide a foundation for promoting the discussion has been presented with the hope that an accepted set of standards will eventually follow.

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