

Electrically Excited Vibrations for Condition Monitoring of Synchronous Machine Windings – An Experimental Study

F. C. Trutt
U. of Kentucky
Lexington, KY

J. Sottile
U. of Kentucky
Lexington, KY

J. L. Kohler
Nat. Inst. Occ.
Safety & Hlth
Pittsburgh, PA



Frederick C. Trutt received his B. S., M. S., and Ph.D. degrees in Electrical Engineering from the University of Delaware, Newark, DE. He has held several positions as a research engineer in industry and began his academic career as a faculty member at The Pennsylvania State University in 1972. Dr. Trutt is presently a Professor of Electrical Engineering at the University of Kentucky where he has also served as the Associate Dean for Academic Affairs in the College of Engineering, Chair of the Department of Electrical Engineering, and Acting Chair of the Department of Chemical Engineering. Dr Trutt is the author or co-author of more than 70 journal papers in Electrical Engineering and has been involved in teaching, research, and consulting in the areas of power systems and electric machines for more than 30 years. He is a Fellow of the IEEE and a Past President of the IEEE Industry Applications Society.



Joseph Sottile received the B. S., M. S., and Ph.D. degrees in mining engineering from The Pennsylvania State University, University Park, in 1984, 1987, and 1991, respectively. He has worked in production and engineering for the Barnes and Tucker Company from 1977 to 1983, and for Consol, Inc., in 1987. He is currently an Associate Professor of Mining Engineering at the University of Kentucky, Lexington. His teaching and research interests include electrical applications in the mining industry. Dr. Sottile is the Past Chairman of the IEEE Industry Applications Society Mining Industry Committee.



Jeffery L. Kohler is Director of NIOSH's Pittsburgh Research Laboratory. Prior to joining NIOSH in September 1998, Dr. Kohler was an Associate Professor at The Pennsylvania State University, where one of his research interests was incipient failure prediction in electrical machinery, and where he participated in this work. Over the past twenty years, he has investigated a number of topics related to condition based monitoring, and has published extensively in this field. He is a senior member of the Institute of Electrical and Electronic Engineers.

ABSTRACT

Efforts to apply mechanical vibration technology in the condition monitoring of ac motors and generators have generally been focused on areas relating to unbalance, bearing condition, eccentricities, and other mechanical phenomena. However, theory predicts that electrical winding deterioration in these machines will modify internal magnetic forces such that the resulting changes in vibration characteristics should be a useful indicator of winding condition. It seems clear that an understanding of these interactions could provide a means for supplemental monitoring of electrical winding integrity as well as information that might be used to discriminate between electrical and mechanical problems. Presented in this paper is an experimental investigation that is applied to the detection of electrical winding deterioration in synchronous machines through the measurement of mechanical vibration. Results indicate a strong relationship between these parameters and provide the motivation for additional study and a basis for future applications.

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INTRODUCTION

While it has been known for many years that relationships exist between electrical winding faults and mechanical vibration (1), schemes for the condition monitoring and the protection of electrical windings in synchronous machines have traditionally emphasized the measurement of naturally occurring or injected parameters related to the stator and/or rotor winding currents and voltages (2-13), induced shaft voltages (14, 15), or electromagnetic fields produced by the fault currents or discharges (16, 17). In many instances, these approaches have provided information which can be used for maintenance scheduling or for a decision to immediately remove a machine from service. However, uncertainties still exist and additional data that could aid this decision making process would be welcomed. The purpose of this paper is to reconsider the potential utility of mechanical vibration measurements as a supplemental source of information for the evaluation of electrical winding integrity in synchronous machines. The discussion is based upon an experimental investigation and will include a description of the laboratory facilities and data collection techniques, the presentation of results, and recommendations for additional research.

EXPERIMENTAL FACILITIES

The simulation of internal electrical winding deterioration in a synchronous machine was conducted on two experimental machines available to researchers at the University of Kentucky. The first of these is a Universal Laboratory Machine Set. The second system is a specially constructed three-phase "brushless" generator. Each of these machines will be described in the following paragraphs.

The universal laboratory machine set is composed of a two-pole universal machine that is mechanically connected to a dc dynamometer. For the purposes of this investigation, the universal machine was connected as a 2-kva 115V 60Hz 3600rpm three-phase synchronous alternator. The dynamometer is connected as a 110V dc shunt motor and the motor field current is adjusted for a mechanical speed of 3600 rpm.

The stator winding of the universal machine consists of 12 coils as shown in Figure 1. These coils may be interconnected in various ways in order to create different stator winding configurations. For the experiments to be described, four of these stator coils were connected in series to form each phase of a balanced wye-connected three-phase armature as

shown in Figure 3. Thus the machine can be operated as a normal 3600-rpm alternator or the junction points between coil connections can be used to simulate turn-to-turn stator winding deterioration or phase-to phase faults. The rotor is accessible through brushes and slip rings through a single coil per pole. Thus there is no effective method to simulate rotor field winding deterioration in this 2-pole machine and the rotor excitation therefore consisted of a constant value of dc current applied through the brushes.

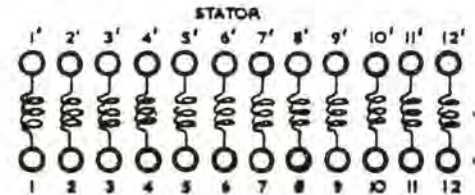


Figure 1. Universal machine stator winding.

Obvious limitations of the universal machine for this investigation included the inability to simulate rotor winding deterioration as well as the requirement that 25% of a stator winding must be involved in a fault simulation. In an effort to circumvent these difficulties, a specialized alternator system was constructed.

Major components of this experimental system include a 4-pole 6.25kva 240V three-phase generator with a "brushless" excitation system that is directly coupled to a 7.5hp 1200rpm 60Hz brushless synchronous motor. Also included is the appropriate exciter for each unit as well as the circuitry for alternator voltage regulation and motor speed control. The stator of the alternator is wye connected with two parallel paths per phase. Each stator winding has externally accessible taps at 1, 2, 3, 4, 5, 10, 21, 42, and 68% of the coil. Thus internal winding or phase-to-phase stator deterioration involving as little as 1% in one parallel path of a winding may be simulated.

On the rotor, taps are available at 0, 5, 10, 25, 50, 200, 350, and 500 turns on one pole of a rotor winding that has 500 series turns/pole (2000 total turns in series). These taps are externally accessible when the rotor is stationary such that rotor deterioration may be introduced prior to startup. Although the structure of the alternator excitation system is brushless in nature, brushes and slip rings have also been provided so that access to the generator exciter output, rectifier diodes, and the actual field voltage and current is available. Thus

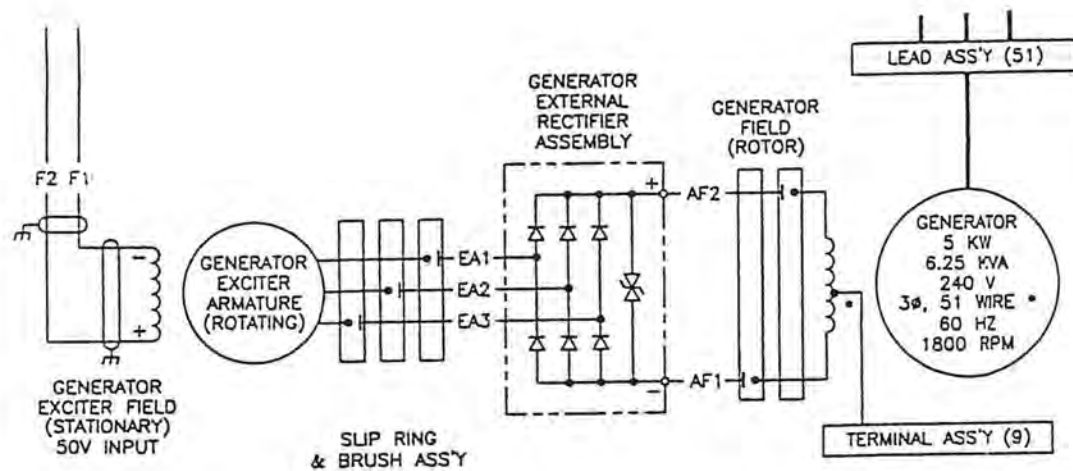


Figure 2. Experimental machine system.

these parameters may be measured while the alternator is running and hence the “brushless” connotation. The structure of this alternator system is illustrated in Figure 2.

In order to collect vibration information, one accelerometer was mounted on the rotor bearing and another accelerometer was mounted on the stator stack of the machine under test. Since the frequencies of interest were less than 1kHz, magnetic mounts were utilized with anti-aliasing filtering having a cutoff frequency of 1.125kHz. Filter outputs were then sampled at a rate of 5128 samples/s and this data was transferred to a laptop computer for analysis.

EXPERIMENTAL RESULTS

A couple examples typical of the results that were obtained will be presented. The first of these is shown in Figures 3-5 for a moderate amount of stator winding deterioration in the universal laboratory machine. In this case the machine is running as a loaded synchronous generator at synchronous speed. Stator coil-to-coil winding deterioration is introduced as shown in Figure 3 where the resistance R_d is varied in order to adjust the deterioration current I_d . For all the levels of deterioration that were simulated, the machine still appears to be running normally and no abnormal heating was apparent.

An acceleration frequency spectrum measured at the stator stack by one of the magnetic mount accelerometers is shown in Figure 4 for both normal operation and for a moderate amount of deterioration current I_d . Comparison of these results shows significant differences, particularly at 180Hz

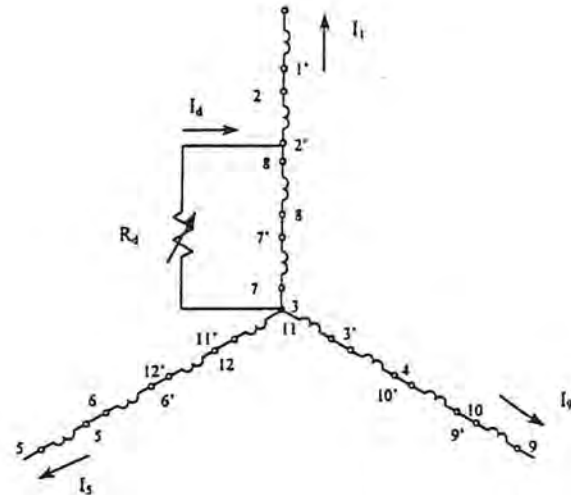
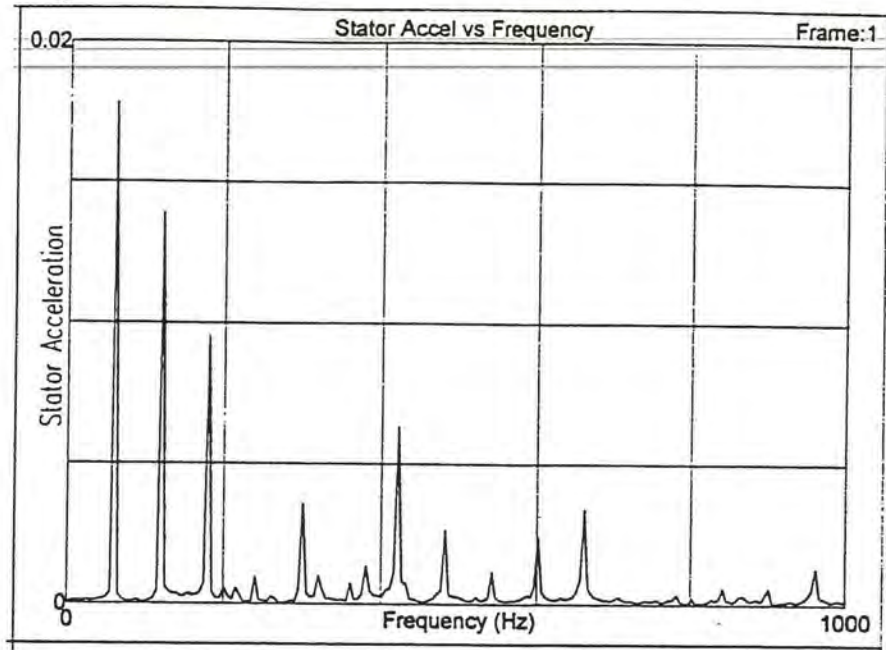


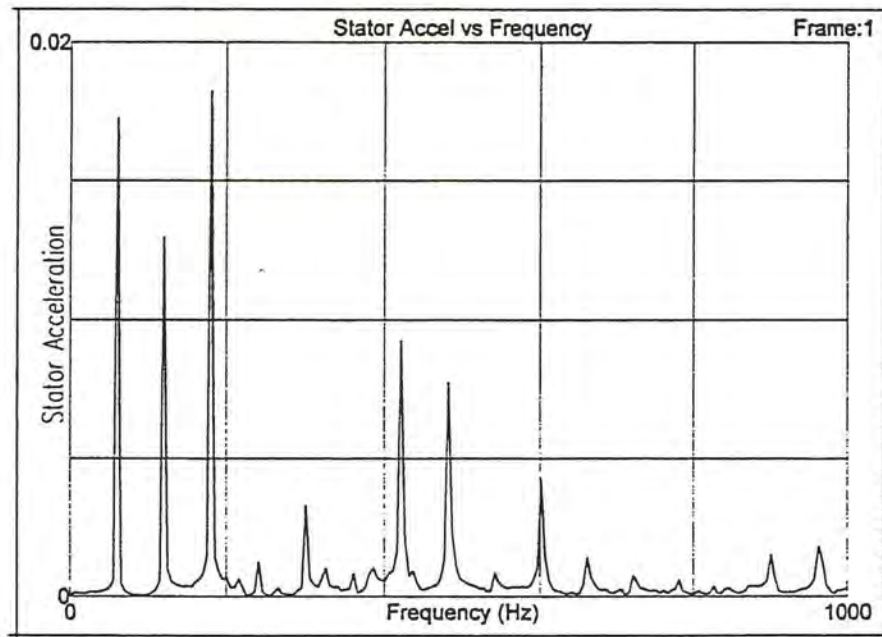
Figure 3. ULM with simulated stator deterioration.

and 480Hz. To further investigate this situation, testing was conducted for levels of deterioration current from 0-2A. While no major changes in output voltages or currents were observed, significant increases in stator vibration occurred as shown in Figure 5. In this figure, the stator accelerations at 180Hz and 480Hz are plotted as a percentage of their values with no deterioration vs. deterioration current. The 200% increase in measured stator acceleration at 480Hz and the 90% increase at 180Hz seem to indicate a clear relationship between these parameters and stator coil-to-coil deterioration.

While it has been possible to show similar results for stator winding deterioration with the three



a. Normal operation



b. With deterioration

Figure 4. Stator acceleration frequency spectra.

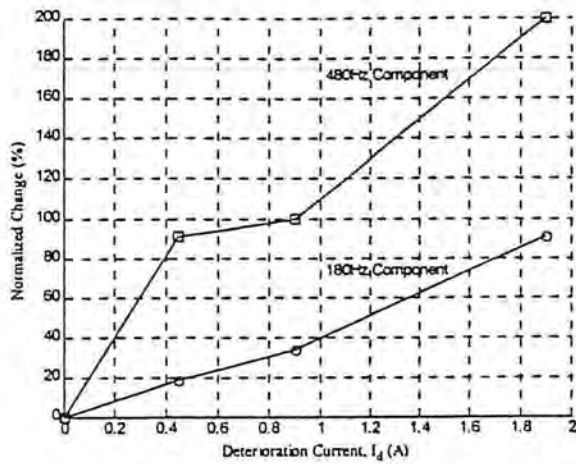


Figure 5. Stator vibration vs. deterioration current.

phase “brushless” experimental generator, it is more interesting to investigate the consequences of rotor winding deterioration in this alternator since such a study was not feasible using the universal machine. In this case, the rotor field winding consists of 500 turns in series/pole on a 4-pole rotor winding as shown in Figure 6. The rotor taps are on pole #3 at the number of turns indicated. Deterioration was simulated by shorting a number of turns between T1 and some other point in the winding on pole #3. The actual dc current that would be shunted from the field winding through these short-circuit connections was limited in practice to the range of 2-3A because of connection resistances and other factors. Thus it was only possible to divert 80-90% of the normal dc field current in this manner. Once again, no appreciable changes in the output voltages or currents were observed as rotor-winding deterioration was added.

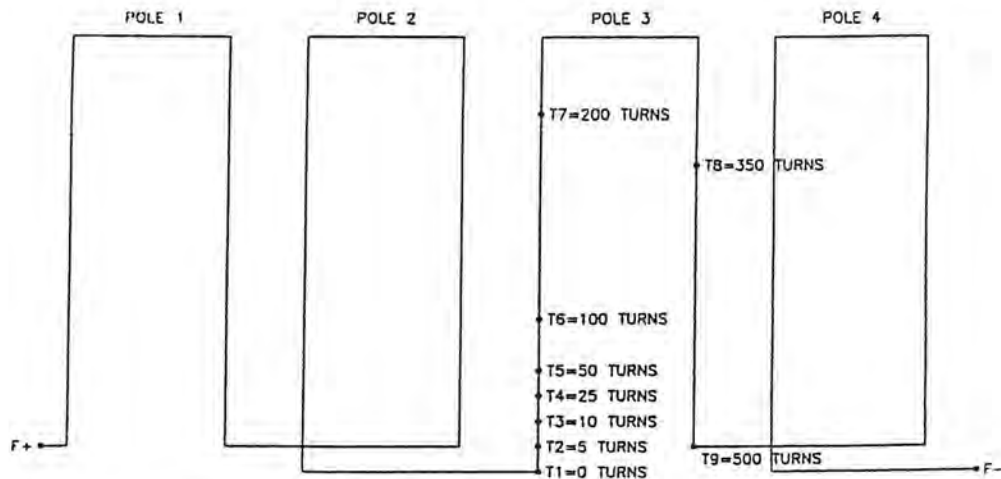
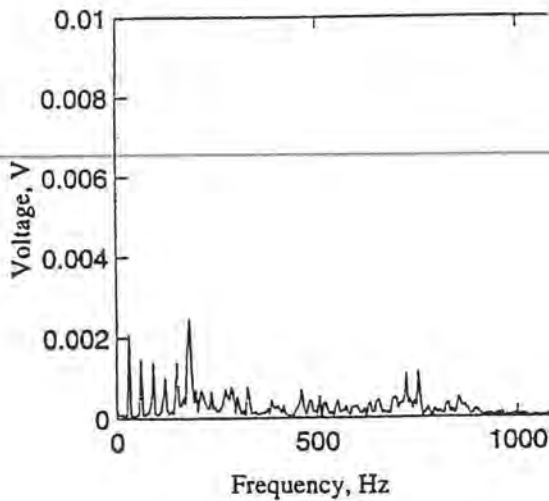


Figure 6. Field winding of the experimental machine.

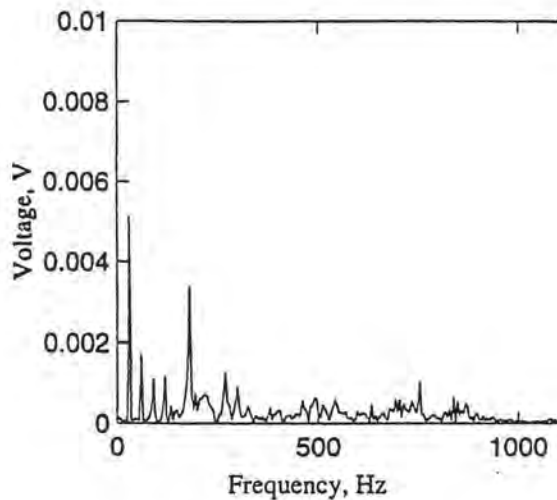
An acceleration frequency spectrum measured by the accelerometer located at the rotor bearing is shown in Figure 7 for normal operation and for a 2A deterioration between taps 1 and 3 of pole #3. This represents a current diversion from only 10 of the 500 turns in series on pole #3. Comparison of these results shows that a large increase in the magnitude of bearing vibration occurs at a frequency of 30Hz when the deterioration is added. If this acceleration parameter is divided by its value under normal operating conditions and then plotted as a function of the number of shorted turns, Figure 8 is obtained. From this figure, it may be seen that only slight additional increases in 30-Hz vibration were obtained as the number of shorted turns were extended from 10 to 100. This result may be related to the difficulty in diverting more than 2-3A from the field winding. This fault current was relatively constant and nearly independent of the number of shorted field winding turns. However, the increase in the 30-Hz component of acceleration was evident in all cases.

CONCLUSION

The purpose of this paper has been to demonstrate a few of the relationships between electrical winding deterioration in synchronous machines and mechanical vibration. Based upon the results presented, it seems clear that vibration predictors have the potential to provide important supplemental information for the electrical condition monitoring of these machines. In addition, an understanding of the differences between vibration signatures related to electrical deterioration and those due to mechanical degradation could be a significant



a. Normal operation



b. 10 rotor winding turns shorted

Figure 7. Bearing vibration vs. frequency.

benefit in avoiding unnecessary mechanical maintenance. It is recommended that these two areas be the subject of further study.

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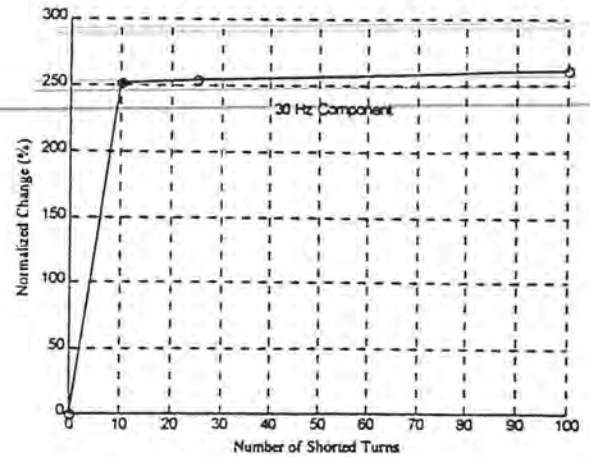


Figure 8. Bearing vibration vs. rotor winding deterioration.

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