Development of a Technique for On-Line Detection of Shorts in Field Windings of Turbine-Generator Rotors: Circuit Design and Testing

Amol S. Kulkarni, Mohamed A. El-Sharkawi, *Fellow, IEEE*, Robert J. Marks, II, *Fellow, IEEE*, George Andexler, Jian Xing, and Isidor Kerszenbaum

***Abstract*—A technique for on-line detection of incipient faults in the windings of turbine-generator rotors has been developed based on the twin signal sensing method. This paper describes the development of power electronic circuits for generation of the twin signals and detection of the reflected signals. The design and fabrication of a lab model to test this technique is summarized along with results of laboratory experiments. The issues involved in using the developed technique for practical applications are addressed and the limitations of the technique are summarized.**

***Index Terms*—Condition-based-maintenance, electronic-circuits, machine-monitoring, on-line-fault-detection, shorted-turn-detection, synchronous-machines, twin-signal-sensing.**

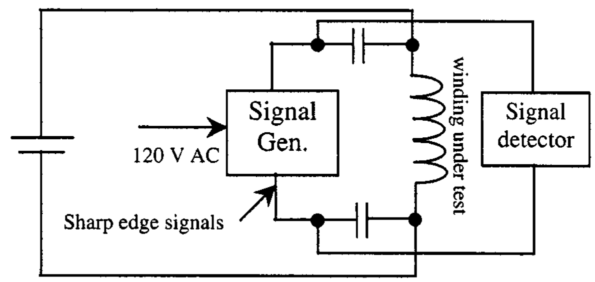


Fig. 1. Block diagram of hardware setup.

I. Introduction

EARLY detection of shorted turns in the rotors of large synchronous turbine-generators is a long standing problem with no satisfactory solution [1], [2]. Shorted turns cause vibrations, which can lead to catastrophic consequences such as mechanical damage to rotors. To avoid such a situation, periodic maintenance of rotors is required, which increases the machine downtime and results in loss of revenue.

Many techniques have been reported for detection of shorted turns, most of which require some modification of the stator windings or placement of flux coils in the air gap [3], [4]. The twin signal sensing technique reported in [4] can be used for on-line detection without any modification to the machine under test. To detect developing or incipient shorts in any winding, two identical pulses are applied to both ends of the winding. The pulses travel through the winding and are reflected back [5]. Any abnormality in the winding results in the applied signals being reflected through nonsymmetrical circuits. The difference between the reflected signals is amplified and used as a signature signal for further processing using novelty detection techniques. This paper is mainly concerned with the description of the hardware circuits for the twin signal detection technique. The problems faced in obtaining reliable signature signals and the modifications required are also described. The construction of a test rotor to obtain training and test data is described and the final test results are reported. This technique has been successfully tested in the field on operational turbine generators. The results of field tests are reported in detail in [5].

Manuscript received September 23, 1998; revised April 28, 1999. This work was supported by the National Science Foundation, EPRI, and the Southern California Edison Company.

A. S. Kulkarni, M. A. El-Sharkawi, and R. J. Marks, II are with the Department of Electrical Engineering, University of Washington, Seattle, WA 98195.

G. Andexler is with the Department of Mechanical Engineering, University of Washington, Seattle, WA 98195.

J. Xing is with Eldec Corporation, Lynnwood, WA 98046.

I. Kerszenbaum is with Edison Mission Energy Inc., Irvine, CA 92612.

Publisher Item Identifier S 0885-8969(00)02205-1.

II. Twin Signal Detection Technique

A block diagram of the hardware setup is shown in Fig. 1. The winding under test is shown as excited by a DC source. The signal generator applies twin signal pulses to the device under test, through two series capacitors, which serve to isolate the high winding voltage from the detection circuits. The circuit is thus designed for use while the winding under test is in normal operation. The reflected signals obtained at the winding terminals are fed to the signal detector through the series capacitors. The signal detector filters these signals, finds the difference between the two and amplifies this difference for further signal processing.

The final output of the signal detector circuit is called the signature signal and reflects the current state of the winding. This signature is captured using either a digital storage oscilloscope or a custom digital scope PC add-on card. It is then compared to the signature obtained from the same winding in the past. If there is a significant deviation in the signature signal, a *novelty* is found, signifying the existence of a short somewhere in the winding. The nature of difference between a previously stored *healthy* signal and the newly recorded signal required for a *novelty* to be detected depends on the novelty detection scheme used and the associated threshold. Use of an elliptical novelty detector is seen to give the best results. This method projects a number of healthy signature signals along the principal components of the signals. Then a hyperellipse is found which encloses the acquired healthy signals. A selected threshold determines the size of this hyperellipse. During testing, the acquired signal is projected onto the same space. If the projected signal lies within the hyperellipse, the rotor is considered to be healthy otherwise it is tagged as faulty. Conventional maintenance methods are then used to identify the location of the short and repair the rotor. The details of various novelty detection schemes used and their performance is reported in [6].

The application of this twin signal detection technique can considerably prolong the time between required periodic maintenance of generators in operation. As long as the signature signals indicate that the rotor is healthy, the generator can remain in operation. If a short is detected, the generator can be taken out of operation and further testing can be done by conventional means to locate the short and repair it. It should be noted that any novelty detector which only uses prior information from a healthy rotor may not find the location of the short. To find the exact location of the short, additional training data containing signature signals for various fault locations is required. This is undesirable since data for shorts is not available unless the shorts occur, and it would be difficult to actually short each healthy machine to obtain such data before or during its use.

III. Circuit Design Specifications

The signal generator circuit produces two low going voltage pulses, which are applied to either end of the winding. To ensure minimum interference with the main circuit and to increase detection sensitivity with respect to pulse magnitude, the failing edge of the pulses needs to be very sharp. These pulses should be applied at or near the zero crossing of the winding voltage if the winding is excited by an AC source. Thus, the design specifications for the signal generator circuit are:

- generate a small duration periodic pulse with a sharp falling (or rising) edge,
- duplicate the first edge of this pulse exactly for application to both ends of the winding, and
- generate the pulses at or near the zero crossing of the AC voltage for an AC excited winding. This calls for synchronization of the applied periodic pulse with the system AC voltage.

As shown in Fig. 1, the signal generator circuit has 120 V AC input and generates identical fast falling edge pulses at its outputs. These pulses are applied to the winding under test through series capacitors, which also filter the effect of the winding resistance on the signal generator circuit. This is in addition to their function of isolating the DC voltage from the signal generator and detector circuits. For maximum sensitivity, the signals are generated at every zero crossing of the AC waveform, that is, once every half cycle. To ensure uniformity of the circuit for all applications and for ease of operation, this synchronization with the AC source voltage is also used for machines with DC windings.

The signal detector circuit needs to amplify the small difference in the reflected waveforms accurately. Since the technique looks for changes in the signatures, it is imperative that the amplification be highly repetitive and free from drift, so as to minimize sensing errors.

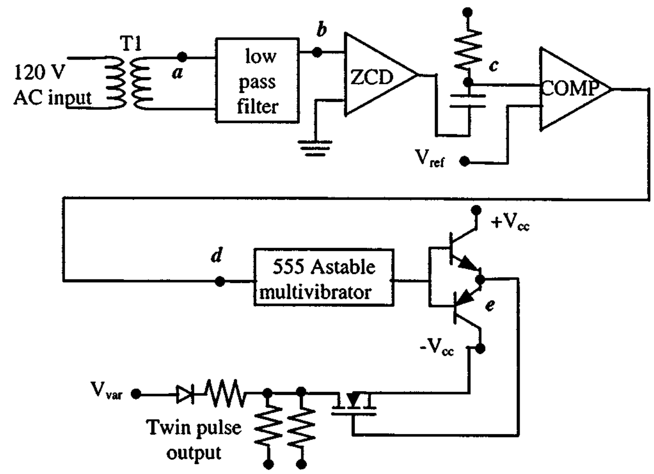


Fig. 2. Main circuit diagram of signal generator.

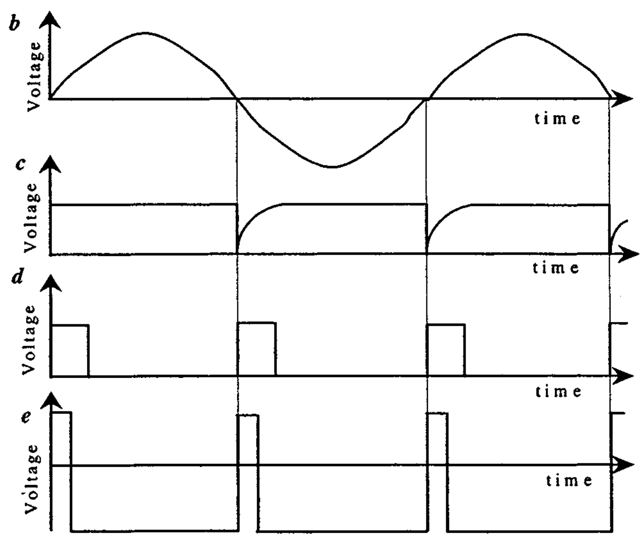


Fig. 3. Waveforms at various points in the signal generator circuit.

Thus, the detector circuit needs:

- a high pass filter to remove the DC offset or the AC voltage on which the twin signals are superimposed and
- a low offset, *drift-free* differential amplifier to accurately amplify these filtered signals.

IV. Circuit Operation

A. Signal Generator

Fig. 2 shows a detailed block diagram of the signal generator circuit. Given the design specifications of the circuit as outlined in the previous section, the zero crossings of the input AC voltage waveform need to be sensed so as to generate the short negative pulses. The input voltage is filtered using a zero phase shift, analog low pass filter to get rid of any high frequency noise present on the supply voltage. This avoids any spurious zero crossings from being sensed. The waveforms at points b, c, and d are shown in Fig. 3. The output at point b is a sinusoid with the same phase angle as the waveform at point a. Two comparators form a zero-crossing detector (ZCD) for this filtered sine

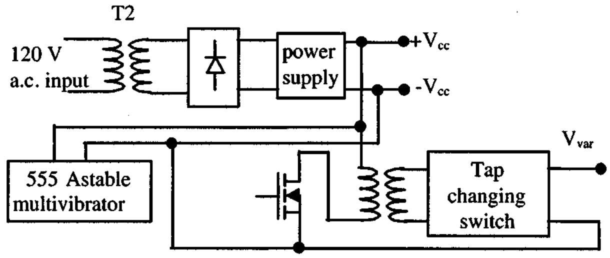


Fig. 4. Power supply circuit for signal generator.

waveform. The output of one comparator goes low at the positive zero crossing of the sine wave while that of the output of the other comparator goes low at the negative zero crossing.

A simple R–C derivative circuit generates a sharp falling edge at each comparator output. These two edges are added by two diodes to get a falling edge at every zero crossing at point c. This voltage is compared with a small DC voltage, V_{ref} using another comparator COMP to obtain short positive pulses at every zero crossing at point d. These short pulses are used as enabling signals for an astable multivibrator which uses a 555 timer. The positive pulses at d are made larger than the positive pulse of the multivibrator but smaller than its period so that only one positive pulse with a sharp rising edge is produced. This output drives a transistor totem-pole producing a bipolar output at e with a small duty cycle, which in turn, drives the main switching MOSFET creating a very sharp falling edge at each zero crossing. The MOSFET drain is connected through resistors to the winding under test, so as to obtain identical waveforms. Although, the electronic components introduce a small delay between the zero crossings and the falling edge of the output pulses, it is not a detriment, since the need is for a constant repetitive delay throughout the operation of the circuit. Low-offset operational amplifiers and low drift discrete components are used to ensure repeatability of the waveforms.

Other blocks in the circuit are shown in Fig. 4 and include a linear power supply for the main circuit components of Fig. 2, and a multi-output isolated buck converter. The multiple output buck converter generates the main power supply for the switching MOSFET of Fig. 2. It is implemented using an astable multivibrator, a MOSFET and a transformer with taps for various turns ratios. The multivibrator generates the gate drive for the MOSFET with a switching frequency of about 40 kHz. A selector switch sets the desired tap on the transformer so as to generate the variable voltage and this variable voltage source V_{var} is used as the supply for the main switching MOSFET of Fig. 2. A variable voltage source is required for changing the amplitude of the twin pulses produced so that a proper magnitude can be selected depending on the winding being tested. Since this variable voltage supply is isolated from the input AC source, the twin signals can be applied to any winding which has additional DC or AC voltage applied to it. The twin signals *float* on the voltage applied to the winding under test.

B. Signal Detector

Fig. 5 shows an internal block diagram of the signal detector circuit. The transformer serves to isolate the input voltage from

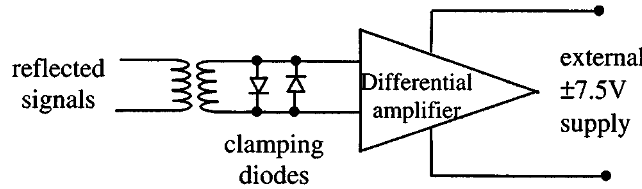


Fig. 5. Block diagram of signal detector circuit.

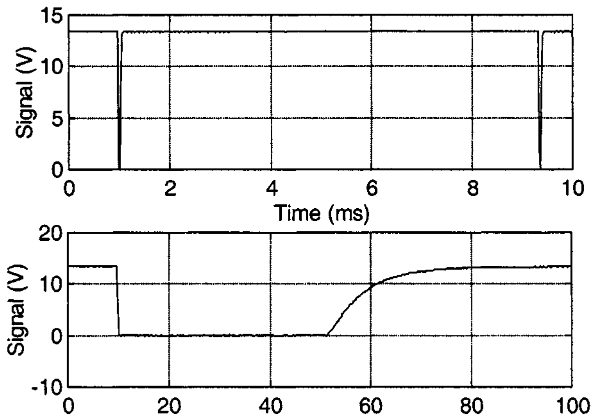


Fig. 6. Signal impressed on device under test.

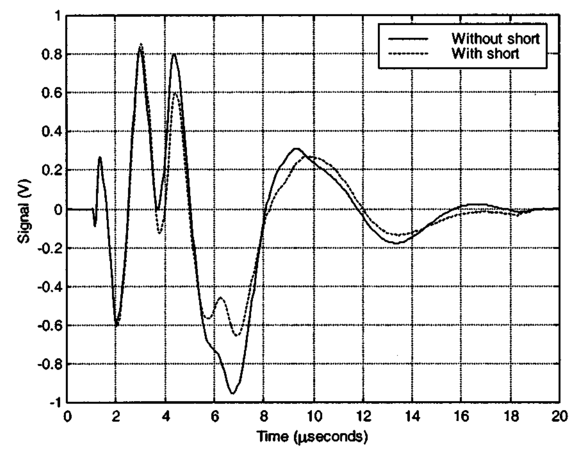


Fig. 7. Typical signature signals for stopped test rotor.

the circuit, so that the detector circuit can also *float* on any DC or AC voltage. A pair of diodes connected in anti-parallel clamps the output of the transformer to a low value.

This bipolar clamped voltage is fed to a low offset, low drift, high bandwidth operational amplifier configured as a differential amplifier. A potentiometer is used to remove the offset of the amplifier and another is used to set the desired gain close to a value of 10. The transformer leakage inductance coupled with the capacitance of the clamping diodes filters some of the high frequencies in the signal. However this filtering is negligible and mainly serves to reduce some of the noise present in the reflected signals.

Figs. 6 and 7 show actual output waveforms for the two circuits captured using a digital oscilloscope. Fig. 6 shows the pulse generated by the signal generator circuit with a zoomed version, and Fig. 7 shows the amplified difference output from the detector circuit.

C. Problems and Modifications

The amplified difference between the reflected twin signals is captured using either a digital storage oscilloscope or a custom digital scope PC add-on card. The amplified signal should be triggered at the instant at which the twin signals are applied to the rotor. The applied signal was fed to an opto-coupler and the isolated signal was used for triggering. However, the delay introduced by the opto-coupler varies as a function of the environmental factors by approximately 800 ns. Since, the signal range of interest has duration of only a few microseconds, the variation in the triggering delay could not be tolerated. To overcome this problem, the signal at the MOSFET drain (Fig. 1) is directly used as a falling edge triggering signal for the oscilloscope. This implies that either the machine winding under test should be isolated from the supply neutral or that the oscilloscope ground should not be connected to the neutral. This is not restrictive since the PC add-on scope card is isolated from the supply neutral.

Care is taken to ensure that there is no ground loop and that each part is grounded with only one wire. This ensures that there is no circulating ground current due to variation in potential. Cables are used for the minimum length necessary and are shielded wherever possible so as to minimize the induced emf due to the high frequency twin signals. The multi-output isolated forward converter causes some differential noise to be added to the twin signals with respect to the circuit ground. This signal gets amplified due to the minor asymmetries and the differential amplifier in the signal detector. This problem can be solved by careful compensation of the stray inductance in the high frequency path of the converter.

The signal detector amplifier had to carefully tuned to achieve the high bandwidth with negligible drift over time. The novelty detection technique is based on data collected from healthy rotor signatures only. It detects shorts whenever there is a significant change in the signature signal. All components in the hardware setup are hence required to maintain the same waveform throughout a large time period. This ensures that any variation in the signature due to changes in the impressed twin signals does not create a false alarm.

V. Testing

This technique was tested on transformer windings with AC excitation. The test winding was built with a facility for creating temporary shorts at various locations. Although the transformer winding can simulate the effect of excitation of a rotor winding, the rotation of the rotor imparts other unique characteristics to the signature signal. The excitation current is fed to the rotor through brushes, which adds brush noise to the signature signal. The rotation causes additional vibration and variation of the signature signal depending on the position of the rotor. To obtain more realistic signals with a facility for creating shorts in any given winding, a test rotor was built.

This rotor has 4 poles and 12 slots with two concentric coils per pole. The inner concentric coil has 36 turns and the outer coil has 18 turns. Thus, each slot has 36 conductors. All the 4 windings are connected in series with appropriate polarity. To enable creation of shorts, one end of the coils is left accessible.

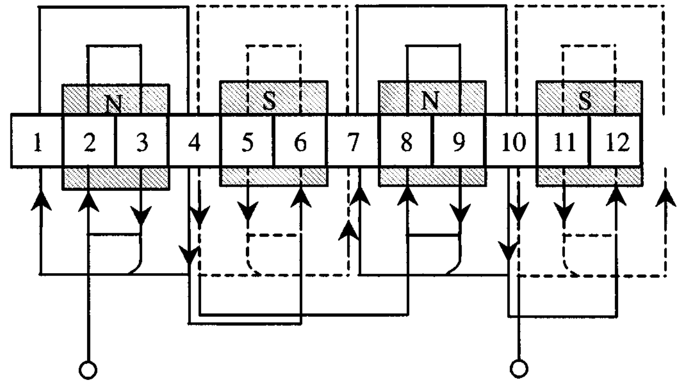


Fig. 8. Winding configuration of test rotor.

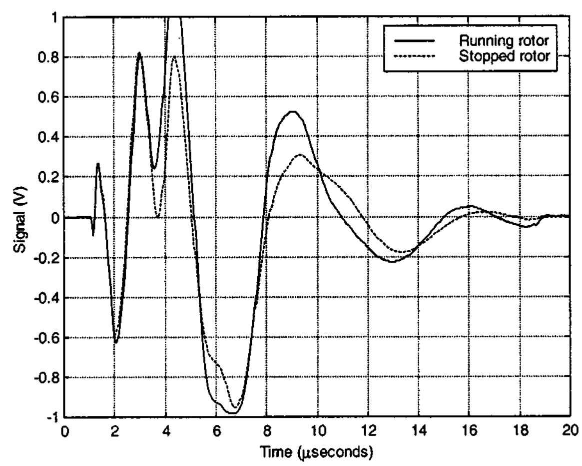


Fig. 9. Variation in signature signals due to speed of rotor (without shorts).

The insulation on several adjacent turns can be removed to allow for creation of shorts externally. Of the 36 turns in the inner coil, 8 groups of alternate turns can be shorted and 4 groups of the 18 outer turns can also be shorted. This permits sufficient variation in the location of the fault. The winding configuration is shown in Fig. 8. A DC motor connected using a belt-pulley drives the rotor. Excitation in the form of a DC or AC voltage can be applied to the rotor through two slip rings connected to the windings. Thus, the test rotor can simulate the effect of rotation of an excited winding. Since, the windings are required to be available for inducing artificial shorts, a stator was not built. Thus, the effect of stator flux on the rotor windings and the signature signal cannot be captured with this setup.

A. Signal Variations

The signature signals obtained from the rotor vary depending on different factors. These include the speed of the rotor and the excitation current, which is proportional to the voltage applied at the brushes. Fig. 9 shows the difference in the signals obtained when the rotor is stopped and when it is rotating at 1800 rpm. Since the novelty detection technique depends on the variation in the signature signals between a healthy rotor and a rotor with shorts [5], it is essential that the changes in the signatures due to shorts be of a different character compared to the changes due to speed, excitation, rotor temperature etc. However, since the variation in the signature due to speed variations is large, the

TABLE I
TEST RESULTS FOR DIFFERENT SPEEDS

Rotor speed →	Stopped	30-60 rpm	1800 rpm
False Alarm rate α	0.0	0.0	0.4
Detection rate β	100.0	100.0	91.0

test data needs to be collected at the same speed as the training data. This is not restrictive in any sense because turbine-generator rotors will typically be tested either at standstill, some small turning speed or at rated speed. Healthy rotor data can be collected at all these conditions. Another problem faced was the voltage induced in the rotor shaft due to high rate of change of voltage applied using the twin signals. Whenever, the shaft is not grounded, this causes a large interference in the signature signal. To avoid this interference, the shaft was grounded using an extra brush. To test the technique, shorts are created at various points to generate test data and this data is tested for false alarms and missed detection. The next section gives a brief description of the detection techniques used and results for the test rotor.

VI. DETECTION TECHNIQUES AND RESULTS

Despite the care taken to ensure repeatability of the signature signals, there are some fluctuations. These are handled by averaging a number of signatures and by using *spherical boundary detection* for removing outliers in the training data. Training data was collected for 3 different speeds—zero, 30–60 rpm (called *turning gear*), and 1800 rpm. To remove possible variations in the signatures, due to temperature, excitation current and other factors, 5 excitation levels were used with the rotor current varying from 0-1.6 A, in steps of 0.4 A. Signatures were also obtained after running the rotor for different time duration so that the rotor temperature variation is taken into consideration. Each training data set, thus, consisted of 1000 signatures collected over the period of one day. Various novelty detection techniques were tried and the best performance was obtained using an elliptical boundary novelty detector [6].

Test data was collected for a *healthy* rotor over a period of three days consisting of five sets of 200 signatures each. Shorts were induced around the periphery of the rotor to obtain test data for *shorted* rotor using three shorts on each inner winding and two on each outer winding for all the excitation current levels, giving a total of 1000 *shorted* rotor test signatures. The elliptical novelty detector was tested on the *healthy* data to obtain the false alarm rate a, which is the percentage of *healthy* signatures identified as *having shorts*. The detector was also tested on the shorted rotor data to obtain the detection rate B, which is the percentage of the *shorted* rotor signatures correctly classified as *having shorts*. The results for different speeds are given in Table I.

Excellent results are obtained for stopped and slowly turning rotors. However the results deteriorate slightly when the technique is tested at rated speed. This seems to be due to the increase in brush noise with speed. An additional factor might be the relative synchronization of the imposed twin signals and the brush noise, since the twin signals are imposed at every zero crossing of the AC line voltage which corresponds to a rotation speed of 1800 rpm.

The repeatability of signals was tested by collecting signature signals over a long duration (more than 4 months). This testing yielded results similar to those in Table I, proving that the signal generator and detector circuits do not suffer from drift problems. This testing also verified the robustness of the method to variation in brush noise since the condition of brushes changed with time and the brushes were deliberately not maintained in ideal conditions. The main limitation of the twin signal approach is the reduced sensitivity to shorts located near the center of the field winding. However this limitation is applicable only for shorts in the exact center, which do not change the reflection path of the applied signals. For most practical rotors, due to the finite number of coils, such a situation will not occur. This is corroborated by the fact that the technique was able to detect all the faults that could be generated on the test rotor including those very close to the center of winding.

VII. CONCLUSIONS

The twin-signal sensing technique has been shown to provide excellent results for on-line detection of faults in rotor windings of turbine-generators. The technique is simple and needs only healthy rotor data. A hardware circuit has been developed to generate the necessary signals. The circuits have the additional advantage of being able to float on any applicable DC or AC voltage so that the testing can be performed on-line for excited windings. Rigorous testing of the technique is performed on a transformer coil and by building a test rotor with a facility for creation of shorts in a variety of locations along the windings. The test results show the effectiveness of the developed methods.

Problems faced in circuit design included the need for assuring exact repeatability of the applied twin signals and ensuring drift-free operation of the electronic circuits. Operational modifications required including taking care of the variations in the signature signals due to environmental factors such as temperature of the machine as well as operational factors like speed and excitation current and elimination of shaft induced voltages using an additional grounding brush. Further work will concentrate on validation of the methods on actual rotors in the field. Some modifications will be required to the signal generation circuit to make sure that the generated signals are not synchronized with device switching on static exciter based systems. This will minimize the effects of the static exciter switching noise on the impressed signals.

REFERENCES

[1] D. R. Albright, "Interturn short-circuit detection for turbine generator rotor winding," *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-90, pp. 478–483, 1971.

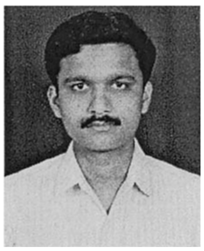
[2] J. Muhlhaus, D. M. Ward, and I. Lodge, "The detection of shorted turns in alternator rotor windings by measurement of circulating stator currents," in *Second International Conference on Electric Machines Design and Applications*, London, UK, Sept. 17–19, 1985, 254, pp. 100–103.

[3] J. W. Wood and R. T. Hindmarch, "Rotor winding short detection," in *IEE Proceedings*, vol. 133, May 1986, pp. 181–189.

[4] M. A. El-Sharkawi, R. J. Marks II, S. Oh, S. J. Huang, I. Kerszenbaum, and A. Rodriguez, “Localization of winding shorts using fuzzified neural networks,” *IEEE Trans. on Energy Conversion*, vol. 10, no. 1, pp. 140–146, March 1995.

[5] R. J. Streifel, R. J. Marks II, M. A. EI-Sharkawi, and I. Kerszenbaum, “Detection of shorted-turns in the field winding of turbine-generator rotors using novelty detectors—Development and field test,” *IEEE Trans. on Energy Conversion*, vol. 11, no. 2, pp. 312–317, June 1996.

[6] S. E. Guttormsson, R. J. Marks II, M. A. El-Sharkawi, and I. Kerszenbaum, “Testing techniques for on-line short detection of excited running rotors,” IEEE Trans. on Energy Conversion, to be published.



Amol S. Kulkarni obtained his B.E. degree from the University of Pune, India, in 1990 and the M.Tech. degree from IIT, Bombay, in 1992. From February 1992 to May 1994, he worked at NELCO Ltd., Mumbai, India on the development of PWM induction motor drives. He is currently working toward the Ph.D. degree at the University of Washington. His research involves application of computational intelligence techniques to drives and motion control.

Mohamed A. El-Sharkawi received his B.Sc. degree in Electrical Engineering in 1971 from the Cairo High Institute of Technology, Egypt. His M.A.Sc. and Ph.D. in Electrical Engineering were received from the University of British Columbia in 1977 and 1980 respectively. In 1980 he joined the University of Washington as a faculty member where he is currently a Professor of electrical engineering. He is the founder of the International Conference on the *Application of Neural Networks to Power Systems* (ANNPS) which was later merged with the *Expert Systems Conference* and renamed *Intelligent Systems Applications to Power* (ISAP). He is the co-editor of the IEEE tutorial book on the applications of *neural networks to power systems.* He has published more than 90 papers and book chapters. He holds five patents: three on adaptive var controller for distribution systems and two on adaptive sequential controller for circuit breakers.

Robert J. Marks, II is a Professor in the Department of Electrical Engineering at the University of Washington, Seattle. Prof. Marks was the first President of the IEEE Neural Networks Council. He is a Fellow of both the IEEE and the Optical Society of America. He is the Editor-in-Chief of the IEEE TRANSACTIONS ON NEURAL NETWORKS and the Associate Editor of the IEEE TRANSACTIONS ON FUZZY SYSTEMS. He is the author of the book, *Introduction to Shannon Sampling and Interpolation Theory* (Springer Verlag, 1991) and is the Editor of *Advanced Topics in Shannon Sampling and Interpolation Theory* (Springer Verlag, 1993) and *Fuzzy Logic Technology and Applications* (IEEE Technical Activities Board, 1994). He the author of more than 150 papers and has 3 patents in the areas of signal processing and neural networks.

George Andexler received his A.A. degree from Phoenix College, Phoenix, AZ, in 1972. He is currently working at the Mechanical Engineering Department at the University of Washington. Earlier he was a Technician in the Department of Electrical Engineering at the University of Washington for 10 years. He was part of research teams working on adaptive var compensators and adaptive sequential controller. He holds two patents on adaptive var compensator.

Jian Xing received the B.S.E.E. and M.S.E.E. degrees from Zhejiang University, PR China, and the Ph.D. degree from the University of Washington in 1982, 1987 and 1996 respectively. His research was focused on the development of an adaptive sequential controller to reduce voltage transients caused by circuit breaker switching and to increase breaker life. He joined Eldec Corporation in 1996 where he is presently a Design Engineer working on aerospace and defense applied power products. He holds two patents on adaptive sequential controller.

Isidor Kerszenbaum was born in Buenos Aires on November 11, 1949. He received the B.Sc. degree in electrical engineering at the Technion-Israel Institute of Technology in 1978, the G.D.E. and Ph.D. degrees in Electrical Engineering from the Witwatersand University, Johannesburg, in 1981 and 1984, respectively. Dr. Kerszenbaum has since been involved in electric power engineering. Currently, Dr. Kerszenbaum is a Senior Electrical Consultant in the Construction and Technical Services Department of Edison Mission Energy. In addition, Dr. Kerszenbaum is a part-time Instructor at CSULB in the Electrical Engineering Department. He is also a consultant to the United Nations Development Program. Dr. Kerszenbaum had published many technical papers, having received several prize-paper awards. He is a Registered Professional Engineer in California.