Sensor Development for Compulsator Driven Railgun Systems

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***Abstract*-- As the technologies of rotating power supplies and thyristor switches advance, new methods of measuring various signals must be developed. The University of Texas at Austin Center for Electromechanics (UT-CEM) has developed new methods to measure compulsator position and speed and has made advancements in health monitoring of the thyristor switches. Technological advancements in machine design have enabled dramatic increases in machine speeds, which in turn increase electromagnetic interference. It is essential to a successful operation to have a method (reliable within this harsh environment) of measuring speed and sensing rotor position to generate gate signals for thyristor switch modules. As the modules switch larger amounts of current and voltage, it is correspondingly important to monitor the switching process, so that any damage to the system caused by a fault condition can be minimized. This paper describes sensors developed at UT-CEM to monitor speed, sense rotor position, and detect fault conditions.**

I. INTRODUCTION

THE University of Texas at Austin Center for Electromechanics (UT-CEM) is developing a compulsator-driven pulse power system which performs at higher speeds than any previously demonstrated. Advancements in mechanical systems have enabled these faster compulsator (CPA) rotor speeds, which in turn place an increased burden on the system controller and sensor components. An on-going development program was initiated to address these issues. This paper focuses on the developments in the area of sensors for CPAs and pulse power systems.

A previous development project at UT-CEM (Subscale Focused Technology Program, abbreviated FTP) produced a compulsator which was used in this research as a sensor test bed. (This sub-scale system is described in [1].) Although the sub-scale machine achieves a lower speed and less field current than the new system, it is a realistic and a very harsh environment in which to test new devices.

The sensors developed for FTP are not sufficient to control the next generation machine currently under design at UT-CEM. The new sensors being developed include: (1) a new encoder system to determine rotor position accurately; (2) a method to record field coil current accurately and without direct connection to the field circuit; and (3) a method to monitor the field converter gating and thyristor health. Each of these new systems was to be designed, built and tested on a subcomponent level.

The first and most critical sensor is the r*otor position encoder,* which provides data to the controller to generate the gating pulses for the converters. Performance requirements included:

- a mechanical resolution goal of 0.5° accuracy.
- reliable performance within a harsh environment filled with electromagnetic noise and possibly oil from bearing lube or hydraulic motor systems
- tolerance of massive deceleration by the rotor during discharge

The existing FTP *field coil current sensor* is a current-viewing resistor (CVR). The field current is to be used as an input by the new controller to control the gating of the new field converter modules, therefore, the output must be an isolated signal. The CVR is capable of measuring the field current; however, the output signal had to be transmitted to the controller using a fiber optic analog link. The fiber optic analog link has three faults; it is battery powered, produces noisy signals, and has about 5% error depending on how often it was calibrated. The size of the CVR is of concern when this system is mounted on a skid where volume and weight is an issue. Pearson current transformers had been used to measure the field current on previous systems. Unfortunately, the core of the Pearson would saturate shortly after the field initiation module (FIM) discharge. It was determined that an accuracy of 1% and a galvanically isolated signal was desired for the field current sensor.

Also needed was a system of *health sensors* for the thyristors in the converters. This system checks the gating pulses generated by the controller and verifies that each thyristor triggered during the desired interval. Incorporated into the health sensor system is a sensor to check the on and off states of the thyristor and verify that the devices are functioning properly. A logic circuit compares data from these sensors against the gating signals from the controller, reporting a fault condition to the controller, and latching the signal so that the faulty device or devices can be identified quickly. The thyristor status sensor would be developed and tested on the converter and a decision would be made as to how to use this

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signal easily without adding too much complication to the system. There is a big concern that a circuit generating faults by looking at thyristor status might generate false faults.

II. ENCODER

An initial effort was made to examine encoders available commercially. The most promising device found was a 1.5 in. encoder made by Renco (Fig. 1), which operates at up to 200 kHz. The rotating inertia of the encoder is low enough to be able to withstand the rotor deceleration. A thin disc of Lexan with etchings is attached to a metal ring, and is the only rotating part of the encoder. The circuit on the encoder generated an optical signal that used the etchings to generate three signals. The first two signals made a quadrature output with a 50% duty cycle. The third signal was an index pulse that occurred once per revolution.

This encoder was mounted to the machine and several motoring runs were performed at 5,000 rpm. (Data from one of these tests can be seen in Fig. 2.) These tests revealed critical inadequacies for the intended application, even though adjustments were made to correct the problems.

- the output signal was so weak it could not drive the input to the oscilloscope; a line driver circuit was built in order to decrease the noise and strengthen the signal
- the sensor was attached to the machine with a set screw so small that it seemed unlikely to survive; a 4-40 set screw was used to connect the small metal ring of the encoder to the rotor shaft

In spite of these additions, the output signal tended to disappear as rotor speed increased. It was discovered, at length, that the Lexan disc was very thin and rubbed on the stationary portion of the encoder. It was decided that this encoder was not adaptable to the rotor environment and that other encoders must be investigated.

The encoder used on the FTP machine is an6 in. aluminum disk (codewheel) machined with a larger radius every 60° and sensed by a commercially available optical encoder. While this sensor system produces only three high and three low pulses per revolution, it has proved to be reliable and rugged through extensive testing. It was decided, therefore, to apply the concept to a new design that could produce the desired accuracy needed for the next generation machine.

A new codewheel was machined at UT-CEM (Fig. 3) which produces the combination of quadrature output signal and an index pulse required by the controller design. A total of 180 slots sensed by two optical sensors produce 720 transitions, which the controller senses as counts per revolution (and which meets the goal of 0.5° accuracy). The mechanical part of the codewheel design was determined by what could be machined easily with the appropriate accuracy. The smallest slot that could be easily machined is 1/16 in. or 62.5 mils. Since a 50% duty cycle was desirable, the slots and the bars would both be 62.5 mils. Using the number and size of the slots, the minimum center point of the slots would be 3.42 in. Using slots this large reduced the minimum required frequency of the optical components. A third optical sensor to generate the 1/rev index pulse could sense a notch on the edge of the 7.26 in. codewheel diameter.

Initially, the same optical sensors used on the old encoder system were used to sense the slots on the new codewheel. That sensor was a Honeywell HOA0901 transmissive encoder sensor (Fig. 4). A custom mount was made for the three required optical encoders. The mount was designed to allow easy positioning of each sensor. One of the quadrature sensors only had adjustment in the axial direction. The second quadrature sensor and the index sensor had both axial and radial adjustment. In order to test this new encoder system, a stand-alone test fixture was assembled using a high speed motor. The new codewheel was attached to the end of the shaft and the optical encoder mount was attached to the vertical mount on the base of the motor. One additional feature was added to the setup: a brake (consisting of both electrical and mechanical components) was needed to slow the wheel to simulate the deceleration the encoder system would experience on the CPA. An electrical brake reverses the polarity of the applied voltage and is triggered by a contact closure attached to a mechanical caliper brake. This setup (Fig. 5) produced results similar to actual deceleration of the rotor during a discharge (Fig. 6).

The new codewheel was mounted to the test fixture and the motor spun; the three encoder outputs were recorded on an oscilloscope and analyzed. The output signal duty cycle of the square wave was not the required 50%. The device data sheets indicated that the encoder had some hysteresis effects in high frequency applications, and ways to compensate for the hysteresis by changing the target. Further analysis revealed that the light beam emitted by the Honeywell encoders was diverging and being sensed before it was in front of the slot. Another light source with less scatter was desired.

The search produced a laser diode for the light source, a 1 mm plastic fiber cable to transmit the light, and a standard fiber optic receiver to sense the light. The laser diode (Fig. 7) produces a parallel beam over a long distance, although the encoder setup requires the beam to travel only 125 mils. The laser diode light is emitted across the slots where a 1 mm fiber optic cable is mounted and connected to a fiber optic receiver; the signal from the receiver is transmitted directly to the controller. A mounting fixture was fabricated to accommodate the three laser diodes and three 1 mm fiber optic cables. The mounting fixture allowed for adjustment of the lasers much in the same manner as the Honeywell encoders described above. A picture of this system mounted on the machine is shown in Fig. 8.

Early tests of the laser diode system revealed that the light source was too intense and was bleeding over to the adjacent fiber optic receiver cables. It was decided to use opaque filters to reduce the amount of light from the laser diodes. Several tests were conducted on the test fixture to determine the proper amount of filtering required. When the results were satisfactory, the setup was mounted on the subscale rotor and several rotor tests were run with the outputs connected to the controller. The two-quadrature outputs are 90° apart and each has a 50% duty cycle.

The resulting output data (Fig. 9) is exactly what the controller requires. The final version of the circuit has a small (3.2 V) power supply in a shielded box to produce the required power for the laser diodes. The mounting fixture allows space for light filters to be placed in front of the laser diode. The 1 mm fiber optic cable is run back to the control room and connected to the receivers inside the controller interface box. This method is extremely immune to noise, since all the voltage is being sensed within the electromagnetically shielded control room.

A. Field Current Sensor

Goals for the measuring of the field current were accuracy and galvanic isolation from the field circuit. Several options were explored in order to meet these goals.

The FTP system uses a CVR with a fiber optic analog link to measure the field current. The CVR was designed for another experiment and was not appropriate for this application because it consists of 28 smaller coaxial CVRs in parallel, potted in a single structure with seven mounting holes on each side. Also, comparison of the output signals of this CVR output to a Pearson current transformer (Fig. 10) shows that the current rise shape differs slightly. The discrepancy is attributed to the CVR resistance varying as current diffused through the CVR. The final problem with this CVR is its direct connection to the field circuit and the need for isolation through a fiber optic analog link. The fiber optic link has 5% error and runs on battery power, both of which are unacceptable.

A Rogowski coil was considered, but it measures di/dt and cannot measure the slow rise of the field current on the subscale system. A similar problem occurs in both the FTP and the system under design, as the core saturates if the current time product is too large.

The solution for the field current sensor is twofold. First, a current transformer will be custom-built to handle the large current time product of both the subscale and the next generation CPA. The resulting device would be capable of measuring field current accurately without saturation, but the weight and size required for this capability are in excess of program goals. The di/dt of the next generation system is large enough that a Rogowski coil (which complies with program mass requirements) can record the desired waveform accurately. Therefore the current transformer purchased will be used to measure the field current and to calibrate the Rogowski coil for accurate in-operation measurement. This solution is suitable both for the subscale and for the next generation system.

Specifications for the current transformer were provided to several prospective vendors:

To measure up to 1 MA peak current with a current time product of 10,000 A/s with +/- 2% accuracy without adding induction and being galvanically isolated from the field circuit. Stangenes Industries came back with the winning quote. The device will output 0.00001 V/A into a 50 Ω load with 0.09% droop. It will meet all of the program goals except the size and weight, which is the reason for using the Rogowski coil on the next generation system. The Stangenes current transformer was connected to the field circuit and several tests were run discharging the FIM into a 2 mH inductive load. The resulting data is shown in Figure 11 compared to the CVR.

B. Gate Sensors

The third type of sensor developed under this effort is the gate sensor for the thyristor gates in the converter circuits. A similar gate drive has been used in past compulsators [2]. Several methods were investigated to determine the best way of achieving program goals. One method was to use current transformers. Several devices were found capable of meeting this task. The problems with the current transformers were cost and weight. Each device cost about $180 and there were many needed to monitor all of the converter thyristors. Further study produced a better method that was very cost effective. The basic theory is that a fiber optic transmitter would be integrated into the thyristor gate circuit to produce light when the device is gated. All this sensor requires is a fiber optic transmitter and a resistor to limit the current. A schematic of the device is shown in Figure 12. The schematic includes some of the gate drive circuit.

Each gate sensor is supplied to a logic circuit designed to determine if a fault condition occurs. The controller generates the fiber optic gate signal and sends it to the gate sensor interface box for each leg. The interface box takes the rising edge of the gate signal and generates an output pulse of uniform width and fiber optically transmits it to the thyristor gating boxes. Additionally, the gating pulse is used to determine if a fault condition occurs. Any fault generated would be sent by a fiber optic cable to the controller as a gating fault. The guilty device or devices would be latched in at the time of the fault, and will illuminate an LED until the operator resets the circuit. A fault is produced by one of two scenarios. First, if the gate sensor produces an output pulse when the controller has generated no gating signal. And secondly, a fault is produced if the output of the gate sensor does not go high and remain there for the duration of the gating event. Because of timing issues associated with the transitioning of the gate sensor and gate pulse, all faults are ignored during a small dead band interval at the beginning and end of the gate sequence. The output from one of these devices and the corresponding gate current is shown in Figure 13.

A similar device was designed to determine the on or off status of the thyristor. This sensor would be mounted in series with the resistor in the snubber of each field converter leg. The device has been designed and built and is waiting testing of each converter module. How this sensor is used to determine faults will be determined after testing of the sensor. The data from the device can be used to determine reliability of the sensor, i.e. how often a false fault is generated.

III. CONCLUSION

The sensor requirements for immediate future compulsator systems have been successfully demonstrated. The new encoder system is mounted on the sub-scale rotor, and has been fully tested. The new current transformer and thyristor monitor are also installed, awaiting further sub-scale tests. Future plans call for additional system testing on the sub-scale compulsator. Although more work remains to be done, the minimum system monitor components are now in place for the operational system testing. As still more advanced and faster compulsators are fielded, the issue of adequate sensors may need to be revisited.

REFERENCES

[1] J.R. Kitzmiller, et. al, "Predicted vs. actual performance of a model scale compulsator system," *IEEE Transactions on Magnetics*, vol. 37, no. 1, January 2001

[2] T.J. Hotz, C.E. Penney, J.R. Kitzmiller, M.D. Werst, "Single Shot Switch Performance on the Cannon Caliber Electromagnetic Gun Program", 9th EML Symposium, Edinburgh, Scotland, May 1998.

Figure 1. 200 kHz Renco encoder

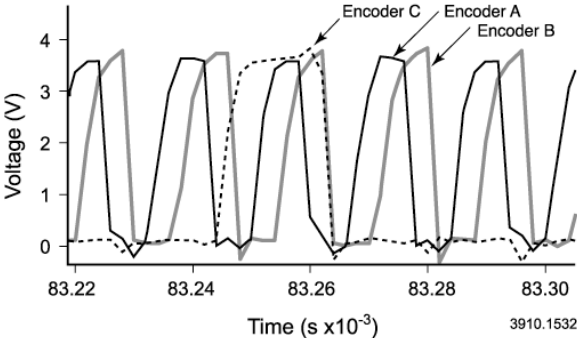

Figure 2. Data from the Renco encoder at 5,000 rpm

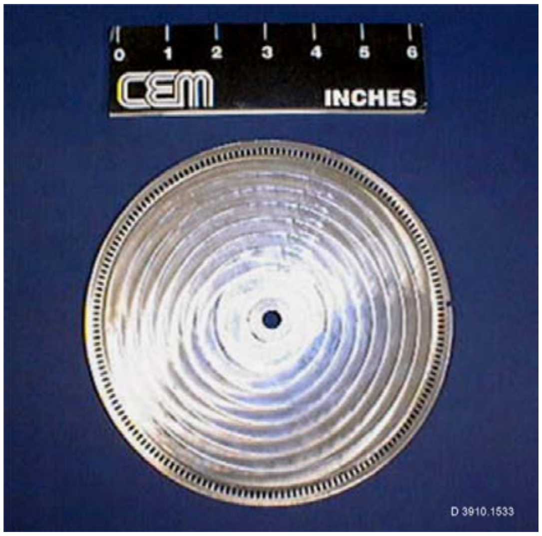

Figure 3. Codewheel developed at UT-CEM

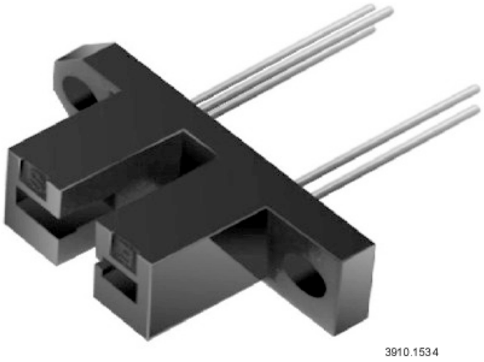

Figure 4. Honeywell HOA0901 transmissive encoder sensor

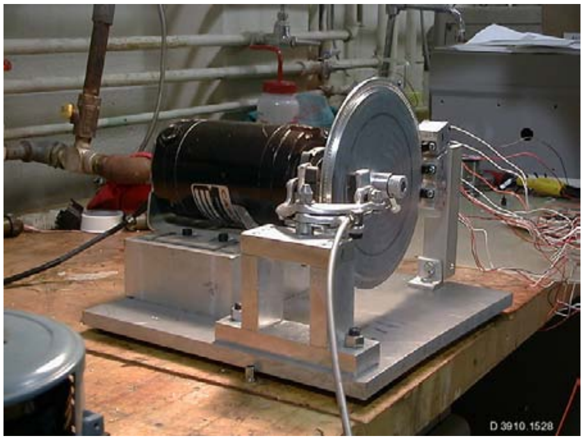

Figure 5. Encode test setup

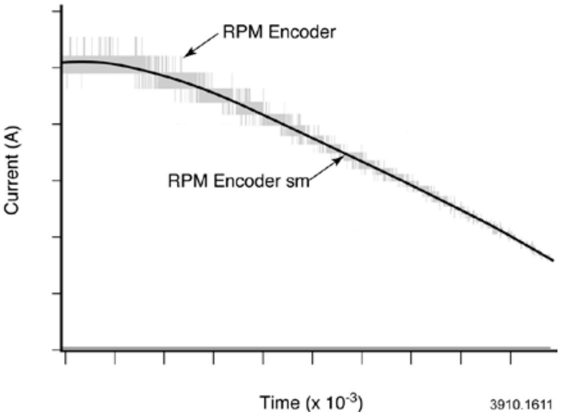

Figure 6. Braking test

Figure 7. Laser diode module

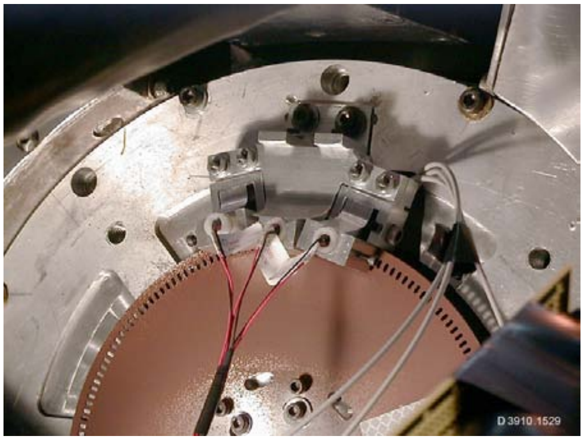

Figure 8. UT-CEM encoder system with laser diode light source

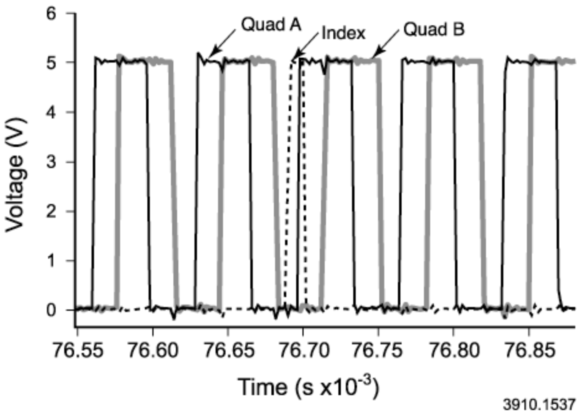

Figure 9. Laser diode encoder output data

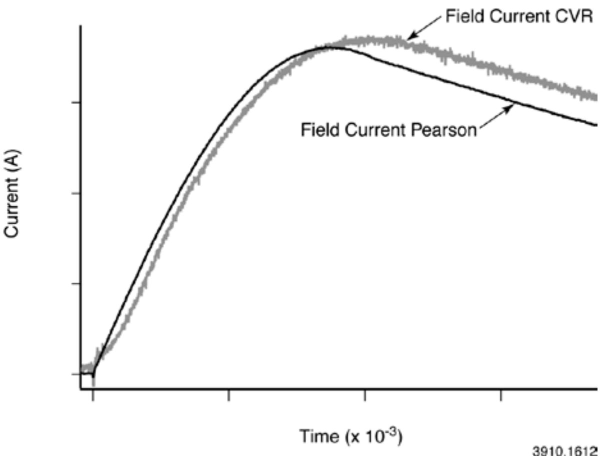

Figure 10. Field current comparison

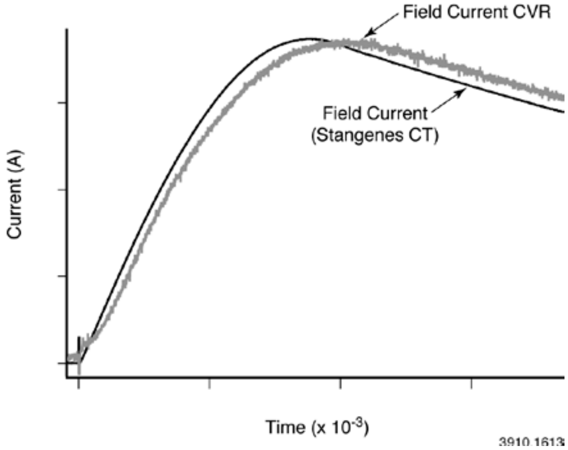

Figure 11. Stangenes current transformer vs. CVR

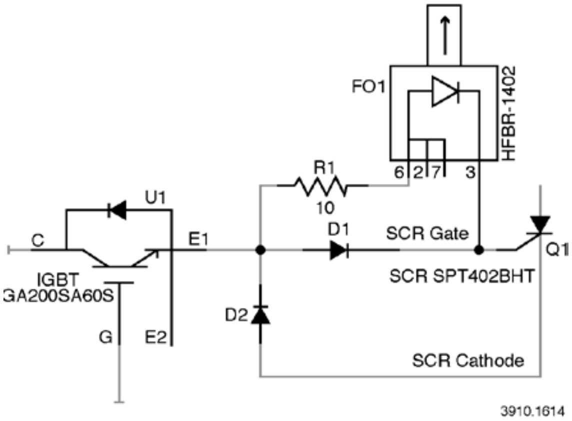

Figure 12. Thyristor fiber optic gate sensor

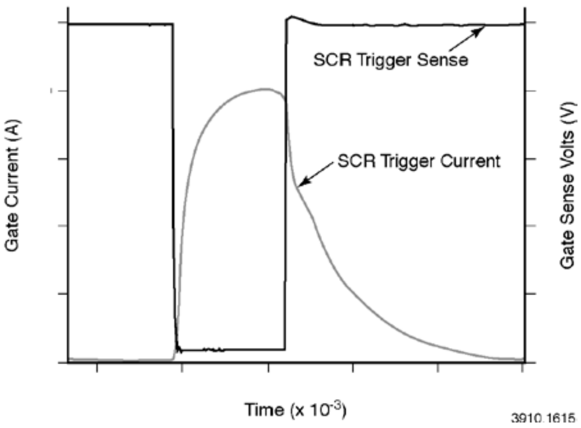

Figure 13. Thyristor gate sensor data