SELF EXCITATION OF IRON CORE HOMOPOLAR GENERATORS

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Abstract - In the interest of reducing homopolar generator (HPG) auxiliary requirements, a self-excited field coil for pulsed duty, iron-core HPG has been developed and tested at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). In order to minimize rotor energy expended during excitation, a low-resistance, low-inductance coil was desired to allow field current to rise as rapidly as possible.

A seven-turn field coil, having a nominal resistance of $500 \mu\Omega$ was fabricated for the CEM-UT compact HPG system tester and subsequently tested. At 6,000 rpm, a field current rise time of 1 s was achieved and resulted in an average peak field density of 1.94 T. Only 300 kJ, about 13% of the 2.27 MJ stored in the rotor was required to fully excite the generator.

INTRODUCTION

Since excitation power requirements for iron-core pulsed HPGs are relatively low, no great need for self-exciting these machines has ever developed. However, as the demand for portable pulsed power supplies increases, elimination or reduction of generator auxiliaries becomes very attractive in terms of weight savings and reduced power requirements. The self-excited coil concept presented uses residual magnetic flux in the rotor iron to initiate excitation, so the need for a field power supply is completely eliminated. Details of the system design, including the coil and sliding current contact arrangement, are discussed. Fabrication and assembly of the device into the compact HPG system tester [1], an existing HPG used specifically for component development, are then reviewed. Finally, the testing program and experimental results are presented.

CIRCUIT ANALYSIS

Figure 1 shows the circuit used to model the field coil performance. The excitation circuit equation is given by:

$$-V + IR + L\dot{I} = 0$$

The current rise time is therefore given by:

$$\dot{I} = (V - IR)/L$$

where:

$V = V(t)$ = machine voltage
 $I = I(t)$ = excitation current
 $L = L(t)$ = coil inductance
 R = coil resistance

Thus, to reduce current rise times, the circuit resistance and inductance must be minimized.

The field coil dimensions and geometry were fixed by the system tester design. Geometry is that of a hollow cylinder of 12.1 cm (4.75 in.) height with 38.1 cm (15.0 in.) and 48.3 cm (19.0 in.) inside and outside diameters, respectively.

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Fig. 1. Field coil circuit.

For ease of manufacture, it was assumed that the coil would be constructed from a single sheet of copper 12.1 cm (4.75 in.) in width, corresponding to coil height. For a given thickness of conductor, a coil length was determined from the number of turns that would fit between the inner and outer diameters. Once coil dimensions were defined, resistance and inductance could be determined.

The mathematics of an iron-free, self-excited HPG are well documented [2]. However, when dealing with an iron-core machine, eddy currents and variable magnetic permeability must be taken into account. A numerical solution to the resulting differential equations was performed on a small computer to simulate the coil and machine performance.

Three coil geometries were selected for comparison and results of the computer simulation are shown in Table 1. In general, it can be seen that for a larger conductor thickness, having fewer turns to the coil, (which minimizes resistance and inductance), the current rise time is reduced.

Another aspect of the coil requirements is the critical rotor speed required for field coil excitation. To drive the coil, sufficient voltage must be obtained from residual flux in the spinning rotor. By minimizing coil circuit impedance, a lower threshold voltage and lower rotor speed will be required to initiate coil excitation.

Field Coil System Design and Installation

The primary difficulty in designing the field coil system was not with the coil itself, but rather determining the means to direct current from the rotor to the coil. Limited space was available to mount brushes, actuators, and field coil terminals under the rotor. Additionally, the reduction of iron from the stator had to be minimized to provide a sufficient flux path for the machine.

Figure 2 shows a cross-sectional view of the self-excited field coil and brush gear assembly as developed for the HPG system tester. As can be seen, the entire brush and brush actuator assembly is located in the removable screw seal plate which measures 14.5 cm (5.70 in.) ID by 37.5 cm (14.75 in.) OD and 2.3 cm

Table 1. Effects of conductor size on field coil and machine performance.

COIL SIZE	COIL RESISTANCE (mΩ)	PEAK COIL INDUCTANCE (mH)	TIME TO PEAK CURRENT (s)	MAGNETIC FIELD AT PEAK CURRENT (Tesla)	ROTOR SPEED AT PEAK AT PEAK CURRENT (rpm)
1/8 x 15 turns	.913	3.20	>4.0	~1.8	~3,000
3/16 x 10 turns	.406	1.44	3.0	1.92	3,010
1/4 x 7 turns	.213	.705	2.4	2.00	3,100

Fig. 2. System tester cross section with self-excited field coil.

(0.91 in.) thick. Brushes were of the copper finger designed and were installed in "piggy back" pairs to reduce current density. Also, their short length provided adequate stiffness making return springs unnecessary.

Annular pieces of a 0.8 mm (0.032 in.) thick silicone rubber sheet were clamped to the screw seal plate to serve as brush actuators. Pneumatic pressure supplied through existing air feed holes in the stator caused the rubber diaphragm to expand against a 3.2 mm (0.125 in.) thick neoprene spacer which provided brush displacement. Adjustment of air pressure was used to tailor brush contact force, and pressures as high as 900 kPa (130 psi) were used with no leaks or rupture in the diaphragm. The greatest advantage of this actuator design was its low height of only 4.8 mm (0.188 in.) thus, minimizing iron removal from the flux path.

Theoretical coil design called for seven turns of a 6.4 mm (0.25 in.) thick by 12.1 cm (4.75 in.) wide copper sheet. However, this would have required only one input and one output terminal, the geometry being unsymmetrical and may have caused a magnetic field imbalance under the rotor. Although the magnitude of this imbalance was not predicted, the possibility of rotor tilt was cause for concern. Thus, in order to uniformly distribute magnetic flux and to reduce

current density in the terminals, a coil with six input and six output terminals was developed.

After examination of the available space for the field coil, the conductor materials chosen were six 15.3 m (50 ft.) long rolls of 12.1 cm (4.75 in.) wide by 0.8 mm (0.032 in.) thick copper sheets. For all practical purposes, the coil may be thought of as six independent coils in parallel, each coil having approximately seven turns. The only drawback to this approach is that each conductor must be insulated from the other which results in a loss of net conductor thickness. Thus, a seven turn coil of this geometry has a net conductor thickness of only 4.8 mm (six layers of a 0.8 mm thick conductor) instead of 6.4 mm for the solid conductor. This drawback is offset by the fact that the coil wrapping forces for the thin, laminated conductor are much less than for a thick, solid conductor.

In an effort to conserve machine iron, it was decided to connect the inner set of field coil brushes directly to the screw seal plate and use it to conduct current from the six inner field coil terminals. Although this caused the stator to be "hot" during coil excitation, it greatly simplified the design by reducing screw seal plate insulation requirements. The outer set of brushes was connected to a copper

brush ring which attached to the six outer field coil terminals and these parts were fully insulated from the stator. Figure 3 shows a partial assembly of the screw plate, brush actuators, and field coil.

Fig. 3. Partial assembly of screw seal plate mounted on winding mandrel showing brushes, actuators, and finished coil.

FIELD COIL CONSTRUCTION

A simple fabrication process was developed for the self-excited field coil. A split, aluminum mandrel was built with a 38.1 cm (15.0 in.) outer diameter corresponding to the inner diameter of the coil, and mounted on the rotating table of a small, vertical boring mill. The six inner coil terminals were soldered to the ends of the six copper rolls, properly oriented, and then bolted between the screw seal plate and the mandrel. Figure 4 shows some of the hardware required for the field coil and its assembly process.

Next, a table with 13 vertical spindles was built and anchored to the floor near the mill. The six copper spools were set on six of these spindles while five spools of 0.13 mm (0.005 in.) and two spools of 0.25 mm (0.010 in.) Mylar® insulation were placed on the other spindles to be fed into the coil conductors while two layers of the 0.25 mm (0.010 in.) insulation separated each group of six conductors. A dual roller tensioning device was then attached to the mill tool holder and the copper and Mylar® sandwich was inserted between these rolls. This winding set-up is shown in Fig. 5.

Once winding was completed, the copper sheet lengths were trimmed, the outer coil terminals attached, and then installed under the screw seal plate and connected to the outer brush ring. Finally, a thick layer (approximately 6.5 mm) of preimpregnated fiberglass tape was wrapped around the coil to prevent unwinding. After curing the tape, the OD was machined to size and the coil prepared for installation.

Fig. 4. Field coil hardware showing clockwise from upper left -- aluminum winding mandrel, copper roll, end terminals, outer brush ring and brush actuator clamps, and screw seal plate.

Testing: Performance and Evaluation

Once the coil and brush assembly were installed in the system tester stator, coil resistance was measured to ensure that no turn-to-turn shorts had occurred. Resistance values obtained ranged from 480 to 520 $\mu\Omega$; thus, a nominal value of 500 $\mu\Omega$ was assumed.

Fig. 5. Field coil winding apparatus.

Although the coil was optimized for 4,000 rpm operation, attempted discharges from 1,000, 2,000, and 3,000 rpm were initially performed to insure proper controller sequencing and data acquisition. In the event the field brushes were not actuated, discharge circuit brushes would have to dissipate the entire rotor energy frictionally. While this presents no problem from low speed, a frictional stop from 4,000 rpm would probably cause some damage to the brush mechanisms.

No excitation was recorded by a Hall Probe mounted in the air gap when the field brushes were dropped from 1,000 rpm. This was not surprising since the rotor had not yet reached critical speed. However, at 2,000 rpm a 67-kA discharge was achieved. Approximately 2.5 s was allowed for the field to rise before the discharge circuit brushes were actuated. As designed, the Hall Probe was to have triggered the discharge sequence when a present field level had been attained; but unfortunately the probe was unoperational and the discharge delay had to be predetermined and written into the control program. A 94-kA discharge from 3,000 rpm was then performed and preparations for testing at the designed optimum speed were made.

Four discharges at 4,000 rpm were then made with time delays varying from 3.5 to 1.2 s. Shorter time delays resulted in higher peak current from the generator. Excitation field had therefore already peaked and was declining for the longer delays. Two 5,000 rpm discharges were then performed with 1.75 and 1.3 s delays. Machine currents produced were 242 and 292 kA respectively, again indicating peak field was achieved very quickly and had begun to decline.

Without a reliable Hall Probe signal or instrumentation for coil voltage, however, a good estimate of an optimum delay for a given rotor speed was not possible. For this reason, another Hall Probe was inserted into the air gap and coil voltage was instrumented.

Tests at 4,000, 5,000, and 6,000 rpm were then accomplished with 1.25 s delays. This delay was chosen to allow the generator ample time for self-excitation to the point of saturation. Because the coil was optimized for voltage generated to 4,000 rpm, higher speed tests appear to have over-excited the machine. Although the Hall Probe indicated 1.45 T on the 6,000 rpm test, the coil voltage of 17 V translates into a flux density of 1.88 T. If an additional 0.5 V is assumed for both coil brush sets to account for resistive losses, then the average field level attained was 1.94 T.

Normal operating field level for the system tester is about 1.7 T. Excitation above this level has caused fringing field problems in the past, and fringing fields during the 6,000 rpm self-excited coil shot did do substantial damage to the outer rim brush straps of the system tester.

The most encouraging aspect of the experiment was how rapidly the generator self-excited from residual magnetism. Theoretical and actual coil currents are plotted in Fig. 6 for the optimized rotor speed of 4,000 rpm. An actual coil current trace for 6,000 rpm operation is also shown and indicated the machine reaches full excitation in about 1 s. Thus, self-excitation required only 300 kJ of the 2.27 MJ stored in the system tester rotor. Differences between the theoretical coil current and actual levels obtained during testing are due to the conservative nature of the model.

Fig. 6. Field coil test results.

Figure 7 shows the field coil brushes after system tester disassembly. Examination of the brushes shows that they are quite worn and that severe thermal discoloration occurs starting at the brush tips and extending approximately 10 mm (0.40 in.) down the brush toward the mounting screws. Thus, frictional energy dissipated by the brushes during excitation is considerable.

Fig. 7. Brush wear inspection during machine disassembly after completion of testing.

CONCLUSIONS

Reductions in HPG auxiliary requirements can be made by the use of field coil self excitation. A low resistance and inductance coil will reduce losses during excitation by permitting faster current rise times. Tests have shown that as little as 13% of the rotor energy is used during excitation, and it is believed that these requirements can be further reduced by closer monitoring of the field during excitation to determine the proper discharge time.

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