SatCon's Hybrid PM/homopolar Generator Offers Compact, Portable Power Generation

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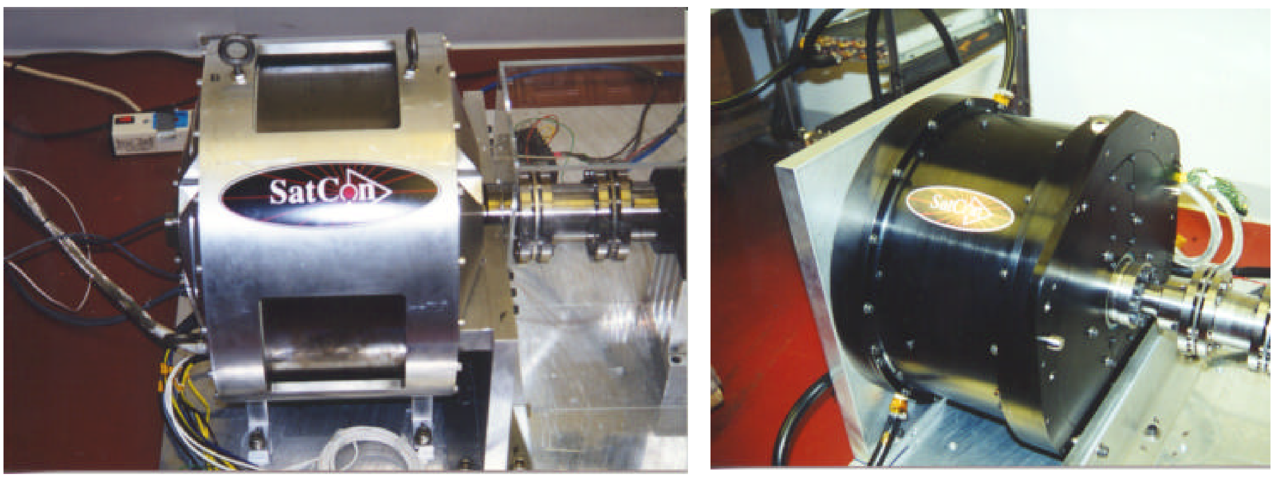
Introduction

SatCon Technology Corporation recently completed a contract for development of a novel hybrid PM/homopolar generator for use as an in-line generator in a US Army HMMWV. During the program the two prototype in-line generators shown in Figure 1 were designed, fabricated, and tested:

1. A laboratory prototype used to evaluate the concept from an electromagnetic point of view
2. A prototype ready for installation in a HMMWV



(a) Laboratory prototype on test stand

(b) HMMWV-installable unit on test stand

Figure 1. Two prototypes were developed and tested during the Phase II program

As Table 1 indicates, the in-line generator must be capable of delivering 10 kW of 3-phase, 120/208 V power to a wide range of loads. This generator, developed by SatCon for the US Army CECOM, is a novel configuration that possesses the advantages of a permanent magnet field and yet allows active regulation of the terminal voltage. The Army intends that this generator be mounted between the engine and transmission of a HMMWV and that it draws power from the output of the engine. In a battlefield scenario the vehicle would be parked with the engine speed set at 1200 rpm, allowing the generator to provide power for battlefield operations. The primary advantages for the US Army are elimination of either bulky towed generator sets or on-board APUs. The result is that two HMMWVs (with power generating capability) can fit on an air transport rather than one (with a towed genset) or that HMMWV personnel or cargo can consume space formerly taken by an on-board diesel-engine powered APU. SatCon, however, believes that the hybrid PM/homopolar generator offers considerable potential in a growing number of applications requiring portable, mobile and reliable power generation.

Table 1. Top-level specifications for the in-line generator

Rated voltage	3ϕ, 120/208 V, 60 Hz @ 1200 rpm
Rated power	10 kW (0.8 lagging –1.0 PF)
Max. weight	100 kg
Max. dimensions	13 in. long x 16 in. dia.
Voltage characteristics	MIL-STD-1332(B), Class 2B
Top speed	3200 rpm (no power generation)
Cooling	Water/ethylene glycol or transmission fluid

Testing of the HMMWV-installable prototype demonstrated that it was readily capable of providing the required 10 kW to a .8 power factor load, while maintaining 120 V phase-to-neutral at the terminals. The generator provided 17.2 kW into a unity power factor load, demonstrating the generator's capability to exceed specifications, while maintaining 120 V at the terminals. The measured temperatures at the hottest locations within the armature winding of the HMMWV-installable prototype steadied out at values below 100 °C during a 3-hour test at the most-demanding load required (10 kW at .8 power factor). The total harmonic distortion (THD) of the voltage waveform of the vehicle-installable unit was generally between 2 and 3% (and never exceeded 3.2%), well below the 5% value allowed by MIL-STD-1332B. The HMMWV-installable prototype (along with the required electronics, wiring and cooling components) has been delivered to US Army CECOM, ready for installation and test in a HMMWV.

Hybrid PM/homopolar field concept

The generator combines the field produced by rotor-affixed permanent magnets with the homopolar field produced by a stationary toroidal field coil. The homopolar field is superposed on to the permanent magnet field, in order to provide active control of the terminal voltage of the generator. With this approach we are able to obtain the recognized benefits of a permanent magnet generator and still have active control of the terminal voltage. Rotors with permanent magnets have negligible losses, improving efficiency and eliminating thermal management issues associated with the heat dissipation of rotor-deployed field coils. Furthermore, no power transfer to the rotor is necessary, improving compactness, efficiency, ruggedness, and reliability.

HMMWV-installable prototype

As a result of the successful performance of the laboratory prototype during testing, we elected to leave the magnetics design relatively unchanged in the HMMWV-installable prototype. Figure 2 shows the armature that was used in the laboratory prototype and later transferred to the HMMWV-installable prototype. Table 2 gives the top-level design parameters for the prototypes.

(a) Stacking of skewed armature lamination stack (b) Fully wound armature with field coil

Figure 2. Armature during lamination stacking and as finished part

A small box of electronics, shown in Figure 3, contains the voltage regulator. Its function is to maintain the 120/208 VAC terminal voltage under varying loads and conditions. Mounted on the voltage regulator box is the generator enable switch. When this switch is in the "on" position, it activates two relays located in a second small box called the relay box. These relays provide the required DC power to the coolant pump, the clutch, and the voltage regulator when the generator is enabled.

Table 2. Design parameters for the in-line generator (both prototypes)

Rated speed	1200 rpm
No. of poles	6
No. of slots	36
Coil pitch	2/3
Coil span	4
Magnet material	Sumitomo Neomax 28UH[1]
Magnet thickness	.68 inches
Rotor pole span	40 deg (mechanical)
Air gap length	.06 inches
Air gap diameter	12 inches
Active axial length	4.1 inches
Homopolar field coil	548 turns, 15 awg wire

The HMMWV-installable unit includes an electrically-powered clutch that allows the generator to either draw power from the drive train or to be entirely disengaged from the drive train. A shaft runs through the middle of the generator, whose function is to transfer the output engine torque from the flywheel to the torque converter. When the generator enable switch is in the "on" position, the clutch is powered, the rotor spins with the drive train of the vehicle, and electrical power generation is available. However, when the generator switch is in the "off" position, the clutch is unpowered, the rotor is disengaged from the drive train, and three braking resistors short the phases of the generator. The braking resistors are intended to prevent unintended rotation of the rotor and the resulting terminal voltage.

A coolant system is included with the unit to remove the heat produced by the generator during operation. A path for coolant flow is provided in the unit that maintains acceptable temperatures at the armature and the magnets of the generator. An external pump and air-fluid heat exchanger are provided with the generator. A water/ethylene glycol coolant that is compatible with aluminum is used.

[1] Although we did ultimately succeed in getting the Sumitomo Neomax 28UH magnets, their delivery was so delayed that we were forced to substitute a comparable material from a Chinese supplier.

Test results on the HMMWV-installable unit

Both prototypes were thoroughly tested at SatCon on the test stand shown in Figure 4, although several tests performed on the laboratory prototype were not repeated on the HMMWV-installable generator. In particular, unbalanced load tests and armature short circuit tests were performed only on the laboratory prototype. In general, the test results for the two prototypes were very similar. This was not surprising, since the magnetics designs for the two prototypes were nearly identical.

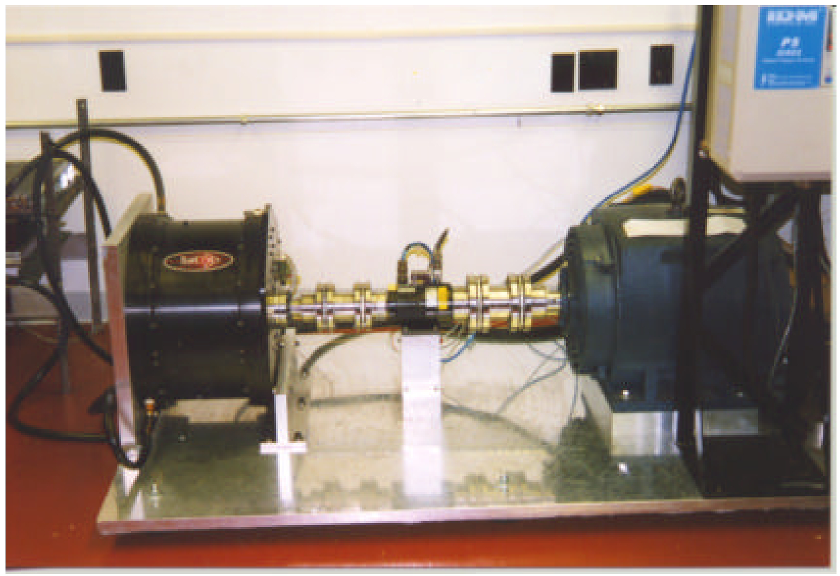


Figure 4. HMMWV-installable generator undergoing testing at SatCon

Load tests (HMMWV-installable unit)

Table 3 gives test results at 9 loaded test conditions. The first four test conditions are unity power factor loads of various magnitudes, whereas the last five are at various lagging power factors at roughly 10 kW. The total harmonic distortion ranges from 2.1-3.2%. You will note that the efficiency of the generator over all these loading conditions is between 84% and 88%, not including power consumption by the clutch, the coolant pump, and the field coil. When these powers are accounted for, overall efficiency drops a bit, falling within the range of 81% to 87%.

No-load tests

With no load attached to the terminals of the generator, the RMS phase-to-neutral voltage was 123 V at 1200 rpm with no field current. We also measured the mechanical torque to be 3 Nm when no electrical power was being drawn from the generator. At 1200 rpm this corresponds to a no-load loss of 380 W. No-load loss consists of windage, friction, and core loss.

Table 3. Measured performance of the HMMWV-installable prototype under load

Output power (kW)	Power factor	Field current (A)	Generator efficiency (%)	Overall efficiency[2] (%)	THD (%)
2.86	1	0	84.5	81.2	3.24
6.26	1	0.4	87.5	85.9	2.60
9.98	1	1.2	87.7	86.7	2.06
17.2	1	3.8	86.2	85.3	---
9.9	.975	2.1	87.4	86.2	2.13
10.	.954	2.6	87.4	86.2	2.24
9.9	.906	3.4	86.6	85.2	2.42
9.7	.860	4.2	85.8	84.1	2.56
9.6	.775	6.0	84.1	81.8	2.84

[2] Includes field coil, pump and clutch losses

Field coil tests

Based on the data presented in Table 3, Figure 5 plots both the field current and the field coil ohmic loss required to maintain 120 V phase-to-neutral as a function of electrical load at unity power factor. It is noteworthy that at unity power factor the required field coil power is only 6.2 W and 62 W at 10 kW and 17.2 kW electrical power, respectively. These values have a negligible effect on overall efficiency of the generator.

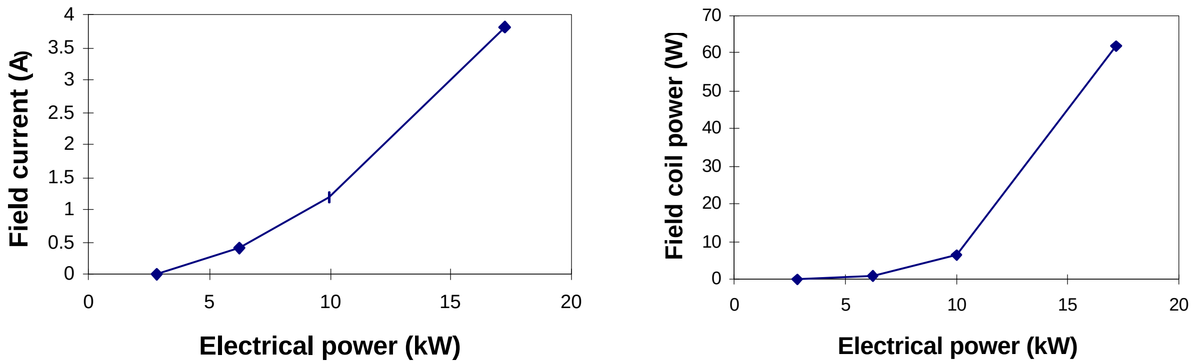


Figure 5. Required field coil current and power as a function of electrical load at unity power factor

In Figure 6 we give the field current and field coil ohmic loss as a function of the power factor when approximately 10 kW of electrical power is being drawn from the generator. Field coil power is greater at lagging power factor than at unity power factor, reaching 155 W at a .78 power factor.

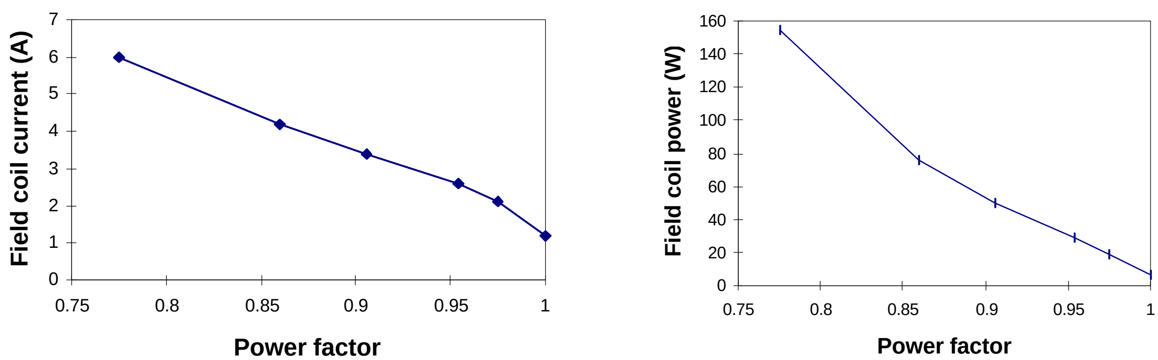


Figure 6. Required field coil current and power as a function of power factor at 10 kW electrical load

Thermal testing

In order to ascertain the heating of the generator under its most demanding load, we monitored temperatures in the armature winding, the field coil, and the coolant for a period of three hours. A small pump circulated WEG at a flow rate of 2.5 gpm through the generator and a fan-cooled heat exchanger. Figure 7 gives the temperatures indicated by thermocouples during this test. (The considerable noise in the data is caused by voltages induced by the fields within the generator, but it is easily averaged-out by eye.) The lower two traces show the WEG coolant temperature steadying out at 38 °C. The top trace and the three traces bunched together just below it give the temperature of the field coil and various locations within the armature winding. These traces show that steady state temperatures at the hottest spots within the generator all remain below 100 °C under the worst-case load of 10 kW, .8 power factor. The insulation in these windings is rated at 180 °C, so there is considerable temperature margin. Although we did not directly measure magnet temperature, our analysis indicates that the magnet temperature will be 48 °C below the armature winding temperature at a WEG flow rate of 2.5 gpm. This would suggest that magnet temperatures reached 50 °C or so during the test. Since a reasonable upper limit on the operating temperature limit for the magnets is 100 °C, there is considerable margin for operating in hotter ambient conditions.

Future applications and commercialization of the hybrid PM/homopolar generator

As discussed above, the hybrid PM/homopolar generator offers a low-loss approach to controlling terminal voltage of a PM-field alternator. The inability to control voltage has been a

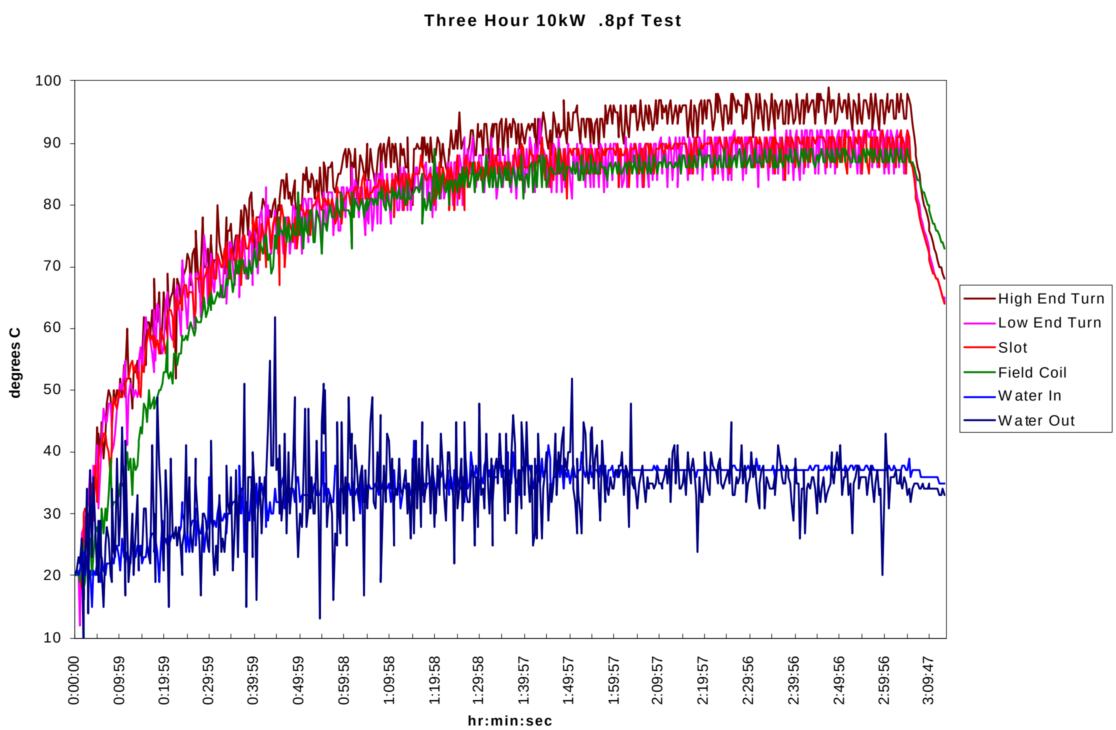


Figure 7. Measured field coil, armature winding, and WEG temperatures vs. time at 10 kW, .8 power factor

stumbling block to their application. Now that the Phase 2 has successfully demonstrated a solution to this problem, SatCon believes that PM-field alternators are a promising alternative to conventional wound-rotor alternators. This is particularly true of those applications that would benefit from the characteristics generally-attributed to PM-field alternators:

1. There is no power transfer onto the rotor, eliminating rotor windings, exciters, and brushes.
2. There are no ohmic losses on the rotor, improving efficiency and the need to aggressively remove heat from the rotor.
3. No external power source is needed to initiate the air gap field.

These characteristics suggest that a PM-field alternator is more compact, reliable, efficient, and power-dense than the equivalent wound-rotor alternator. Since the permanent magnets are not electrically powered, there is no need to provide an external power source when starting the alternator. The PM-field immediately produces sufficient voltage to self-power its voltage regulator. Perhaps the tent-pole with respect to cost of PM-field alternators in high volume is the magnets, if high energy product rare-earth materials are used. However, the manufacture of the hybrid PM/homopolar alternator is conventional in nature. SatCon believes that the hybrid PM/homopolar alternator offers a promising alternative to wound-rotor alternators for mobile and portable power generation: battlefield power, ship and submarine power, emergency vehicles, construction, and remote-site industrial power.

The hybrid PM/homopolar concept offers a practical method for field-weakening PM-field motors. This is an important feature of motors being used to power electric and hybrid electric vehicles, since it allows the motor to be wound such that its air-gap voltage at full-field reaches the maximum available voltage at base speed rather than top speed. This greatly reduces the VA-requirement of the inverter that drives the motor. However, it has been generally accepted that PM motors can not be practically field-weakened. The program has clearly demonstrated that field-weakening is a practical reality for PM-field electric machines. It remains to be seen whether the range of field adjustment necessary for motor field-weakening can be practically realized.