

# Doubly Salient Synchronous Generator for Gas Turbine Engines

David Meeker

**Abstract**—A novel generator topology with stationary field windings is proposed for use as a synchronous generator. The generator is initially intended to be directly mounted to the power turbine shaft of an aviation-class gas turbine engine. This topology also has several attributes which make it well suited to be “embedded” (integrated within) aircraft, land or sea based gas turbines onto the high or low pressure rotor shafts. In the initial application, the combination of the generator and engine forms a very compact, portable power source for applications that require power in the range of 150-300kW. A mathematical model of the machine is presented. Predicted performance is then compared to experimental results from a proof-of-concept prototype machine.

## I. INTRODUCTION

Although doubly salient machines may seem like an unusual approach to airborne power generation, they are actually a venerable approach to direct-drive power generation. “Flux switch alternators” were used to power the electronics on missiles in the 1960’s. These machines were relatively simple single phase machines, and the machines were typically excited by permanent magnets rather than a wound field. A seminal work on this sort of machine is by Rauch and Johnson [1]. The basic operational principles of the single phase flux switch alternator is pictured here as Figure 1. The rotor consists of a laminated bar of iron. As the rotor spins, it switches permanent magnet flux between the two teeth on each PM pole tip. The switching of flux reverses the direction of the flux linkage of coils wound around the pole tips, inducing a voltage in the coils.

In the 1990s, three-phase versions of the flux switch alternator were developed [2], with a layout as shown in Figure 2. These machines are now generally known as “Doubly Salient Permanent Magnet” (DSPM) machines. At about the same time, machines that either used a combination of magnets and a field winding [3] or just a field winding [4] were also proposed to allow a variable magnetizing field to be applied to the machine. These configurations placed additional field coils on the stator, either replacing the permanent magnets or supplementing permanent magnet’s MMF. However, these machines were viewed fundamentally as variants of switched reluctance motors (SRMs). With the configuration of these machines, inductance versus position is triangular and the torque versus position is flat, leading to switched reluctance-type operation. Research on DSPM-type machines continues up to the present, also considering related machines more sinusoidal back-EMF [5] and linear variants [6].

The goal of this paper is to describe a machine that is related to the DSPM by virtue of some similarities in construc-

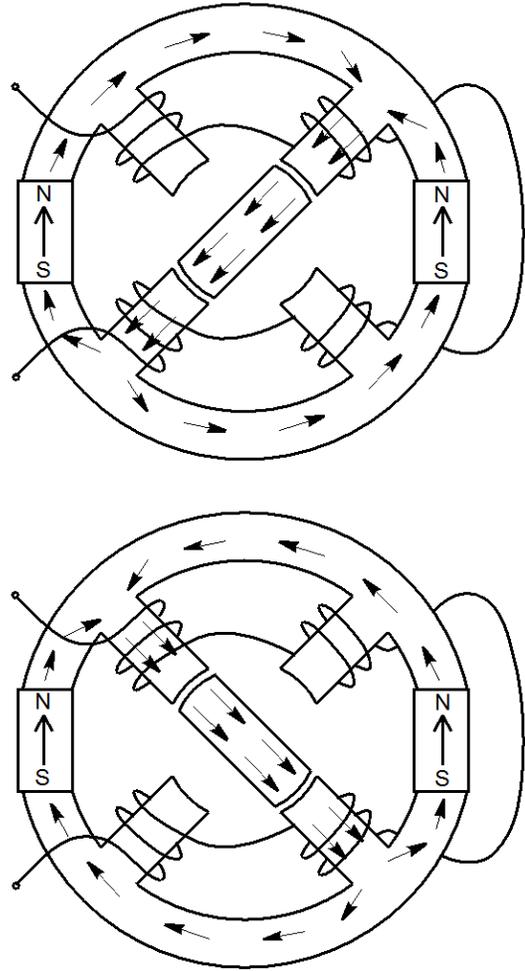


Fig. 1. Single-phase alternator schematic illustrating the flux-switch principle.

tion. The machine described in this paper is called “Doubly Salient Synchronous Machine”, because it has a doubly salient configuration similar to the DSPM, but additional features of the machine enable it to act functionally similar to a round rotor synchronous generator. This machine aims to retain the simplicity of construction of the DSPM (*i.e.* simple, laminated rotor construction and bobbin-wound coils) and modify it to obtain the good attributes of a synchronous generator (low torque ripple, sinusoidal output voltage, easy voltage regulation via field coil current). A mathematical model of the machine is developed. Then, a specific proof-of-concept design is presented, along with comparative experimental data.

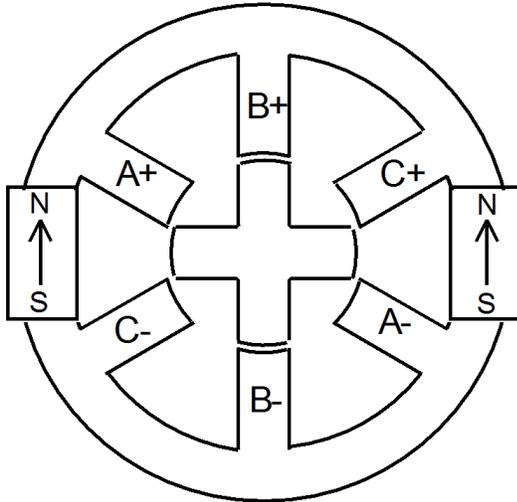


Fig. 2. Three phase "Doubly Salient Permanent Magnet" motor.

## II. MATHEMATICAL MODEL

The present machine has a structure that is superficially like the DSPM's wound field variety. The best way to understand the differences between a DSPM and the present machine is to consider a linear version of the DSPM.

Figure 3A shows the linear version of the DSPM configuration. The DSPM has two three-phase groups of poles. The total area of rotor covered by the poles in a three-phase group does not change as a function of position, but flux travels to the rotor via different poles as the rotor moves. However, the back EMF of any particular phase is not symmetric as the rotor moves, and the motor experiences a high degree of cogging due to fringing flux.

A version of the linear motor, shown in Figure 3B, that reduces cogging and creates a symmetric waveform is realized by shifting one of the three-phase groups by a further 1.5 stator tooth widths so that the two poles associated with a given phase are  $180^\circ$  out of phase (see, for example, [6]). However, there is still some cogging, and there is position-dependence to the self and mutual inductance of each phase that is not desirable (*i.e.* does not contribute to the force in a "clean" way, e.g. by adding saliency to the D and Q axes of the machine in a way that will augment force).

A third variation is shown in Figure 3C increases the width of each rotor tooth so that, in aggregate, the back EMF waveform is more sinusoidal and so that position-dependence of the self and mutual inductances is minimized. Not shown in the figure, a skew in the rotor teeth of half a stator tooth width over the axial length of the rotor eliminates the remaining fundamental component of cogging. The machine in 8C fundamentally behaves a linear PM synchronous motor rather than as a relative of a linear switched reluctance machine.

A rotating machine can be recouped by "rolling up" any of the linear configurations. It can be noted that the DSSM structure could be repeated every 15 stator tooth widths, implying the PM-excited rotating machine pictured as Figure 4.

However, for the presently considered set of applications,

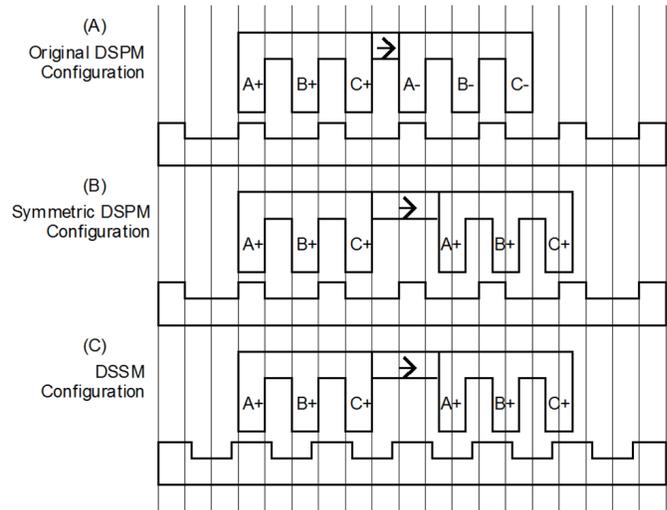


Fig. 3. Various linear configurations.

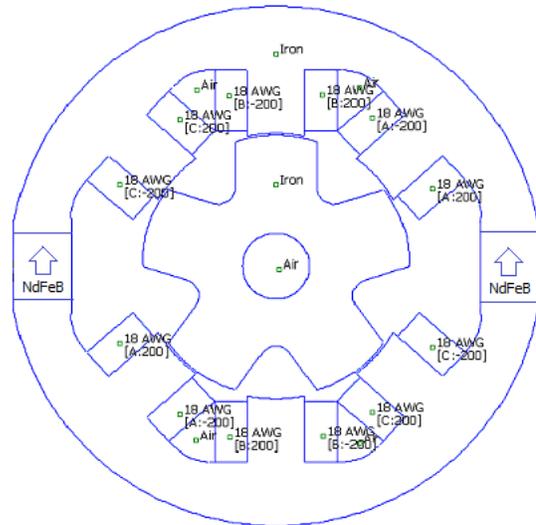


Fig. 4. Permanent Magnet 5-pole Doubly Salient Synchronous Generator realization.

it is advantageous to have a wound field rather than a PM-driven field. A wound field allows the output voltage to be precisely regulated over varying speed and load without the use of complicated power electronics. The use of a wound field allows the machine to be de-excited in the case of faults or for maintenance. A realization of a wound field machine is shown in Figure 5, where the magnets are replaced with an equivalent piece of iron wrapped by field winding turns. In Figure 5, the green lines represent the end turns connecting field coil cross-sections. Each three-phase group could be thought of as wrapped by a field coil.

### A. Unsaturated Model of 5-Pole Machine

Under highly loaded conditions, saturation in the machine cannot be ignored. However, building an unsaturated model of the machine builds intuitive understanding of the machine, allows preliminary sizing, and predicts testable quantities like

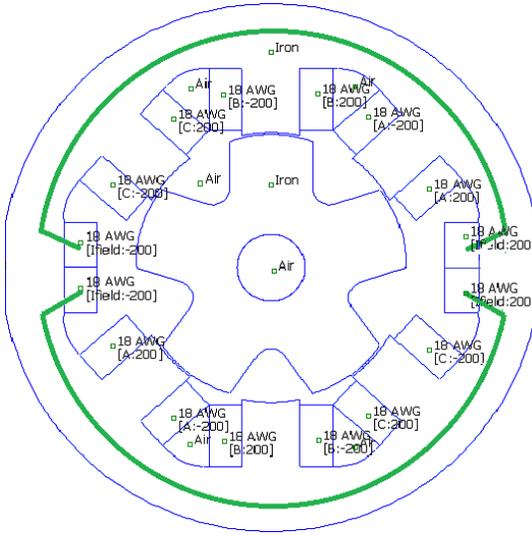


Fig. 5. Wound Field 5-pole Doubly Salient Synchronous Generator realization.

back EMF voltage. For those reasons, a linear model of the machine will be explored in this section.

For the unsaturated analysis, it is assumed that the permeability of the iron core is so high that its reluctance is negligible in comparison to the reluctance of the air gaps between the rotor and stator. With the effects of skewing and fringing, the reluctance is a relatively smooth function of position. For this analysis, it is assumed that the permanence of each stator pole air gap,  $P_g$ , takes the form:

$$P_g = \frac{\mu_o (a_o + \frac{1}{2}a_p (1 + \cos[5(\theta - \phi)]))}{g} \quad (1)$$

where  $\theta$  is an angle orienting the rotor;  $\phi$  is the angular orientation of a particular stator tooth;  $g$  is the air gap between rotor and stator tooth tips;  $\mu_o$  is the permeability of free space. As shown in Figure 5, there are teeth located at

$$\phi = [(90 - 48)^\circ, 90^\circ, (90 + 48)^\circ, (270 - 48)^\circ, 270^\circ, (270 + 48)^\circ] \quad (2)$$

When the rotor and teeth are aligned for a particular gap, the permanence is:

$$P_g|_{aligned} = \frac{\mu_o(a_o + a_p)}{g} \quad (3)$$

and when the teeth are unaligned, the permanence is:

$$P_g|_{unaligned} = \frac{\mu_o a_o}{g} \quad (4)$$

In (3),  $a_p$  represents the area of a stator pole. If  $w$  is the width of the pole and  $l$  is the axial length of the pole,

$$a_p = w * l \quad (5)$$

Area  $a_o$  accounts for leakage flux when the poles are completely unaligned. To obtain an approximate value for  $a_o$ , the ideal unaligned domain shown in Figure 6 can be considered. This domain considers an “unrolled” machine in the case where air gap  $g$  between the rotor and stator goes to zero. In the case pictured in Figure 6, there are four more or less similar

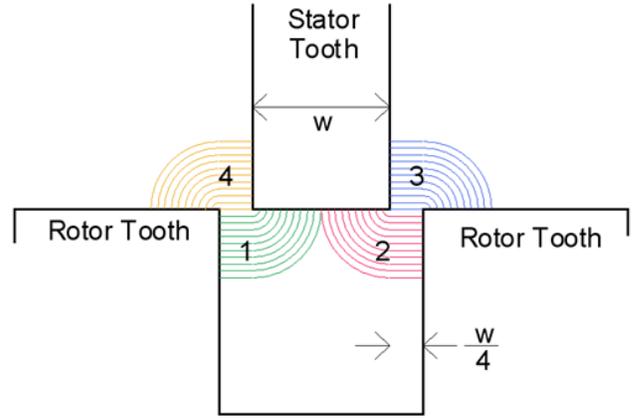


Fig. 6. Domain for Fringing Calculation.

fringing regions that encapsulate the interaction between the sides and bottom of a stator tooth and the sides and top of the adjacent rotor teeth. For a  $90^\circ$  fringing interaction like each of the four pictured in Figure 6, a rule-of-thumb for calculating fringing effects from [7] suggests a fringing permanence of  $\mu_o l$ . Since there are four such fringing interactions, the total fringing permanence is  $4\mu_o l$ . An apparent air gap area can then be determined by equating the unaligned air gap permanence with the rule-of-thumb permanence:

$$\frac{\mu_o a_o}{g} = 4\mu_o l \quad (6)$$

to yield:

$$a_o = 4gl \quad (7)$$

Once the gap permanence is defined, a magnetic circuit model, as shown in Figure 7, can be used to solve for the magnetic flux inside the generator. Figure 7 is a circuit representation of the same machine shown in Figure 5, where each phase coil has  $n$  turns and each field coil has  $n_f$  turns. Once the flux linkage of each phase is determined, the electric circuit equations of the generator can be written.

To solve for the fields in the motor, the magnetic scalar potential of the rotor,  $\mathcal{F}_r$ , must first be determined. The rotor's potential can be determined by writing and solving an equation for conservation of flux going onto and off of the rotor. Specifically, the rotor flux conservation equation is:

$$(n i_a + n_f i_f - \mathcal{F}_r) * P_{g1} + (n i_b + n_f i_f - \mathcal{F}_r) * P_{g2} + (n i_c + n_f i_f - \mathcal{F}_r) * P_{g3} + (n i_a - n_f i_f - \mathcal{F}_r) * P_{g4} + (n i_b - n_f i_f - \mathcal{F}_r) * P_{g5} + (n i_c - n_f i_f - \mathcal{F}_r) * P_{g6} = 0$$

The rotor flux conservation equation can be re-arranged to yield groups associated with each winding:

$$n i_a (P_{g1} + P_{g4}) + n i_b (P_{g2} + P_{g5}) + n i_c (P_{g3} + P_{g6}) + (n_f i_f - \mathcal{F}_r) (P_{g1} + P_{g2} + P_{g3}) - (n_f i_f + \mathcal{F}_r) (P_{g4} + P_{g5} + P_{g6}) = 0$$

The first three terms are the sums of reluctances associated with one phase from opposite sides of the stator. Because the

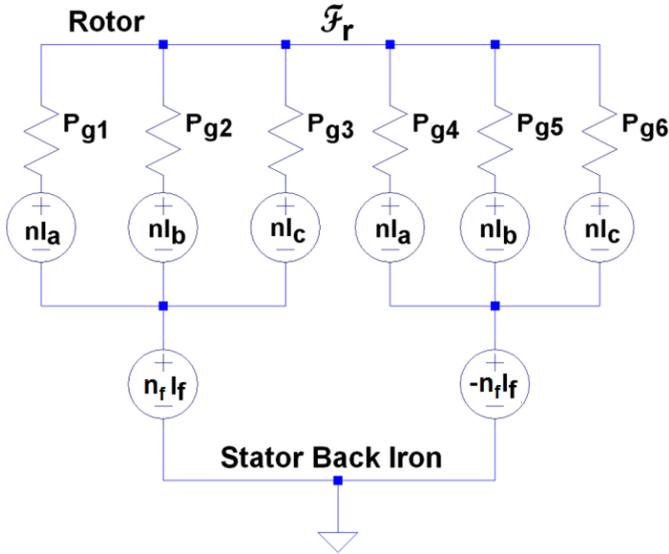


Fig. 7. Magnetic circuit model of 5-pole motor.

gaps are 180 degrees out of phase, the cosine terms cancel out in each case, yielding:

$$(P_{g1} + P_{g4}) = (P_{g2} + P_{g5}) = (P_{g3} + P_{g6}) = \frac{\mu_o(2a_o + a_p)}{g} \quad (8)$$

The cosine terms also sum to zero over each three-phase group of permanences:

$$(P_{g1} + P_{g2} + P_{g3}) = (P_{g4} + P_{g5} + P_{g6}) = \frac{3\mu_o(2a_o + a_p)}{2g} \quad (9)$$

Substituting these simplifications into the current sum equation yields the following solution for the magnetic potential of the rotor:

$$\mathcal{F}_r = \frac{1}{3} (n i_a + n i_b + n i_c) \quad (10)$$

If the windings are Y-connected as is typical for a three-phase winding, the sum of the three currents is always zero, such that:

$$\mathcal{F}_r = 0 \quad (11)$$

Since both the rotor and stator magnetic scalar potential is zero, one can consider each path essentially in isolation. For example, to get the flux linkage for the "B" phase, one can write:

$$\begin{aligned} \lambda_b &= n ((n i_b + n_f i_f) P_{g2} + (n i_b - n_f i_f)) \\ &= \frac{\mu_o n^2 (2a_o + a_p)}{g} i_b + \frac{\mu_o n n_f a_p \cos 5\theta}{g} i_f \end{aligned}$$

where  $\lambda_b$  represents the flux linkage of the B phase. A generic per-phase electric circuit equation is then:

$$\frac{d}{dt} \lambda_b + R i_b = v \quad (12)$$

Under steady-state conditions, the electrical equation can be written in phasor notation as:

$$j\omega L i_b + R i_b = v_b - j\omega M i_f \quad (13)$$

where

$$L = \frac{\mu_o n^2 (2a_o + a_p)}{g} \quad (14)$$

$$M = \frac{\mu_o n n_f a_p}{g} \quad (15)$$

$$\omega = 5 \omega_{mech} \quad (16)$$

and  $v_b$ ,  $i_b$ , and  $i_f$  represent the phase voltage, phase current and field current, respectively. Frequencies  $\omega$  and  $\omega_{mech}$  are the electrical frequency and the mechanical speed of rotation.

Eq. (13) fundamentally describes the behavior of the generator, subject to the inductance parameters defined in (14) and (15). Eq. (13) is identical to the equation for steady-state performance of a round-rotor synchronous generator.

### B. Unsaturated Model of 10-Pole Machine

Although the 5-pole machine is feasible and has a simple mathematical model, a practically undesirable aspect of the 5-pole machine is that it has unbalanced side forces. Balanced side forces can be obtained by employing four three-phase quadrants rather than only two three-phase groups, yielding the configuration pictured in Figure 8. If windings from each phase are wound in series for all four quadrants, the electrical circuit equation has the same form as (13) except that the parameters are redefined as:

$$L = \frac{2\mu_o n^2 (2a_o + a_p)}{g} \quad (17)$$

$$M = \frac{2\mu_o n n_f a_p}{g} \quad (18)$$

$$\omega = 10 \omega_{mech} \quad (19)$$

The overall electrical equation is identical; each of the inductance parameters are multiplied by 2, since there are twice as many poles, and the electrical frequency vs the mechanical speed is twice as high.

## III. PROOF-OF-CONCEPT DESIGN AND PERFORMANCE PREDICTIONS

The linear description of the machine lends insight into how the machine operates; however, at moderate and high output power levels, saturation plays a significant role in the machine's performance. It is possible to make an enhanced and more complicated version of the circuit in Figure 7 that incorporates saturation of the iron in the pole tips into the permanences. However, the geometry is also amenable to 2D finite element analysis. 2D FEA is now computationally inexpensive enough to be used as a primary design tool for this class of machine, rather than simply a design verification tool.

A proof-of-concept machine was designed using FEMM 4.2. A script was made to define a model of the machine parametrically. The parametric space was then searched for a size-minimizing design that delivers the design power to a resistive load while obeying constraints about the allowable current density in the field and phase coils, stress

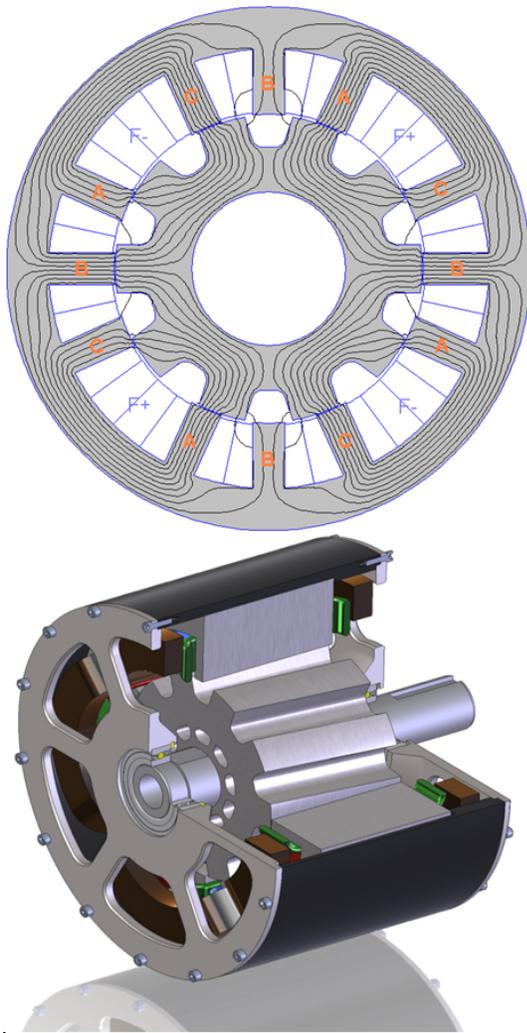


Fig. 8. DSSM with 10-pole skewed rotor.

TABLE I  
INITIAL PROOF OF CONCEPT (IPOC) MACHINE PARAMETERS.

Parameter	Value
Maximum Design Power	20kW
Desired Line-to-Neutral Voltage	240V <sub>rms</sub>
Rotor Outer Radius	3"
Stator Outer Radius	5.125"
Pole Width ( $w$ )	0.63"
Axial Length ( $l$ )	4.00"
Air Gap Length ( $g$ )	0.02"
Number of phase coil turns ( $n$ )	36
Phase coil wire size	11 AWG equivalent Litz
Number of field coil turns ( $n_f$ )	120
Field coil wire size	10 strands of 24 AWG
Rotor Skew	6°
Core Material	AK DI-MAX HF-10
Lamination Thickness	0.010"
Lamination Stacking Factor	95% stacking factor
Nominal Electrical Frequency	3770 rad/s (600Hz)

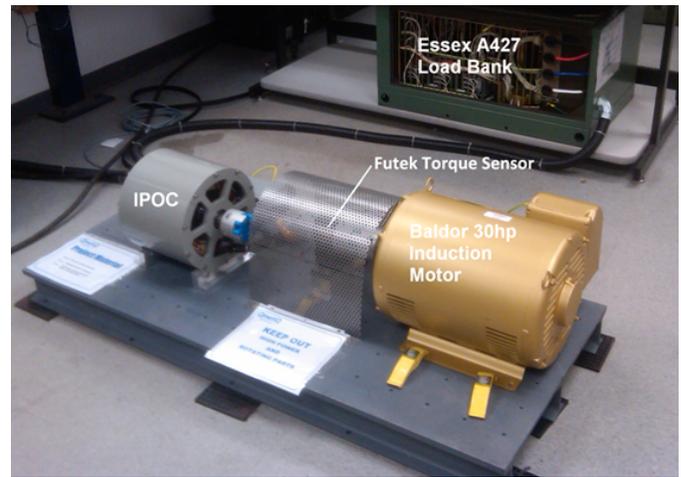


Fig. 9. Photograph of IPOC Test Setup.

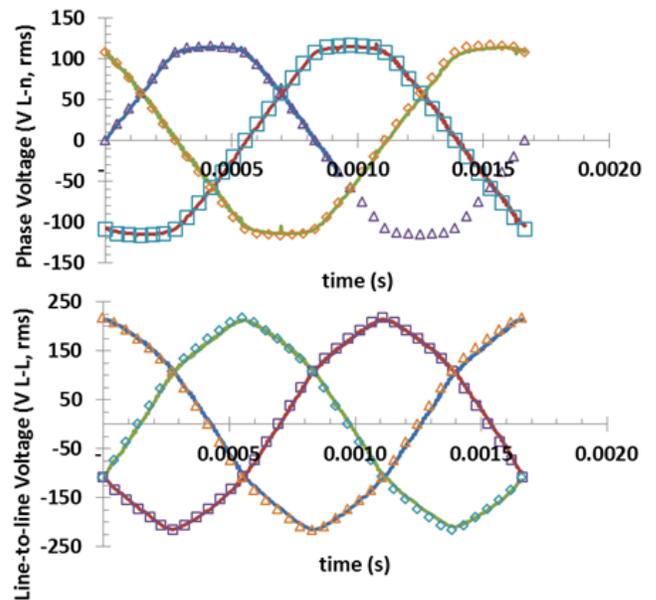


Fig. 10. No-load voltage waveforms.

in the rotor and minimum air gap. The parameters of the Initial Proof of Concept (IPOC) machine are listed in Table I.

The machine described in Table I was constructed and installed in a testbed connected to an inverter-driven 30hp 2-pole induction motor. The completed machine and testbed are pictured as Figure 9. Performance of the actual machine was then compared to predictions from finite element analysis. The predicted and measured no-load voltage waveforms resulting from a 1A current applied to the field winding at a 3600RPM mechanical speed is shown in Figure 10, where solid lines represent measured values and triangles, squares, and diamonds represent finite element predictions. Agreement of both the amplitude and harmonic content of the predicted and measured waveforms is good.

Finite element and measured no-load phase voltage versus field current was then compared. Again, a good agreement was obtained. The effects of material saturation are clearly in

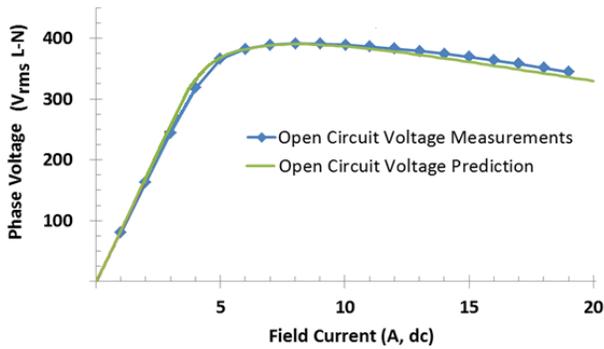


Fig. 11. No-load Phase Voltage vs. Field Current.

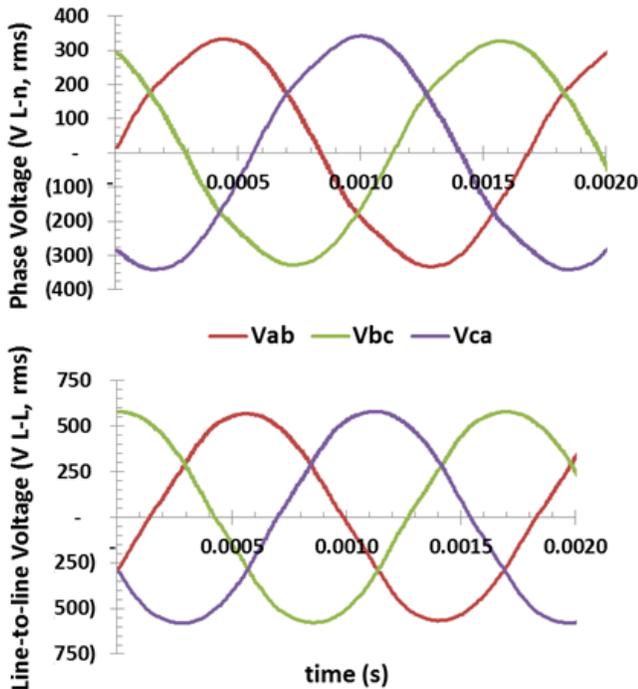


Fig. 12. Voltage Waveforms under load.

evidence. In this test, saturation limits the phase voltage for field currents greater than 5A.

Tests were then performed under load, using a wye-connected three-phase resistive load bank. At moderate loads, the waveforms are somewhat smoother than at no load. Waveforms for the machine running with at 12kW load are shown as Figure 12.

The required field current vs. load is pictured in Figure 13. Two loading conditions were considered: three-phase resistive load bank and three-phase resistive load bank in series with a  $10.8\mu\text{F}$  capacitor on each phase. In both cases, the field current was controlled to deliver a  $240V_{rms}$  voltage at the load bank. The capacitor reduces the required field current needed for a given load. The capacitors also change the loading of the iron in the generator, ultimately allowing a higher power output. Without the capacitors, output is limited to about 14kW. With capacitive compensation, the generator can run at steady-state

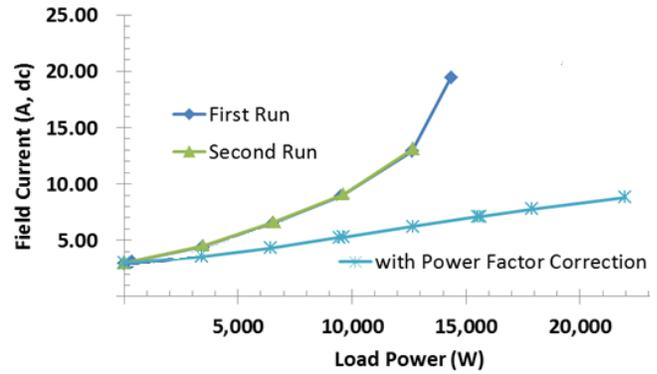


Fig. 13. Field current vs. Output Power

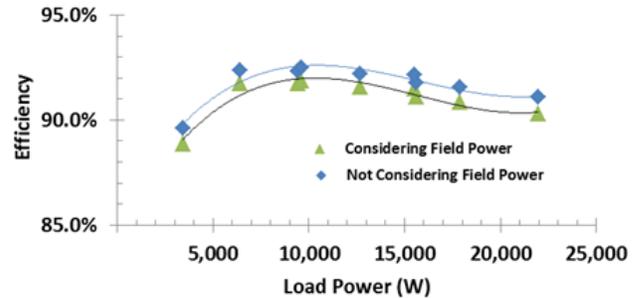


Fig. 14. Efficiency vs. Output Power.

with a 22kW output, essentially matching the 30hp steady-state capability of the testbed's drive motor. In general, the efficiency of the generator (including losses supplied to the field coil by a separate amplifier) is around 90%, as shown in Figure 14.

#### IV. CURRENT WORK

A higher power prototype machine is presently under construction (see Figure 15), but data on the machine's operation is not available at present. This machine, spinning in excess of 30kRPM, is intended to supply up to 150kW to a 600Vdc load bank. The machine is mechanically configured to allow eventual direct integration onto the power turbine spool of a small dual-spool gas turbine engine. Based on a 150kW output and the machine's electromagnetic mass (*i.e.* mass of rotor and stator laminations and windings), the machine's expected power density is 7 kW/kg. For comparison, the power density of an aggressively designed, liquid-cooled switched reluctance motor of a similar output and speed (also based on electromagnetic mass) is reported in [8] as approximately 9 kW/kg.

#### V. CONCLUSIONS

The background, modeling, and proof-of-concept implementation of a "Doubly Salient Synchronous Generator" have been reviewed in this document. The machine has a construction reminiscent of a switched reluctance machine (*i.e.* no magnets; toothed rotor; concentrated, bobbin-wound coils), but

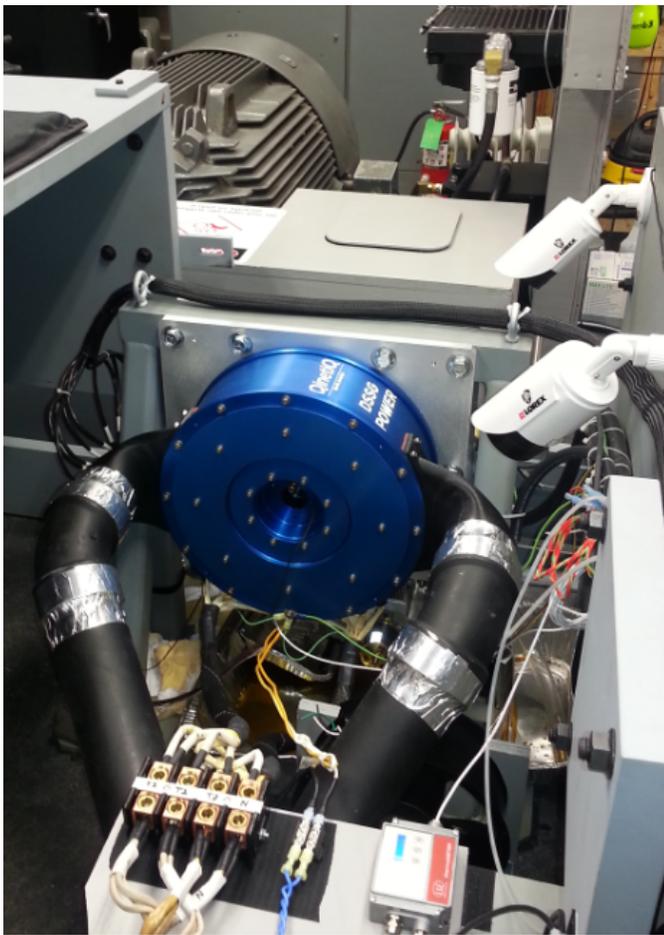


Fig. 15. High speed generator testbed.

the machine has electrical characteristics similar to a round rotor wound field synchronous machine. However, unlike a wound field generator, all field windings of the DSSG are located on the stator. Experimental data shows a good match between mathematical models of the machine and experimental data.

Because the machine has a simple, robust construction and because the machine is straightforward to control as a generator, the machine is suitable for direct integration into a gas turbine engine with the goal of creating a compact, portable power supply. A second prototype machine running at gas turbine engine-representative speeds and power levels is nearing completion, but experimental results are not available at present.

However, applications for this class of machine are not limited to high speed generator applications. Specifically, the machine has attributes that may be beneficial for electric vehicle applications. EV applications usually need the highest torque at low/no speed. At higher speeds, the motor is essentially a constant power device, producing less torque as speed increases. To reduce inverter requirements, it is beneficial to turn down the field at higher speeds, lessening the required voltage. Since the proposed machine is excited by a field winding, naturally supports field weakening. The machine's simple, robust design would also be a benefit for the rugged

environment associated with electric vehicles. More generally, the machine could be used as a replacement for PM servo motor or brushless DC PM motors, running off the same drive electronics as is used for PM motors.

#### REFERENCES

- [1] S. Rauch and L. Johnson, "Design principles of flux switch alternators," *Transactions of the AIEE, Part III, Power Apparatus and Systems*, 74(3):1261-1268, Dec 1955.
- [2] Y. Laio, F. Liang, and T. Lipo, "A novel permanent magnet motor with doubly salient structure," *IEEE Transactions on Industry Applications*, 31(5):1069-1078, Sep/Oct 1995.
- [3] Y. Li and T. Lipo, "A doubly salient permanent magnet motor capable of field weakening," 26th Annual IEEE Power Electronics Specialists Conference, Jun 1995.
- [4] F. Liang and T. Lipo, "A new variable reluctance motor utilizing an auxiliary commutation winding," *IEEE Transactions on Industry Applications*, 30(2):434-432, Mar/Apr 1994.
- [5] Y. Wang and Z. Deng, "Comparison of hybrid excitation topologies for flux-switching machines," *IEEE Transactions on Magnetics*, 48(9):2518-2527, Sep 2012.
- [6] M. Cheng et al., "A linear doubly salient permanent-magnet motor with modular and complementary structure", *IEEE Transactions on Magnetics*, 47(12):4809-4821.
- [7] M. A. Plonus, *Applied electromagnetics*, McGraw-Hill, 1978.
- [8] A. Radun, "Design considerations for the switched reluctance motor," *IEEE Transactions on Industry Applications*, 31(5):1079-1087, Sep/Oct 1995.