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***Abstract-* This paper presents the principles of operation, design and transient analysis of a newly developed Single Phase Doubly Salient Permanent Magnet (DSPM) generator. Design equations, finite element, and dynamic analysis of the new generator are described. The single phase DSPM generator has an extremely simple structure with two permanent magnets and four poles wound equipped with armature windings. The rotor of the variable reluctance machine has six poles and is laminated iron without windings. Both stator and rotor have a salient pole structure. Hence, the machine has the inverse geometry of recently reported three phase DSPM motor topologies.**

I. INTRODUCTION

Doubly salient structures for alternators which are termed as homopolar inductor alternators have attracted attention in the past for high speed or high frequency applications. These homopolar inductor alternators can be categorized into two groups. The first group has singly salient machines with conventional sinusoidally distributed stator windings. A typical example for this group is the Lundell generator which is in common use in automobile charging systems. The second category includes doubly-salient alternators which have concentrated, short-pitched stator windings wound around magnetic poles. This type of alternator is sometimes used in high frequency, high speed applications such as aircraft use but is a less developed family of homopolar machines.

In a recently reported paper on Doubly Salient Permanent Magnet (DSPM) motor topologies, it has been shown that by introducing permanent magnets in the doubly salient structure of Variable Reluctance Machines (VRM), a new motor geometry can be realized [1]. This topology appears to afford the possibility of improved performance in terms of torque production and higher efficiency when compared with induction or variable reluctance machines.

The objective of this paper is to present a newly-developed single phase/two phase doubly salient single phase generator wherein the field excitation is again supplied by permanent magnet installed in the stator yoke. It is also possible to use an auxiliary winding wound around the yoke to provide for additional excitation.

II. GENERATOR CONFIGURATION

Fig. 1 illustrates a basic 2-phase, 4/6 pole DSPM generator of the type revealed in this paper. It can be noted that the stator of the DSPM generator has four poles. Two permanent magnets are placed inside the stator yoke to provide field excitation for generator action. Permanent magnets are made of high energy density material with linear demagnetizing characteristic such as that of a rare earth material. For proper operation, permanent magnets are to be chosen so that they can, if necessary, sustain the magnetization and demagnetization of the armature reaction. The rotor of the basic generator has six poles. Since there is no winding on the rotor, the structure is clearly very simple and the rotor inertia is small. It can be observed that the six rotor/four stator pole arrangement is effectively the inverse of the four stator/six rotor pole configuration recently reported for motor operation [1]. However, the operation of this machine, being essentially a single phase machine, is substantially different than previous DSPM motor topologies.

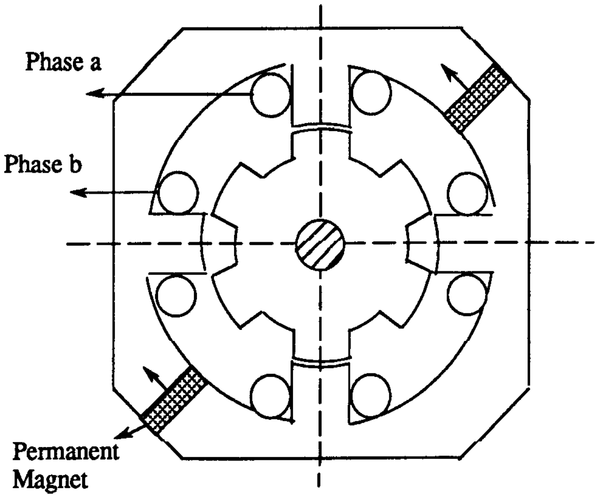

Fig. 1. Magnetic Structure of Doubly Salient Single Phase Permanent Magnet Generator.

It can be noted that since both stator and rotor arc are chosen to be same length, ($\pi/6$ radians), the air gap reluctance seen by the magnet, which contributes the most reluctance, is invariant with rotor position. Therefore, assuming PM flux linkage varies linearly at no load, the voltage induced in the stator windings are trapezoidal. When machine is loaded, armature reaction occurs. This phenomena causes the flux to circulate through the companion overlapped pair as can also be seen in finite element flux contour plots in the forthcoming sections. Consequently, the active stator phase winding has a minimum inductance for a given active stator phase winding occur at both *aligned* and *unaligned* rotor positions. The maximum inductance occurs when the poles are *half-overlapped* as shown in Fig. 2.

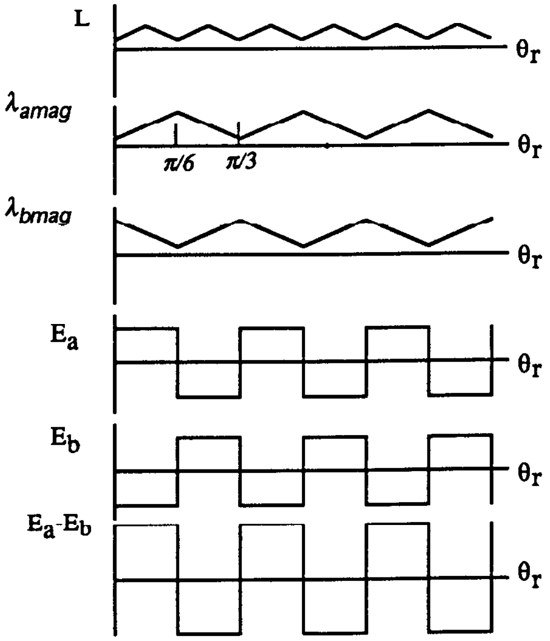

Fig. 2. The phase inductance and permanent magnet flux variations with respect to rotor position. From top to bottom: L - inductance of phases a and b, λ_{amag}, λ_{bmag} - magnet flux linking a and b phases, E_a, E_b - emfs induced in a and b windings.

It will be assumed that, for simplicity, the rate of change of the winding inductance and the PM induced flux of a given active stator phase winding are piece-wise linear and spatially dependent only. This first order approximation is shown in Fig. 2 . Because of the overlapped poles, the inductance of each of the windings rises and falls twice during each rise and fall of the magnet flux linking the windings. Note from Fig. 1 that the machine has two independent phases. Fig. 2 shows a plot of the flux linking the stator phase windings showing the magnet flux linkages with each of the two phases. It can be further noted that the flux linking one of the phase rises (falls) while the flux in the other phase falls (rises). Hence, the emfs induced in the two windings are 180° out of phase. Consequently, if these two windings are connected in series such that their emfs polarities add, a simple single phase generator with a square wave emf can be constructed. This type of waveform is clearly ideal when such a generator voltage is rectified since the output voltage of a rectified square wave is a dc voltage with (ideally) no ripple. An illustration of the rectified system configuration is shown in Fig. 3.

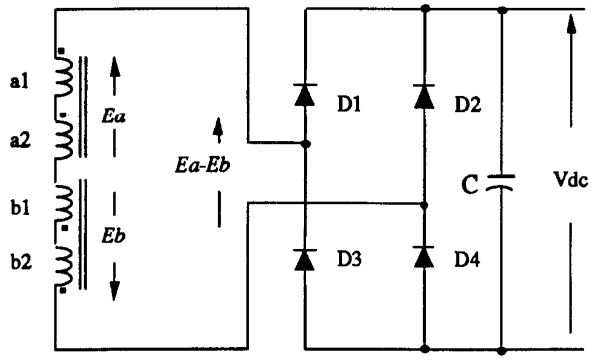

Fig. 3. Generator Phases and Bridge Rectifier Configuration

III. DESIGN

A DSPM generator is designed to evaluate generator performance and to extract important quantities such as the minimum and maximum inductance. A summary of the important required input design parameters as well as output quantities for the design program are given in TABLE 1.

TABLE 1. Data Sheet for the DSPM generator design program and FEM analysis.

MAIN DIMENSIONS & OTHER REQUIRED DATA

Stack length	:	120 mm
Stacking factor	:	0.9
Airgap length	:	0.6 mm
Stator pole arc	:	30 degrees
Rotor pole arc	:	30 degrees
Stator outer diameter	:	200 mm
Stator inner diameter	:	101 mm
Stator tooth length	:	34 mm
Rotor tooth length	:	15 mm
Stator tooth width	:	26 mm
Rotor tooth width	:	26 mm
Mean length of stator length	:	370 mm
Number of turns/phase	:	24
Remenance flux of permanent magnet	:	1.1 T

GENERATOR ELECTRICAL DATA

Rated current	:	150 A
Rated voltage	:	25 V
Open circuit voltage	:	75 V
Frequency	:	360 Hz.

CALCULATED MOTOR PARAMETERS AND OTHER IMPORTANT OUTPUTS

Stator wdg. resistance: 0.0068 ohms at 100 degrees Celsius
Minimum inductance : 3.01 mH
Maximum inductance : 5.87 mH
Efficiency(%) : 89.3
Copper losses : 157.6 W
Iron losses : 931.7 W
Mechanical losses : 187.1 W

IV. FINITE ELEMENT ANALYSIS

To predict the instantaneous and steady state performance, the DSPM generator has been analyzed by using MSC/EMAS, an electromagnetic finite element analysis package. A zero magnetic vector potentials were imposed as a constraint on the outer grids of the stator. In two dimensional finite element methods, following assumptions are made;

1) Only a z-component of magnetic vector potential is non-zero while x and y components are zero. Thus the magnetic flux density has two non-zero components. (Bx and By),
2) The current density is uniform within the armature conductors,
3) Because of low operating frequency, displacement currents are negligible,
4) The eddy (induced conduction) current in the iron is ignored because of the high resistance of the steel laminations in the axial directions,
5) The permeability of the core is isotropic,
6) The effect of the pins, holes and other manufacturing effects are ignored.

A) DSPM Generator Materials

The rotor and stator laminations are assumed to be made of M36 Electrical Grade steel. The slots and airgap have a relative permeability of 1. The relative permeability of the permanent magnets is assumed to be 1.05 with a coercive force of 800,000 A/m.

B) DSPM Windings and Excitation.

Each pole has one winding with 24 turns of copper wire. Each winding can be considered as having two slots having positive and negative current. The windings are connected in series such as one phase is supporting the flux due to the permanent magnet while the other phase is opposing the flux due to the permanent magnet. This sequence depends on the position of rotor with respect to stator (i.e. entering or leaving). FEM analysis was carried out for different rotor angles ranging from full-alignment to full-misalignment. The full-alignment of the rotor is assumed to occur at 0 degrees while the full-misalignment occurs at 30 degrees. Note that the solution of one pole flux for the case where the rotor leaves the stator will be the same as for the solution of the adjacent pole for the case the rotor comes towards to the stator.

For each rotor position, five different excitation cases were simulated, no load, 30 A, 90A, 120A, and 150A. Based on the solutions, the flux distribution and other important physical quantities were obtained.

C) Flux distribution and Magnetic Flux Density

Contour plots of the field variable magnetic vector potential A are extremely useful in analyzing and visualizing the magnetic field inside a machine. The flux density distribution gives details on the degrees of magnetic saturation, fringing as well as demagnetization. A flux plot of the DSPM generator for the 15 degree rotor position under no-load and full-load condition are shown in Fig. 4 and Fig. 5 as an example. It can be observed from these plots that the flux is mostly concentrated at the stator-rotor teeth overlap region.

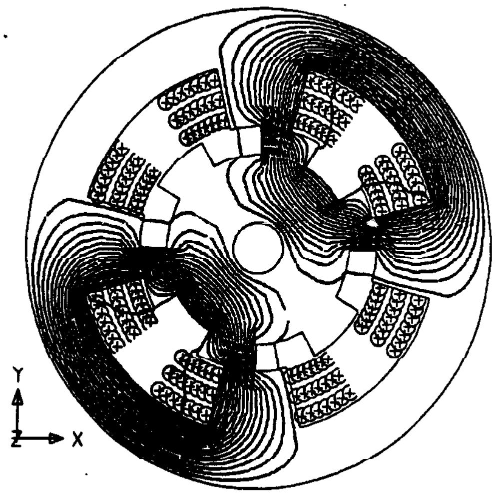

Fig. 4 Flux Plot for No Load Condition at Half Aligned Rotor Position.

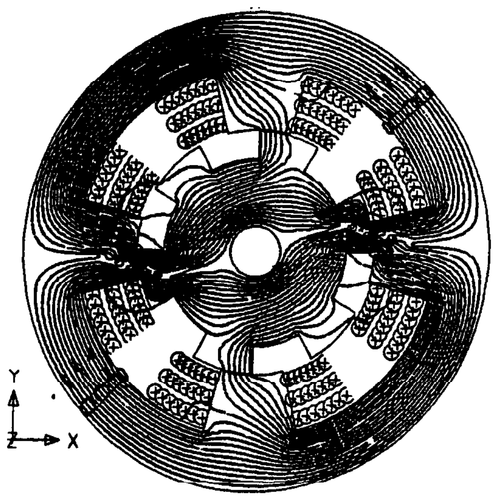

Fig. 5 Flux Plot for Full Load Condition at Half Aligned Rotor Position.

Detailed studies of the magnetic flux linkage as a function of rotor position and current in the windings have been carried out using the finite element method and the results are shown in Fig. 6. Fig. 6 shows the variation of flux linkage with respect to the armature current for a pole where the rotor teeth is arriving and leaving this particular stator tooth. It can be observed from these plots that the flux on the poles experiences an armature reaction effect. As the stator and rotor poles becomes misaligned, the maximum saturation occurs at the pole tips. Therefore, flux reverses on the adjacent pole. From finite elements, the flux variation within the permanent magnet has been investigated and it has been found that demagnetization is not severe (up to 10% flux change occurs for full load armature current).

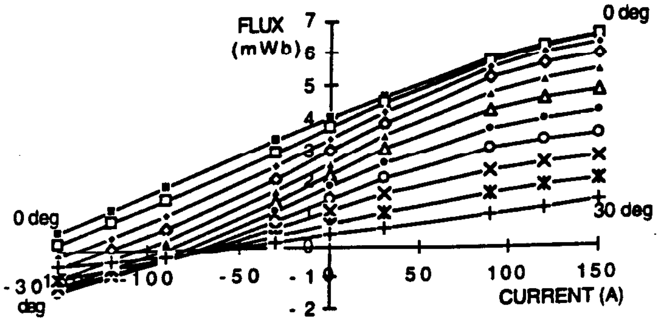

Fig. 6. Variation of Flux Linkage of One Armature Phase with Respect to Phase Armature Current and Rotor Position.

V. DYNAMIC SIMULATION

A) *Power Production of the DSPM generator*

The newly developed single phase permanent magnet generator presented above has been simulated to evaluate its dynamic performance. In the simulation, the variation of the armature winding inductance and permanent magnet induced flux linkage are assumed to be piecewise linear and spatially dependent only. However, as future work these simulations will also be carried out by using the nonlinear variations of the flux linkages obtained from finite element results. By realizing the fact that the armature winding inductance is a function of both rotor position and armature current, it is possible to express the terminal voltage equation as,

$$e = \frac{d\lambda}{dt} = v + R\,i \qquad (1)$$

where the e is the armature induced emf, v is the terminal voltage. λ is the total flux linkage. R is the phase resistance and i is the a.c. current

The total flux linkage λ is the sum of the permanent magnet induced flux linkage λ_{mag} and the armature reaction flux linkage ($-Li$). Assuming that positive current flows from the armature to the supply

$$\lambda = \lambda_{mag} - L\,i \qquad (2)$$

Therefore, the armature induced emf becomes

$$e = \frac{d\lambda}{dt} = \frac{d\lambda_{mag}}{dt} - L\frac{di}{dt} - i\frac{dL}{dt}$$

$$= E - L\frac{di}{dt} - i\frac{dL}{dt} \qquad (3)$$

Finally, the terminal voltage is

$$v = E - L\frac{di}{dt} - i\frac{dL}{dt} - Ri \qquad (4)$$

The dynamic simulations are carried out by using the parameters obtained from the magnetic design. The back emf due to the permanent magnets is taken as 75 V, while minimum and maximum inductance are 0.3 and 0.567 mH respectively.

B) *Dynamic Simulation with Diode Bridge Rectifier*

As shown in Fig. 3, one means of utilizing a.c. terminal voltage of the generator is to use a bridge rectifier connected to a DC voltage bus. In this configuration, the two phases of

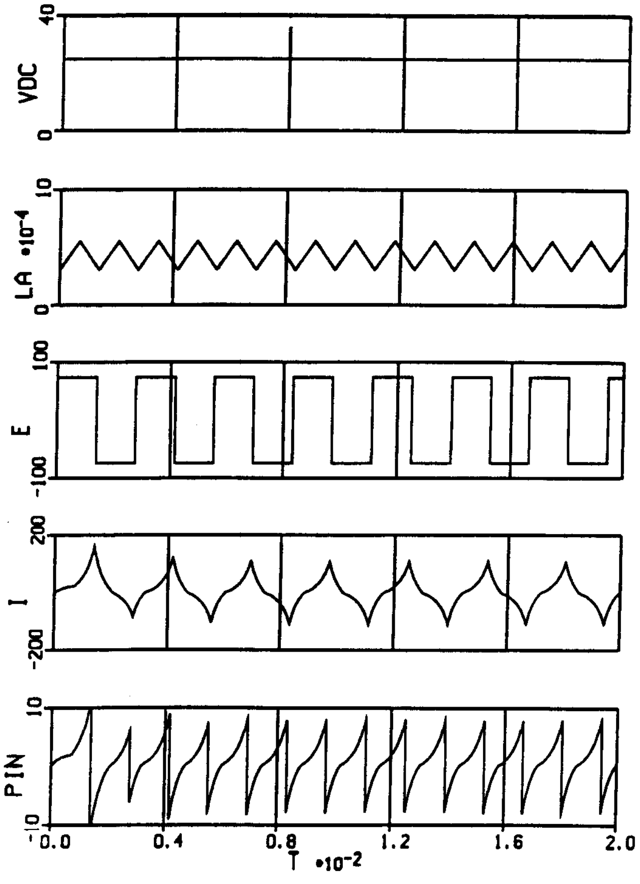

Fig. 7. Simulation results for bridge rectifier connected to a DC voltage link. From top to bottom: Vdc - dc link voltage, E - no-load emfs induced in a and b windings, I - armature phase current, Pin - input power component due to permanent magnets.

the generator are connected in series in such a manner so that their emfs are additive. Assuming the output voltage of the rectifier (25 V.) is kept constant by a large capacitor in parallel (DC voltage link), an ac armature current governed by Eqn. 4 will flow. If the armature current is positive diodes D1 and D4 conduct, if negative, diodes D2 and D3 conduct.

In Fig. 7, the waveforms of typical parameters as well as current and input power are shown. As it can be seen the current has considerable ripple. This type of waveform for current is typical in doubly salient structure due to the inductance variation with respect to rotor position and current. However, the generator can clearly produce a substantial amount of power.

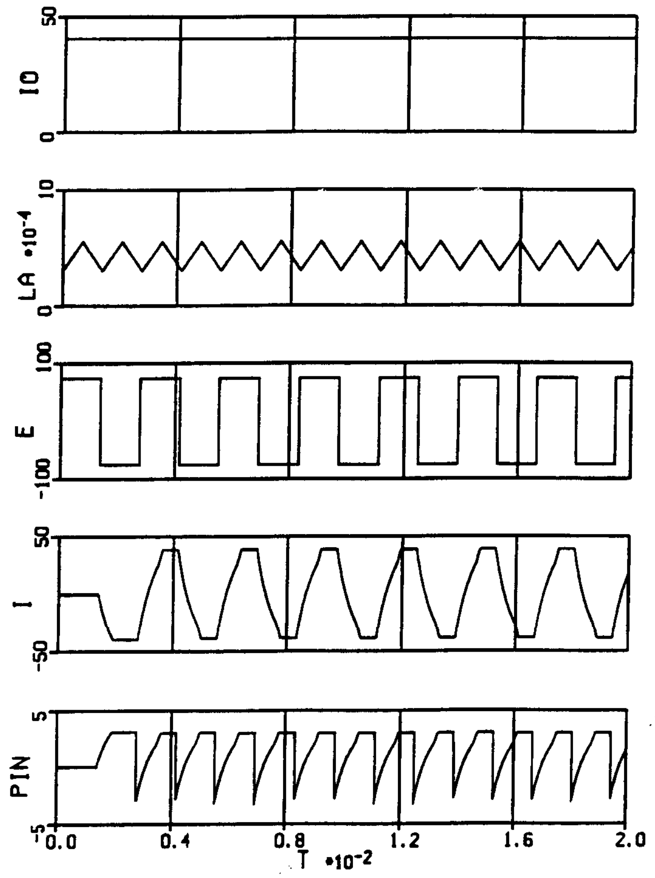

Fig. 8. Simulation results for bridge rectifier connected to a DC current link. From top to bottom: Io - dc link current, La phase inductance, E - no-load emfs induced in a and b windings, I - armature phase current, Pin - input power component due to permanent magnets.

Fig. 9 shows three additional modes of operation. In Fig. 9a the voltage link has been replaced by a DC current link. In this case the waveforms are more square wave in nature and the output power has been increased as noted in Fig. 8.

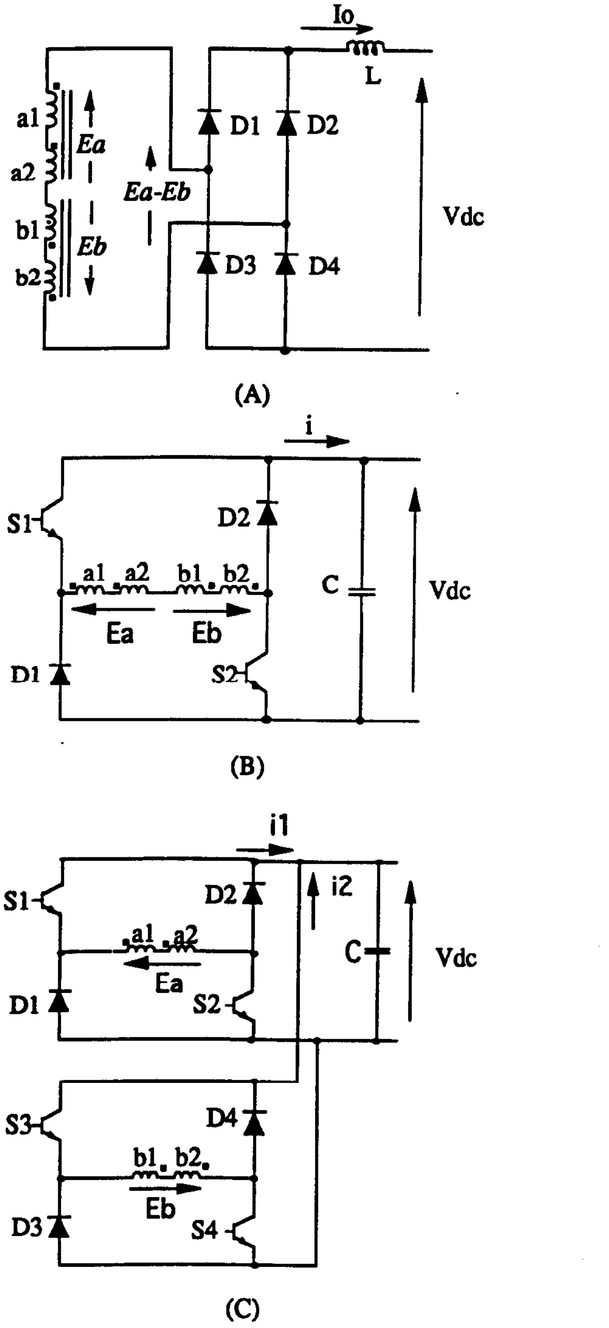

Fig. 9. Proposed different power electronic circuits for utilizing the a.c. terminal of the generator.

A - Diode bridge rectifier configuration with a constant DC link current

B - Two switch converter with PWM control

C - Two PWM converters in parallel configuration

C) Dynamic Simulation with Pulse-width Modulation

One means of reducing the ripple content of the armature current is to shape the current to a square wave waveform by means of pulse width modulation as shown in Fig. 9b. A reference current waveform with a hysteresis band is used to shape the current to square wave form. As long as the current is lower than the upper limit of the hysteresis band, active switches are kept turned-on, otherwise turned-off enabling the diodes to conduct. This sequence repeats itself for positive and negative cycles of the armature current. As in bridge rectifier configuration, the two phases of the generator are connected in series where their emfs adds up. Also the output of the rectifier is assumed to be constant, but in order to achieve PWM control output dc voltage should be greater than the positive magnitude of the no-load voltage of the generator. Eqn. 4. is used as well in conjunction with the pulse-width modulation technique.

In Fig. 10, the results of the PWM control are shown. As it is seen the armature current has low ripple and is essentially in phase with the internal emf of the motor

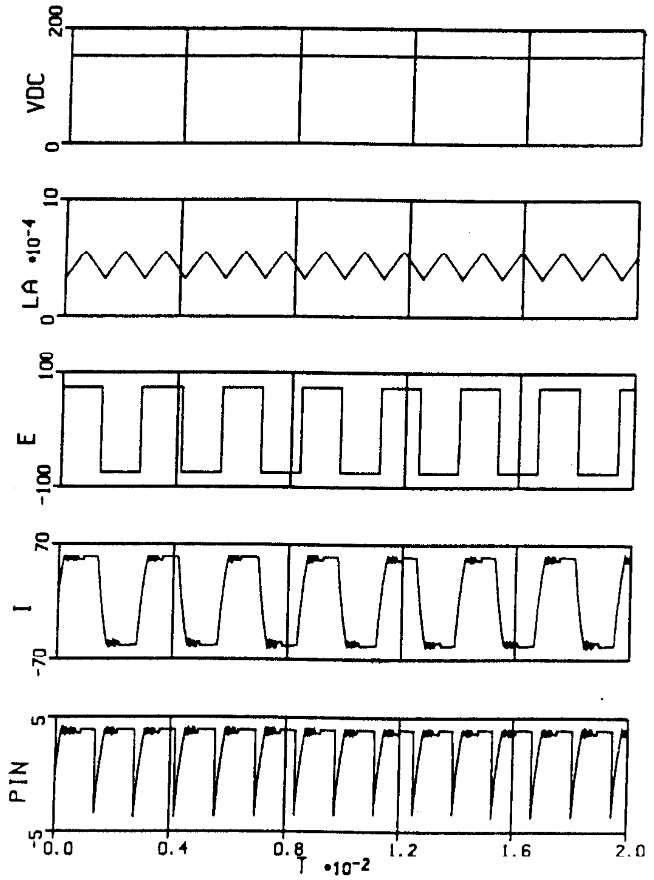

Fig. 10. Simulation results for two switch PWM modulated converter. From top to bottom: Vdc - dc link voltage. La - armature inductance of one phase, E - no-load emfs induced in a and b windings, I - armature phase current, Pin - input power component due to permanent magnets.

Another option for utilizing the output of this generator is to use two pulse-width modulated converters, one for each phase as shown in Fig. 9c. This type of configuration provides the possibility of controlling the operation of the each armature winding independently, hence operating the generator and converter combination more optimally. Since the currents in this mode of operation are unidirectional, only two active switches and two diodes for each phase can achieve this type of control. This concept stems from the fact that as finite element work shows, the flux linkage variation is nonlinear and a certain operation area on flux linkage vs. current curve provides an optimized generator energy output. Fig. 11 shows the results for this mode of operation. Note that less torque pulsation occurs with this mode while the current again is in phase, and has the same shape as the emf.

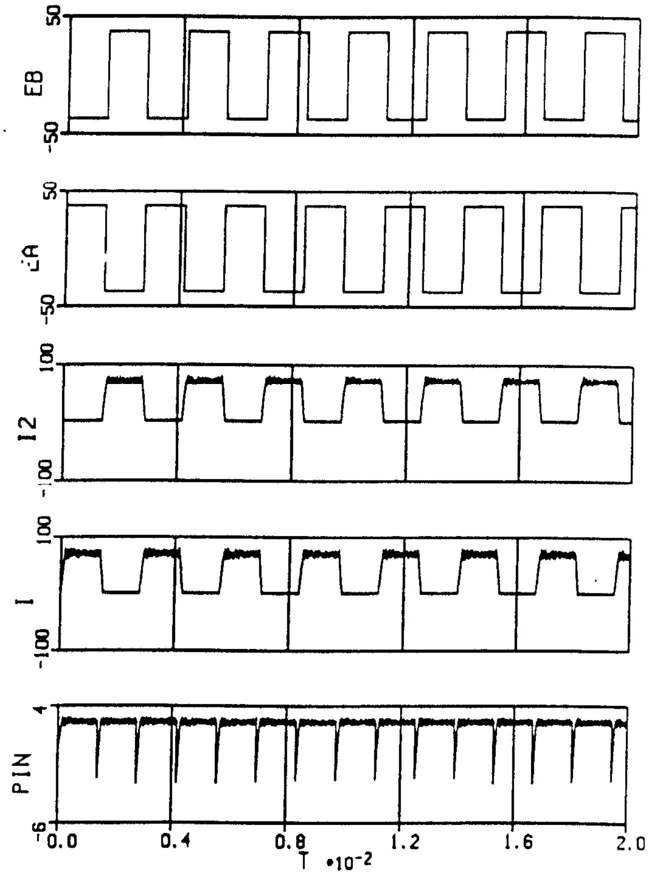

Fig. 11. Simulation results for two PWM converters in parallel configuration From top to bottom: Ea, Eb - no-load emfs induced in a and b windings, I and I2- armature phase currents for phase a and b, Pin - input power component due to permanent magnets.

VI. CONCLUSION

In this paper, the design, finite element, and nonlinear analysis of a newly developed single phase square wave generator have been presented. This generator has a very simple magnetic structure which is amenable for low cost manufacturing. By utilizing high density permanent magnet, it has been shown that power generation can be obtained without the excitation penalty of a variable reluctance generator.

The DSPM generator has the advantages summarized below:

- High power output and efficiency.
- No rotor windings, thus low inertia and no loss component in the rotor.
- Simple structure and no electrical field excitation.
- Nearly optimal waveform for use in conjunction with a diode bridge or PWM two switch converter for a dc power supply.

Work is proceeding on the construction of this machine and will be reported in a future paper.

VII. ACKNOWLEDGMENT

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