Research Report

95-18

A Novel Doubly Salient Permanent Magnet Generator Capable of Field Weakening

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A NOVEL DOUBLY SALIENT PERMANENT MAGNET GENERATOR CAPABLE OF FIELD WEAKENING

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Abstract—Applications of permanent magnet (PM) machines are increasing due to concerns over efficiency. However, the operating speed range in many potential applications require operation over a wide "constant power" speed range. However, the constant power range is very limited due to the difficulty of achieving field weakening in PM structures. Also in electrical power generation systems, the capability of field-adjustment is also required not only for wide speed range but also for absorbing reactive power from utility. A new generator topology is proposed in this paper which offers a low cost realization of field weakening in a doubly salient PM structure. It is shown that the air gap flux linkage produced by the permanent magnets can be reduced to zero with 60-90% of the rated field current ampere turns. Hence, machines of high efficiency throughout a field weakened speed range exceeding 5 to 1 can be readily obtained.

I. INTRODUCTION

The advent of modern permanent magnets (PMs) especially the NdFeB rare earth PM has greatly changed the direction of the development of electric machine design topologies. Many machine structures employing PM excitation have been developed to obtain high efficiency and power density in industrial applications. However, not many of the available PM structures have been used commonly for applications that require a wide speed range because of the difficulty of field weakening and comparatively high PM material cost in these electric machines. For this reason, the conventional wound field synchronous generator remains predominant in electrical power generation in all types of applications due to its feasibility of field-adjustment, which makes this type of generator capable of regulating terminal voltage and absorbing reactive power from utilities and hence improving system quality. It is clear that the capability of field weakening for PM structures becomes crucial for generator applications.

It has recently been established that doubly salient PM (DSPM) structures possess the capability for higher power density and more robust mechanical configuration than conventional machines [1-3]. The previous doubly salient PM generator design [1] has the advantages mentioned above. However, field weakening capability is absent from this design and the use of rare earth PMs is preferred in this configuration which leads to a relatively high cost for the machine materials.

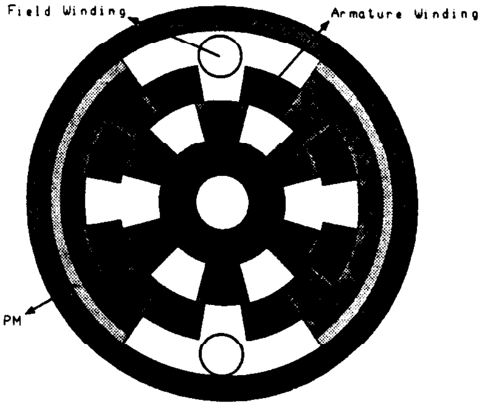


Fig. 1 Structure of the proposed FWDSPM generator

A new type of doubly salient PM generator capable of field weakening (FWDSPM) is proposed in this paper (see Fig. 1). The design not only maintains all the advantages of the previous design but also solves its structural problems. The new achievements are listed as follows:

A. A round cylindrical machine is achieved by the special arrangement of permanent magnets. This arrangement allows much more magnet area, thus permiting the use of ferrite PM materials which have far lower cost, less sensitivity to demagnetizing effect and wider range for field flux control as compared to rare earth magnets. Since the permanent magnets are buried in the stator, the leakage flux will also be less than in pervious designs.

B. The stator has only two windings. One is the armature winding which functions in the same manner as an armature winding in a conventional 4/6 pole switched reluctance machines (SRM), the other one is the field winding which is always coupled with the main flux path of the machine. The field winding has two functions:

a. When this winding is excited, it can be used to produce necessary magnetizing or demagnetizing ampere turns to boost or weaken the existing field that is established by permanent magnets.

b. When not excited, this winding could be used to detect the rotor position by measuring the voltage induced in the winding by the variation of the flux linking the winding by armature coils, as a function of rotor angle. Using this feedback, a sensorless or encoderless control could be achieved, although further work is required for substantiation.

By controlling the field winding, field weakening (or boosting) capability can be easily obtained since the PM reluctance seen by the field winding is much smaller than that in previous designs due to the special arrangement of the permanent magnets.

C. The self inductance waveform has the same frequency as that of the variation of the PM flux linkage which leads to the possibility of cancellation of the reluctance torque for normal speed operation. This result guarantees much smoother torque production and less current ripple than in other doubly salient structures.

II. OPERATING PRINCIPLE AND CONTROL TOPOLOGIES

Two operational modes of the FWDSPM generator can be investigated: one is "Bi-directional mode" (BDM) and the other one is "Unidirectional mode"(UDM). Figure 2a-2b and Fig. 3a-3b show the winding connections and the control topologies respectively.

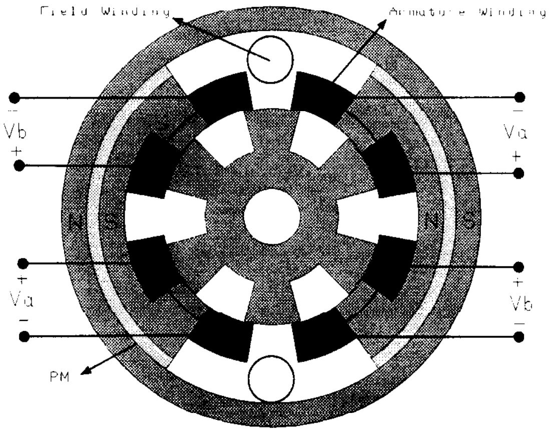


Fig. 2a Winding connection of FWDSPM generator (BDM)

As shown in Fig. 2a, BDM is based on that the two pole windings under one piece of PM are connected as one phase which causes a double frequency variation of self inductance compared to that of the PM flux and no mutual inductance should be considered. In this case, the phase current is bi-directional resulting in energy conversion in two quadrants of the B-H plane (shown in Fig. 4a). The reluctance torque will pulsate at normal speeds to cause current harmonics so that the inductance of the machine should be designed to be as small as possible.

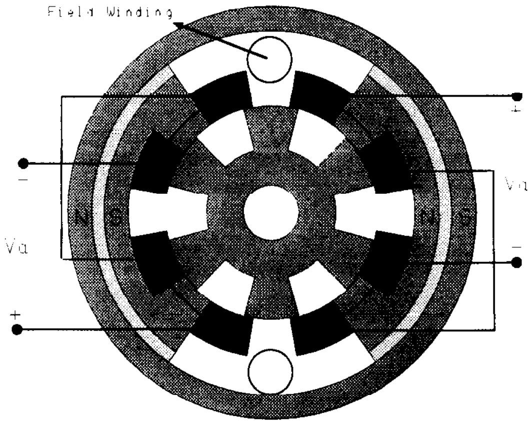


Fig. 2b Winding connection of FWDSPM generator (UDM)

On the other hand the UDM is based on a two phase connection of the armature winding (shown in Fig. 2b). In this case, the machine is operated similar to a SRM and the energy conversion occurs only in the first quadrant on the B-H plane (shown in Fig. 4b) so that only a half period for each phase is used to produce armature reaction so as to always magnetize the PM field and thus drive the machine to a highly saturated condition. Armature reaction is made useful in the UDM in the form of reluctance torque for which higher inductance could be designed and the control topology is simpler (see Fig. 3b) similar to those for SRMs. The frequency of inductance variation vs. rotor angle for UDM is the same as that of the PM flux linkage, which contributes to a smooth reluctance torque production. Torque production for both operating modes are depicted in Fig. 5:

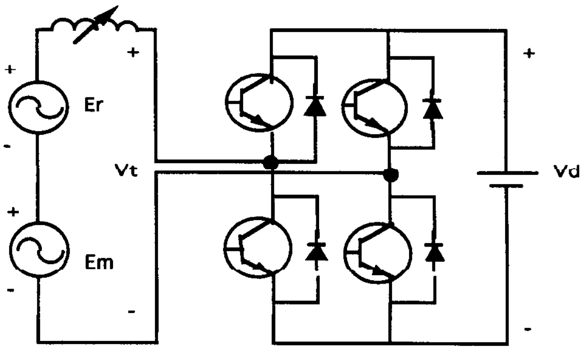


Fig. 3a Control topology of FWDSPM generator (BDM)

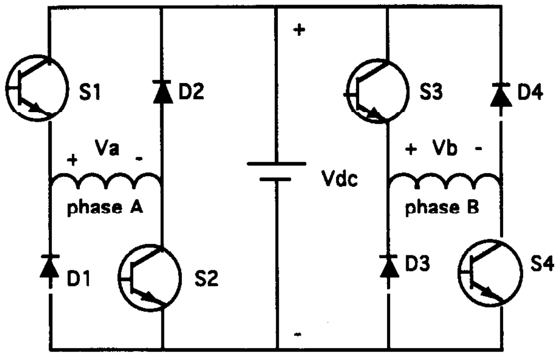
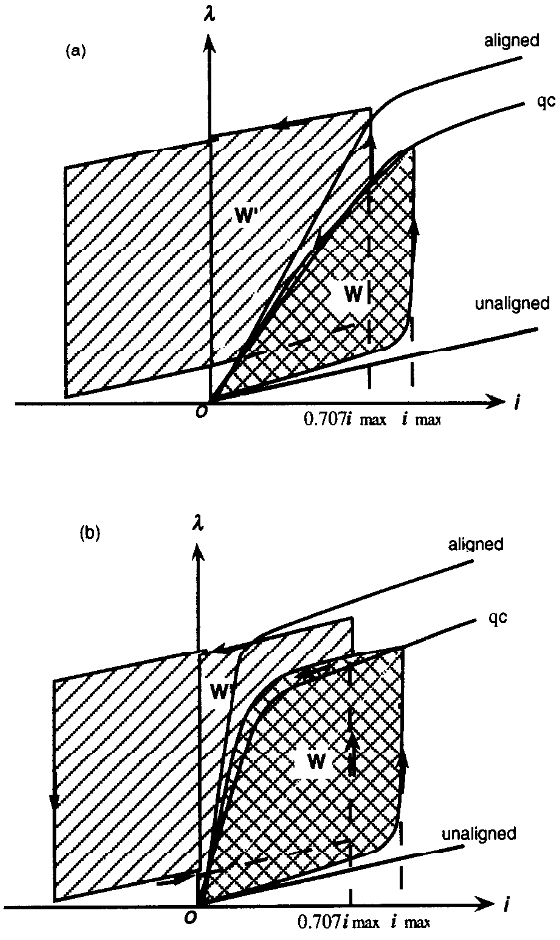
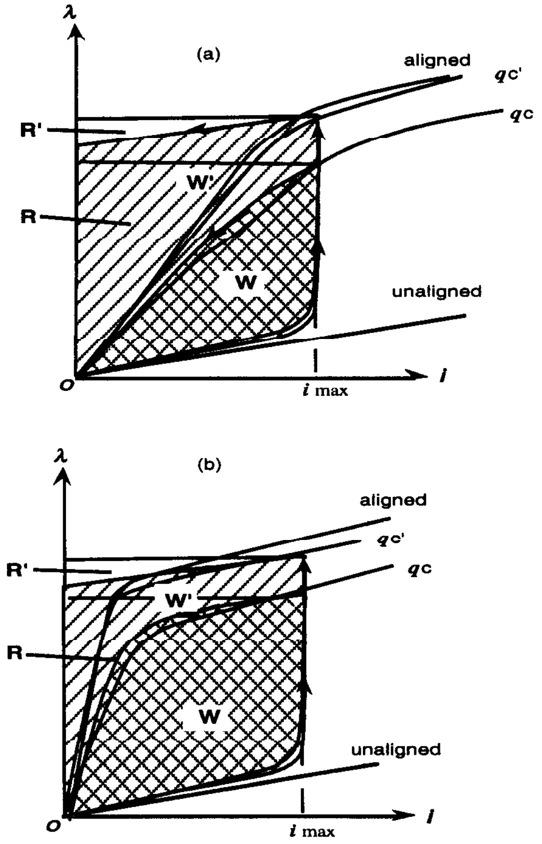


Fig. 3b Control topology of FWDSPM generator (UDM)



(a: with slight saturation b: with high saturation)
Fig. 4a Illustration of energy conversion of FWDSPM generator (BDM) compared with SRM's



(a: with slight saturation b: with high saturation)
Fig. 4b Illustration of energy conversion of FWDSPM generator (UDM) compared with SRM's

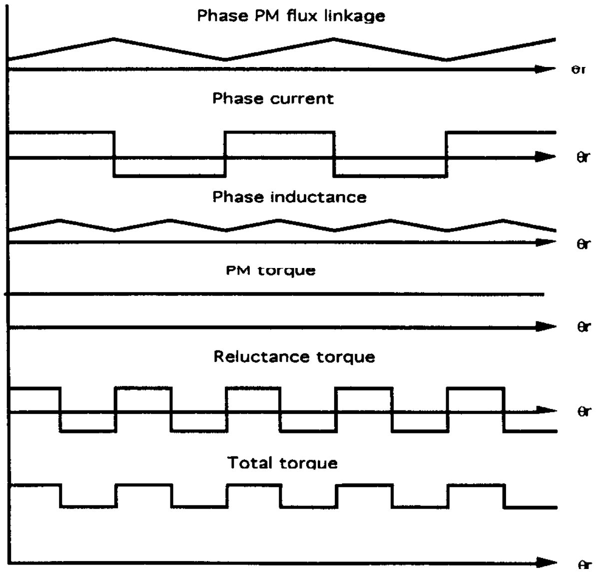


Fig. 5a Illustration of torque production of FWDSPM machine in the bi-directional mode (idealized)

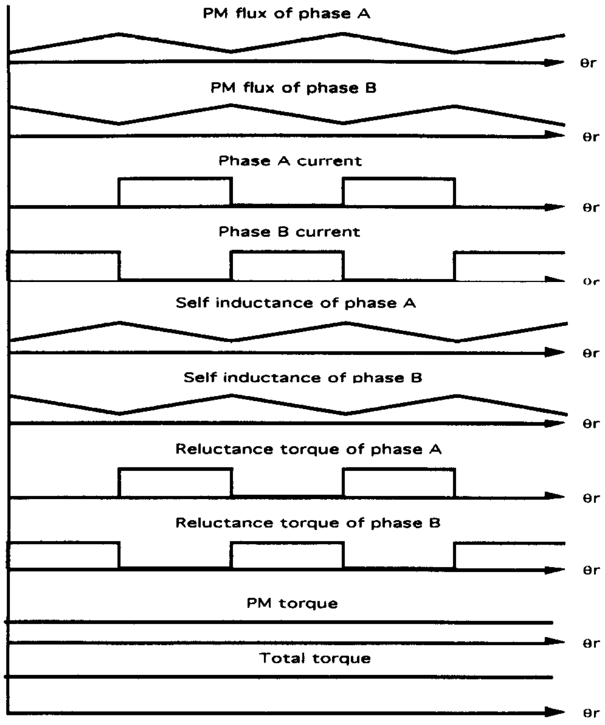


Fig. 5b Illustration of torque production of FWDSPM machine in the unidirectional mode of operation (idealized)

III. DERIVATION OF THE PHYSICAL MODEL

The phase voltage equations of this new machine can be expressed as the follows:

$$\begin{bmatrix} ua \\ ub \end{bmatrix} = \begin{bmatrix} ra & 0 \\ 0 & rb \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} + \begin{bmatrix} ema \\ emb \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda a \\ \lambda b \end{bmatrix} \tag{1}$$

where

$$\begin{bmatrix} \lambda a \\ \lambda b \end{bmatrix} = \begin{bmatrix} Laa & Mab \\ Mba & Lbb \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} = [L] \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{2}$$

and

$$\frac{d}{dt} \begin{bmatrix} \lambda a \\ \lambda b \end{bmatrix} = [L] \begin{bmatrix} ia \\ ib \end{bmatrix} + \begin{bmatrix} \dfrac{d[L]}{dt} \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{3}$$

So that

$$\begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} ua \\ ub \end{bmatrix} = \begin{bmatrix} ia & ib \end{bmatrix} [R] \begin{bmatrix} ia \\ ib \end{bmatrix} + \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} ema \\ emb \end{bmatrix} + \begin{bmatrix} ia & ib \end{bmatrix} [L] \begin{bmatrix} ia \\ ib \end{bmatrix} + \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} \dfrac{d[L]}{dt} \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{4}$$

Eq. (4) can be interpreted as follows:

$$P_{in} = P_{cu} + T_m \times \omega_r + T_r \times \omega_r + \frac{d}{dt} W_f \tag{5}$$

where

a) the input power is

$$P_{in} = \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} ua \\ ub \end{bmatrix} \tag{6}$$

b) with copper loss

$$P_{cu} = \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} ra & 0 \\ 0 & rb \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{7}$$

c) the PM portion of the torque is

$$T_m = \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} \dfrac{d\psi_{ma}}{d\theta_r} \\ \dfrac{d\psi_{mb}}{d\theta_r} \end{bmatrix} \tag{8}$$

d) and the reluctance torque is

$$T_r = \frac{1}{2} \begin{bmatrix} ia & ib \end{bmatrix} \begin{bmatrix} \dfrac{d[L]}{d\theta_r} \end{bmatrix} \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{9}$$

where

$$[L] = \begin{bmatrix} Laa & Mba \\ Mab & Lbb \end{bmatrix}$$

e) energy stored in armature windings

$$W_f = \frac{1}{2} \begin{bmatrix} ia & ib \end{bmatrix} [L] \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{10}$$

Also from (1), the dynamic equations of the FWDSPM generator can be expressed by:

$$\frac{d}{dt} \begin{bmatrix} ia \\ ib \end{bmatrix} = [L]^{-1} ([V] - [E]) - [L]^{-1} \left([R] + \begin{bmatrix} \dfrac{d[L]}{d\theta_r} \end{bmatrix} \omega_r \right) \begin{bmatrix} ia \\ ib \end{bmatrix} \tag{11}$$

where

1) [V] is the control vector

$$[V]=\begin{bmatrix} ua \\ ub \end{bmatrix} \tag{12}$$

2) [E] is the PM voltage vector

$$[E]=\begin{bmatrix} ema \\ emb \end{bmatrix} \tag{13}$$

3) [R] is the resistance matrix

$$[R]=\begin{bmatrix} ra & 0 \\ 0 & rb \end{bmatrix} \tag{14}$$

Machine parameters in (11) can be obtained from finite element analysis (FEA) and a digital computer simulation can be carried out by using the dynamic equations which have been presented. Furthermore, control strategies or the trajectory of vector [V] can be studied based on this model. In particular, the PM field control characteristics of the machine must be examined and will be the subject of a future paper. The PM voltage vector can be written as:

$$[E]=\begin{bmatrix} ema \\ emb \end{bmatrix}=\begin{bmatrix} \frac{d\psi ma}{dt} \\ \frac{d\psi mb}{dt} \end{bmatrix}=\begin{bmatrix} \frac{d(\phi ma+Lmaif)}{dt} \\ \frac{d(\phi mb+Lmbif)}{dt} \end{bmatrix} \tag{15}$$

$$=\begin{bmatrix} \frac{d\phi ma}{dt} \\ \frac{d\phi mb}{dt} \end{bmatrix}+\begin{bmatrix} \frac{dLma}{dt}if \\ \frac{dLmb}{dt}if \end{bmatrix}+\begin{bmatrix} Lma\frac{dif}{dt} \\ Lmb\frac{dif}{dt} \end{bmatrix}$$

where

ϕ_{ma} - no load PM flux linked by phase A

ϕ_{mb} - no load PM flux linked by phase B

L_{ma}- magnetizing inductance of the field winding for phase A

L_{mb}- magnetizing inductance of the field winding for phase B

i_f - field winding current

In general, the field winding current i_f varies very slow and the waveforms of L_{ma}, L_{mb} are the same as those of ϕ_{ma}, ϕ_{mb}. Hence equation (11) remains valid although [E] becomes a function of the field winding current I_f and I_f can be considered as another control variable.

IV. FINITE ELEMENT ANALYSIS OF FWDSPM GENERATOR

A finite element analysis for a 5 kW prototype FWDSPM generator has been done to demonstrate the operation principle. The task of this analysis is to obtain the necessary parameters for both designing and controlling the machine.

Fig. 6 shows flux distribution when PM excitation exists only. The very high concentration of magnet flux in one of the stator poles is apparent. Flux densities in the air gap on the order of 1.5 tesla can be readily achieved even though the remenant flux density of the ferrite magnet was only 0.4 tesla. This in turn, demonstates a flux focussing ability of a factor of four, far in excess of conventional bauried PM machines.

Fig. 7 shows flux distribution when armature current exists only. The maximum inductance position is shown which occurs when the stator and rotor poles are half-overlapped. The reluctance torque produced by the armature current is zero at this point.

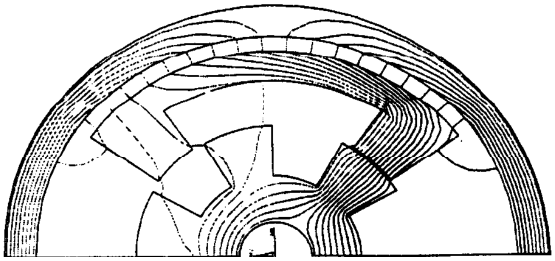


Fig. 6 Flux distribution of the prototype FWDSPM generator when PM excitation exists only

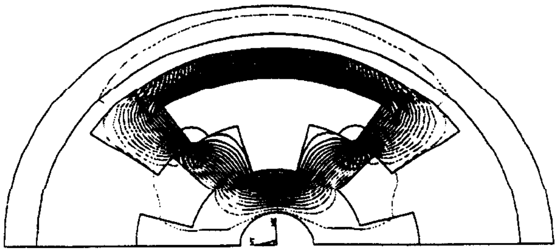


Fig. 7 Flux distribution of the prototype FWDSPM generator when armature current excitation exists only

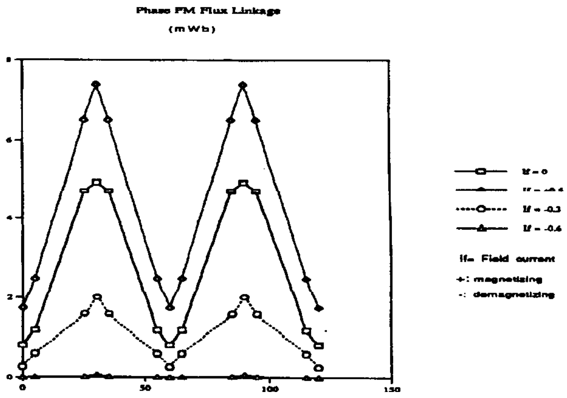


Fig. 8 Phase PM flux linkage versus rotor angle under different levels of field current excitations

Fig. 8 shows phase PM flux linkage versus rotor angle under various levels of field current excitation. Note that very high field forcing is possible when the field current and magnet act to produce flux in the same direction. Conversely when the two fields oppose, the net flux in the gap can be driven to zero. The FEA indicates that the PM field can be fully canceled by the demagnetizing MMF provided by the field winding only by using 60~90% of the per unit field current (unity field current here is defined as the point where the volume current density of copper reaches 3000 A/in^2).

V. SIMULATION RESULTS

Digital simulations have been carried out for the design of a 5 kw prototype FWDSPM generator. Machine data and performance calculation results are shown below:

Machine Data		
stator outer diameter	28.5.0	cm
stator inner diameter	20.0	cm
stack length	18.3	cm
stator pole number	4	poles
rotor pole number	6	poles
stator/rotor pole arc	$20^0/30^0$	
stator slot depth	1.8	cm

Machine Performance(BDM)		
DC bus voltage	150	volts
maximum inductance	0.81	mH
minimum inductance	0.20	mH
phase peak current	75	A
phase current RMS	64.5	A
output power	5.31	kw
efficiency	96.0%	

Machine Performance(UDM)		
DC bus voltage	150	volts
maximum inductance	0.76	mH
minimum inductance	0.57	mH
phase peak current	63	A
phase current RMS	55.4	A
output power	5.21	kw
efficiency	96.0%	

The simulations are based on the derived dynamic equations and the parameters obtained from the FEA. The current and voltage waveforms are shown in Fig. 9 and Fig. 10 for both operating modes respectively. While this simulation was based on a finite element study, several rotor positions were chosen to calculate inductances and a simple linear inductance variation between two adjacent positions assumed. Also it can be noted that, as a result, the inductance is assumed to vary linearly and that the EMF is "square". While this model gives a good estimation of the power that can be achieved with a given generator and converter design, a more accurate model is needed for estimating such important performance parameters as torque ripple. Work on a more accurate simulation model is progressing.

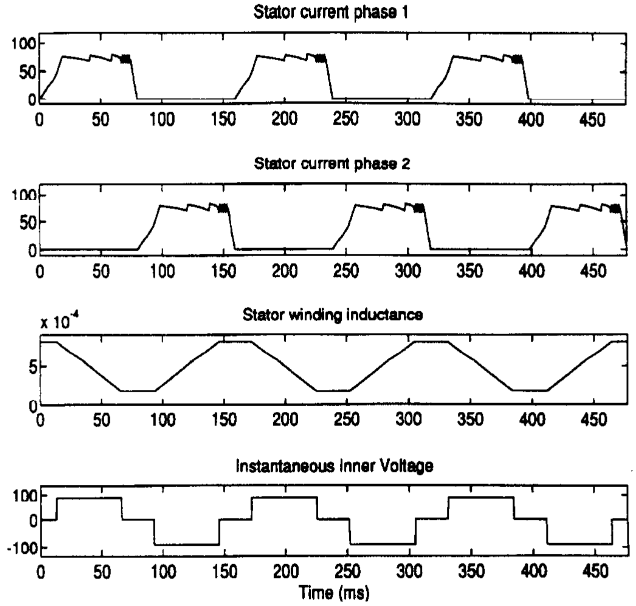


Fig. 9 Simulation results of the prototype generator (UDM)

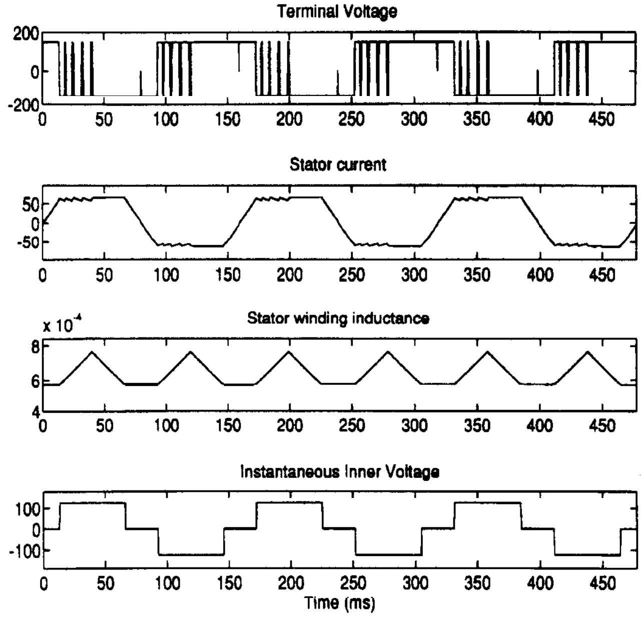


Fig. 10 Simulation results of the prototype generator (BDM)

VI. CONCLUSIONS

A new electrical machine with capability for field weakening with PM excitation, combined with high power density, low cost and a mechanically robust structure can been realized based on the proposed concept in this paper.

From the analyses, this generator can be operated in a very wide speed range without losing high performance which indicates that this new type of PM generator has high potential for variable speed (especially high speed) electric generation applications. The low cost realization of field weakening capability of this PM generator should make widespread use of this type of machine possible in the near future. A prototype of the machine type described in this paper is under construction.

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