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Abstract*—This paper presents a feasibility study of the use of permanent magnets for the purpose of self exciting a variable reluctance generator. A suggested concept for evaluation is the use of permanent magnet material extended axially on the stator core, but separated from the magnetic material stack by an insulator. As a part of this study electric and magnetic analyses on candidate concepts have been performed.

I. INTRODUCTION

Variable reluctance (VR) machines have experienced a resurgence of interest since the late 1960s as confidence began to accumulate over its torque producing capability when compared with more conventional machines. One feature that is peculiar to VR machines is the fact that each of the phases of the machine is essentially decoupled from each other. This feature is of particular importance when the machine is used as a generator since the faulted phase (usually shorted) will not conduct current should the remaining phases continue to operate. This advantage over other contenders (permanent magnet machines primarily) has led to intensive development of high speed VR generators.

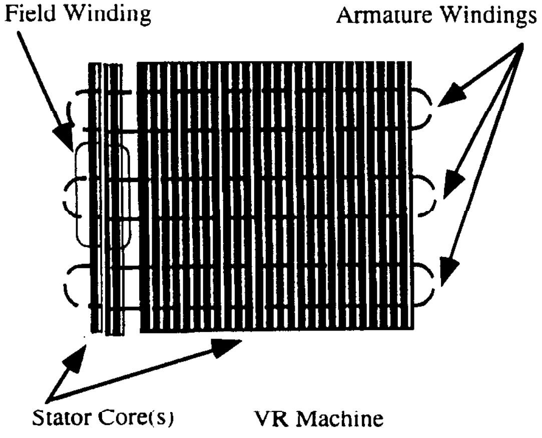


Fig. 1 Doubly salient doubly excited VR machine.

One problem concerning the effective deployment of such high speed generators concerns problems with self excitation. Whereas most high speed machines have self excitation capability, namely PM and Lundell generators, VR generators are inherently completely passive and have no internal excitation means. This study has investigated means by which excitation could be provided to self excite the VR generator thereby permitting easy stand-alone operation without the need for a large bulky exciting means.

While VR generators have no self-excitation capability of their own, a separate stack and winding could be installed to provide its excitation requirements during starting as shown in Fig. 1. The right hand side of this figure corresponds to the lamination stack of the main VR generator (viewed in a plane having one axis in the direction of rotor rotation). The left hand side of the figure shows a separate stator lamination stack into which is fitted a small field winding. The armature windings of the VR armature are extended so that they also enclose the poles of the second lamination stack. Hence, field current applied to the field winding will induce voltages in the main armature windings which, in turn, can be rectified. In general, the VR generator power is fed to a hard variable PWM converter and from there to a dc link capacitor. Hence, once the required excitation is supplied for a brief period, the dc link capacitor could be charged by extracting energy from the prime mover. After the field winding current is removed, both stacks could be used for electromechanical energy conversion in the usual manner.

As an alternative to the use of a wound field winding, magnets can be placed on the core of the second lamination stack as shown in Fig. 2. Excitation of the machine takes place in much the same manner as before. However, in this case, the magnet cannot be "turned off" and must remain in the armature winding circuit at all times. The magnets must now be sized to withstand the effects of armature reaction. While the magnets may become a problem at high speeds in which the emf they produce equals or exceeds the associated converter voltage capability, they could be sized so this situation would not occur. With proper sizing of the magnets, their magnetization of a portion of the machine could be used to produce additional useful permanent magnet torque.

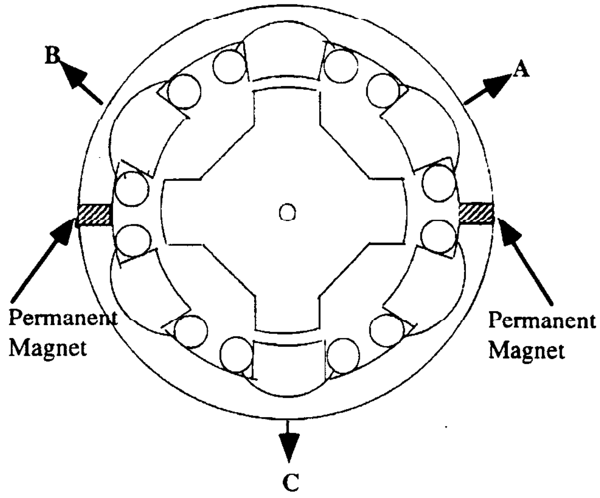


Fig. 2 Showing side view of excitation when employing permanent magnets.

II VOLTAGE EQUATIONS FOR A SELF EXCITED VARIABLE RELUCTANCE GENERATOR

The voltage equation for a self excited variable reluctance generator can be expressed as a sum of the two voltage equations, one for a variable reluctance generator and another for a doubly salient permanent magnet generator as shown in Eq. 1. An equivalent circuit for a self excited variable reluctance generator is shown in Fig. 3.

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} u_{a1} \\ u_{b1} \\ u_{c1} \end{bmatrix} + \begin{bmatrix} u_{a2} \\ u_{b2} \\ u_{c2} \end{bmatrix} \tag{1}$$

where u_{a1}, u_{b1}, u_{c1} are the stator phase voltages for a variable reluctance generator and u_{a2}, u_{b2}, u_{c2} are the stator phase voltages for a doubly salient permanent magnet generator.

The voltage equation of a variable reluctance generator is described as

$$\begin{bmatrix} u_{a1} \\ u_{b1} \\ u_{c1} \end{bmatrix} = \begin{bmatrix} r_{a1} & 0 & 0 \\ 0 & r_{b1} & 0 \\ 0 & 0 & r_{c1} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{a1} \\ \lambda_{b1} \\ \lambda_{c1} \end{bmatrix} \tag{2}$$

where

$$\begin{bmatrix} \lambda_{a1} \\ \lambda_{b1} \\ \lambda_{c1} \end{bmatrix} = \begin{bmatrix} L_{aa1} & L_{ba1} & L_{ca1} \\ L_{ab1} & L_{bb1} & L_{cb1} \\ L_{ac1} & L_{bc1} & L_{cc1} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{3}$$

and r_{a1}, r_{b1}, and r_{c1} denote stator resistance, L_{aa1}, L_{bb1}, and L_{cc1}, self inductance, M_{ab1}, M_{bc1}, and M_{ca1}, mutual inductance of a variable reluctance generator.

The voltage equation of a doubly salient permanent magnet generator is described as

$$\begin{bmatrix} u_{a2} \\ u_{b2} \\ u_{c2} \end{bmatrix} = \begin{bmatrix} r_{a2} & 0 & 0 \\ 0 & r_{b2} & 0 \\ 0 & 0 & r_{c2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \lambda_{a2} \\ \lambda_{b2} \\ \lambda_{c2} \end{bmatrix} + \begin{bmatrix} e_{ma} \\ e_{mb} \\ e_{mc} \end{bmatrix} \tag{4}$$

where

$$\begin{bmatrix} \lambda_{a2} \\ \lambda_{b2} \\ \lambda_{c2} \end{bmatrix} = \begin{bmatrix} L_{aa2} & L_{ba2} & L_{ca2} \\ L_{ab2} & L_{bb2} & L_{cb2} \\ L_{ac2} & L_{bc2} & L_{cc2} \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{5}$$

and

$$\begin{bmatrix} e_{ma} \\ e_{mb} \\ e_{mc} \end{bmatrix} = \begin{bmatrix} \frac{d\Phi_{ma}}{dt} \\ \frac{d\Phi_{mb}}{dt} \\ \frac{d\Phi_{mc}}{dt} \end{bmatrix}$$

where r_{a2}, r_{b2}, and r_{c2} denote stator resistances, L_{aa2}, L_{bb2}, and L_{cc2}, self inductances, M_{ab2}, M_{bc2}, and M_{ca2}, mutual inductances of a doubly salient permanent magnet generator. Φ_{ma}, Φ_{mb}, and Φ_{mc} denote the no load permanent magnet flux linked by each phase windings.

The 30 kW variable reluctance generator of references [1, 2] was used for the purpose of the analysis of this research. The speed range of the generator is from 27,000 rpm to 46,850 rpm and the rated output power is 30 kW, 270 Vdc at 46,850 rpm. The VR generator has a 6/4 pole topology, 6 stator poles, and 4 rotor poles.

III. POWER CONVERTER CIRCUIT FOR A SELF EXCITED VARIABLE RELUCTANCE GENERATOR

The converter configuration of Fig. 3 was chosen for this PM based VR generator exciter, which is the same power converter configuration for conventional variable reluctance generators, where each phase has two active switches, IGBTs, and two passive switches, diodes.

The converter has three different operating modes. One is the Charging Mode, where the capacitor is charged up by the induced voltage of the doubly salient permanent magnet machine through the diode rectifier circuit. The initial capacitor voltage is considered as 0 volts. The capacitor is charged up to few volts with this mode of operation. Fig. 4 illustrates the three phase induced voltage and flux linkage waveforms of the doubly salient permanent magnet machine. The induced voltage of each phase is rectified by the half diode bridge circuit and the capacitor is charged up to the peak value of the induced voltage (minus the diode forward voltage drops).

The next step is the Voltage Build Up Mode, where the capacitor voltage is increased up to the rated voltage with help of the switching of the IGBTs. The switching action to build up the capacitor voltage is similar to the Generating Mode. The phase A current starts flowing in the phase A circuit from zero when the switches S_{A1} and S_{A2} are turned on and increases using the energy from the capacitor until the switches are turned off. When the switches S_{A1} and S_{A2} are turned off the current in the switches is commutated to the diodes and continues to flow until the current reduces to zero. Hence, the direction of the energy flow is changed from the machine to the capacitor and then the capacitor voltage increases. The amount of the energy flow can be controlled by controlling the turn on and turn off timing of the switches.

IV. FINITE ELEMENT ANALYSIS STUDY OF A SELF EXCITED VARIABLE RELUCTANCE GENERATOR

The 30 kW variable reluctance generator was analyzed with a finite element analysis program to obtain the machine parameters in the presence of saturation. The machine dimensions are 158.75 mm stator outer diameter, 84.12 mm stator inner diameter, 0.76 mm air gap length, and 63.5 mm stack length. The number of turns per pole is four. The two pole windings are connected in series. The induction curve of TELCON HS50 was used for this analysis. The finite element analysis study was carried out for five different rotor positions. Figure 5 shows one of the finite element analysis results to show the magnetic flux distribution, where the rotor is rotated 10 mechanical degrees from the aligned position. Fig. 6 (a) shows the self inductance L_s of the variable reluctance machine when one of the rotor poles is aligned to the stator pole, and Fig. 6 (b) and (c) when the rotor pole is 20 and 45 degrees, respectively, away from the aligned position.

The finite element analysis study was carried out also for the doubly salient permanent magnet machine to obtain (1) magnetic flux in the stator poles per unit core length and (2) the machine parameters. The doubly salient permanent magnet machine has the exactly same geometric dimensions as the variable reluctance generator. Two permanent magnets are placed in the stator yoke as shown in Fig. 2. The permanent magnet of N_d-F_e-B with the remnant induction B_r of 1.1 T was assumed for this analysis. Figure 7 shows the magnetic flux distribution when the machine is excited by the permanent magnet. The magnetic flux inside of one of the three phase stator poles of the machine per unit core length versus the rotor position is plotted in Fig. 8.

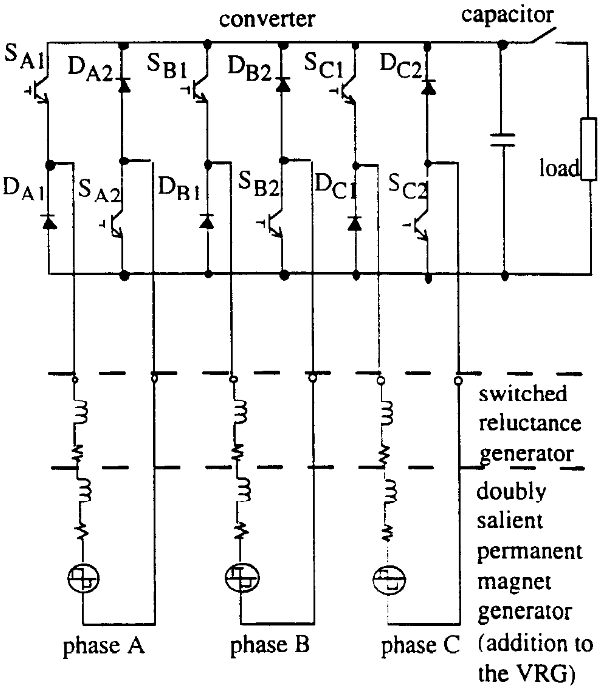


Fig. 3 A power converter circuit for a self excited variable reluctance generator.

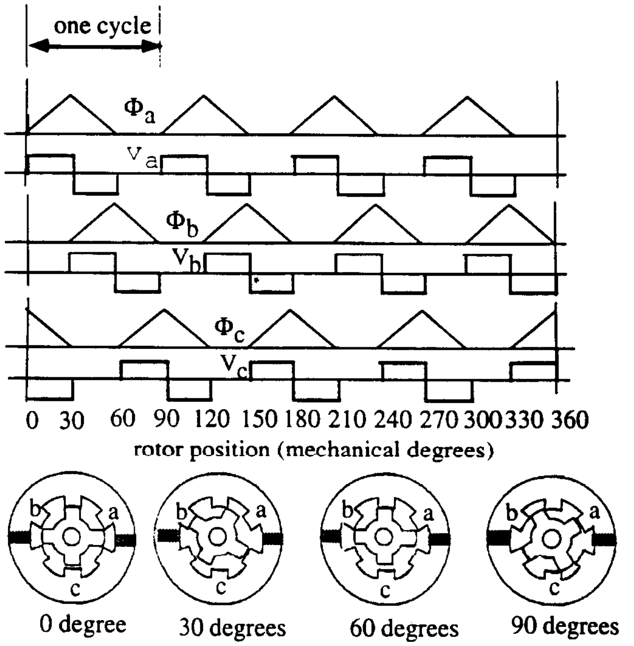


Fig. 4 Illustration of the three phase voltage and flux linkage waveforms of the doubly salient permanent magnet machine.

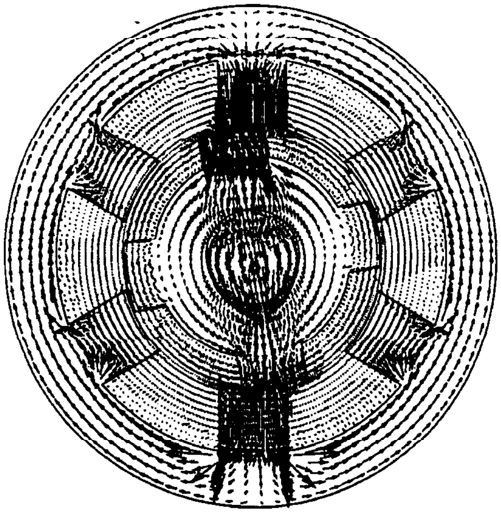
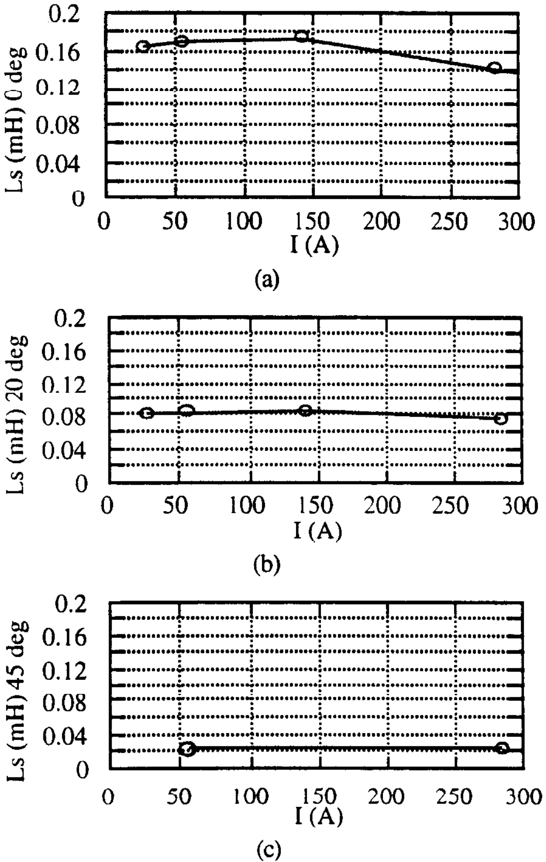


Fig. 5 Finite element analysis result to show the magnetic flux distribution of the variable reluctance generator with the phase 2 excitation, where the rotor is rotated 10 mechanical degrees from the aligned position.



(a)

(b)

(c)

Fig. 6 Self inductance L_S of the variable reluctance machine for the rotor position of (a): 0 mechanical degree shift from the aligned position, (b): 20 mechanical degree shift from the aligned position, and (c): 45 mechanical degree shift from the aligned position.

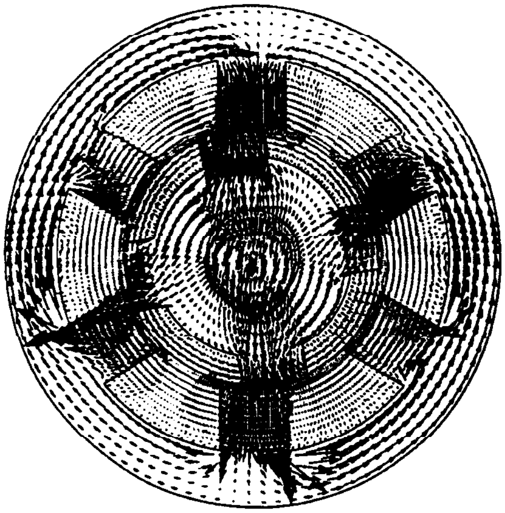
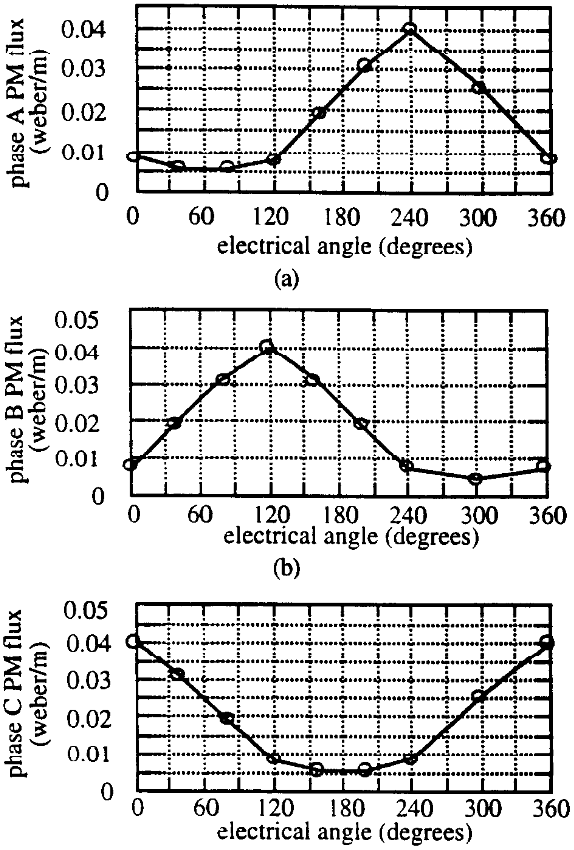


Fig. 7 Finite element analysis result to show the magnetic flux distribution of the doubly salient permanent magnet machine when the machine is excited by the permanent magnet, where the rotor is rotated 10 mechanical degrees from the aligned position.



(a)

(b)

(c)

Fig. 8 Magnetic flux per unit core length (1 m) versus the rotor position inside of one of the stator poles of the doubly salient permanent magnet machine.

The induced voltage of the doubly salient permanent magnet machine can be expressed as

$$e_{ma} = \frac{d\,\Phi_{ma}}{dt} \tag{7}$$

By observation of Fig. 8, the slope of the PM flux per unit core length between 120 and 180 electrical degrees is

$$\frac{d\,\Phi_{ma}}{L_{core}} = \frac{(0.0196 - 0.0077)}{L_{core}} \cdot N_t \ \text{(weber/m)} \tag{8}$$

where L_{core} is the effective core length and N_t, the number of turns per pole. and

$$dt = \frac{240 - 120}{360} \frac{1}{\frac{RPM}{60}} \frac{1}{4} \frac{1}{3} \text{(sec)} \tag{9}$$

where RPM denotes the rotor speed. The induced voltage per unit core length at the rotor speed of 27,000 rpm is

$$\frac{e_{ma}}{L_{core}} = 771 \ \text{(volts/m)} \tag{10}$$

Another finite element analysis study was carried out to find the effect of the leakage flux with the modification of the doubly salient permanent magnet machine model, which includes the narrow steel bridges inside of the permanent magnets and the air portion outside of the stator yoke. Figure 9 illustrates the machine model and the corresponding flux density distribution is shown in Fig. 10. The flux linkage at the stator pole is reduced about 27 % due to the leakage flux and the induced voltage per unit core length is reduced to

$$\frac{e_{ma}}{L_{core}} = 561 \ \text{(volts/m)} \tag{11}$$

With the doubly salient permanent magnet machine having a 10 % of the core length of the variable reluctance generator the estimated induced voltage is about 3.5 volts peak at the rotor speed of 27,000 rpm.

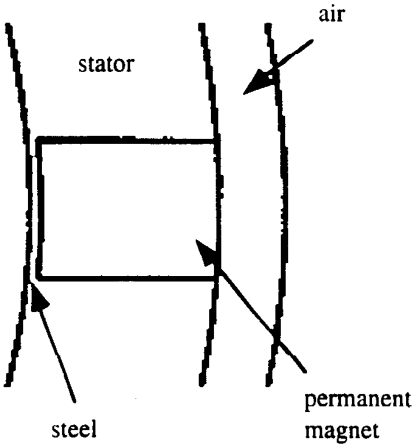


Fig. 9 The doubly salient permanent magnet machine model for a finite element analysis study including air portion outside of the stator yoke and the narrow steel bridges inside of the permanent magnets.

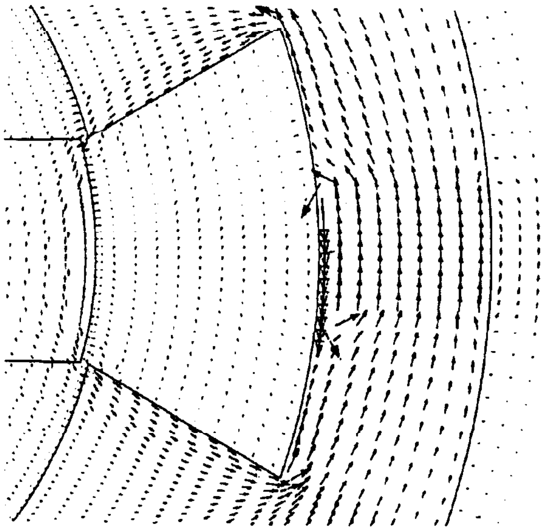


Fig. 10 A finite element analysis result to show the magnetic flux distribution of the doubly salient permanent magnet machine when the machine is excited by the permanent magnet, where the rotor is aligned to the phase B stator pole. The analysis includes the narrow steel bridges inside of the permanent magnets and the air portion outside of the stator yoke to find the effect of the leakage flux.

V. SIMULATION STUDY

A simulation program has been developed to study the operation of the proposed self excited variable reluctance generator. The program has three major purposes which are to simulate the charging process of the capacitor with the induced voltage of the doubly salient permanent magnet machine, to simulate the voltage build up operation with the active switch operation, and to simulate the steady state generating operation.

The simulation program includes losses to determine the possible lowest induced voltage of the PM machine, that is, to determine the possible shortest core length of the PM machine portion of the variable reluctance/PM machine. The included losses are the switch losses (IGBTs and diodes), the copper loss (the IR drop loss), and the iron loss. The switch losses include the on state loss of the IGBTs, the turn off loss of the IGBTs, the on state loss of the diodes. The turn on loss of the IGBTs can be neglected because the IGBTs turn on at the point where the stator current is zero. The iron loss is assumed to be 5 % of the machine power, that is, $P_{iron} = 0.05 * I * V$.

A simulation result of the charging operation is shown in Fig. 11, where the waveforms of the capacitor voltage and current, and the three phase generator currents and induced voltages are presented. The assumed induced voltage is 2 volts at 27,000 rpm and the capacitor voltage is charged up to 0.2 volts because of the forward voltage drops of the two diodes.

Figures 12 and 13 show a simulation result of a self excited permanent magnet generator for 0.6 msec at the start of the voltage build up operation, where the capacitor voltage is building up to the rated voltage. The generator phase current, voltage and self inductance of each three phase are shown in Fig. 12. The capacitor voltage and current, the energy flow into the capacitor, the generated energy and the energy loss waveforms are shown in Fig. 13.

At t = 0 the phase C IGBTs are turned on and the phase C current starts flowing. The rotor position is assumed to be the zero degree case of Fig. 4 at t = 0 and anti clockwise rotation is assumed. The current direction is from the capacitor to the machine and a part of the capacitor energy is consumed. At about t = 0.1 msec the phase C IGBTs are turned off and the current commutates from the IGBTs to the diodes. The current direction is changed to flow to the capacitor from the generator and the generated energy flows into the capacitor until the phase C current is reduced to zero at about t = 0.23 msec. At about t = 0.18 msec the phase A

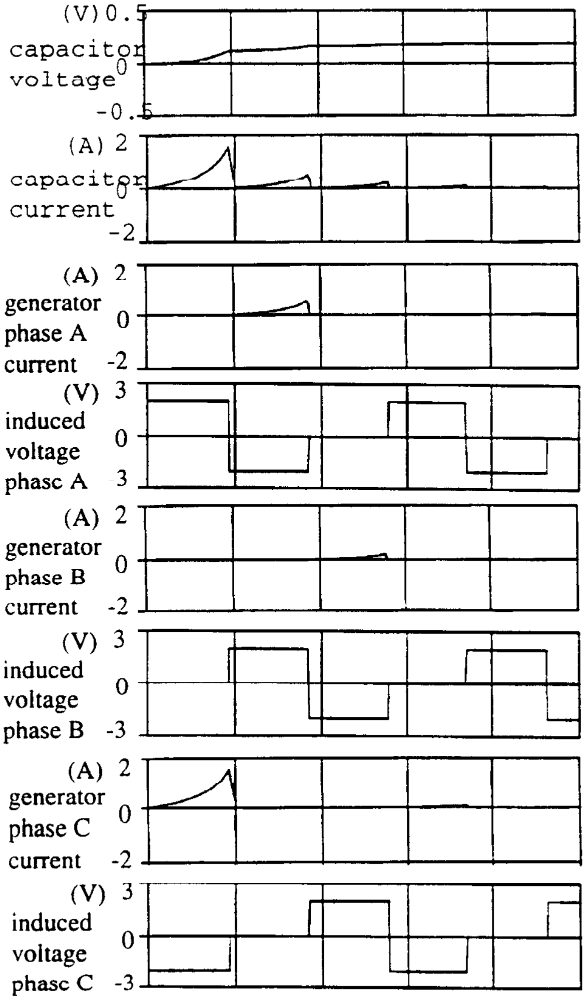


Fig. 11 A simulation result of the charging operation. The induced voltage is 2 volts at 27,000 rpm. The waveforms from top to bottom; capacitor voltage, capacitor current, generator phase A current and voltage, generator phase B current and voltage, and generator phase C current and voltage.

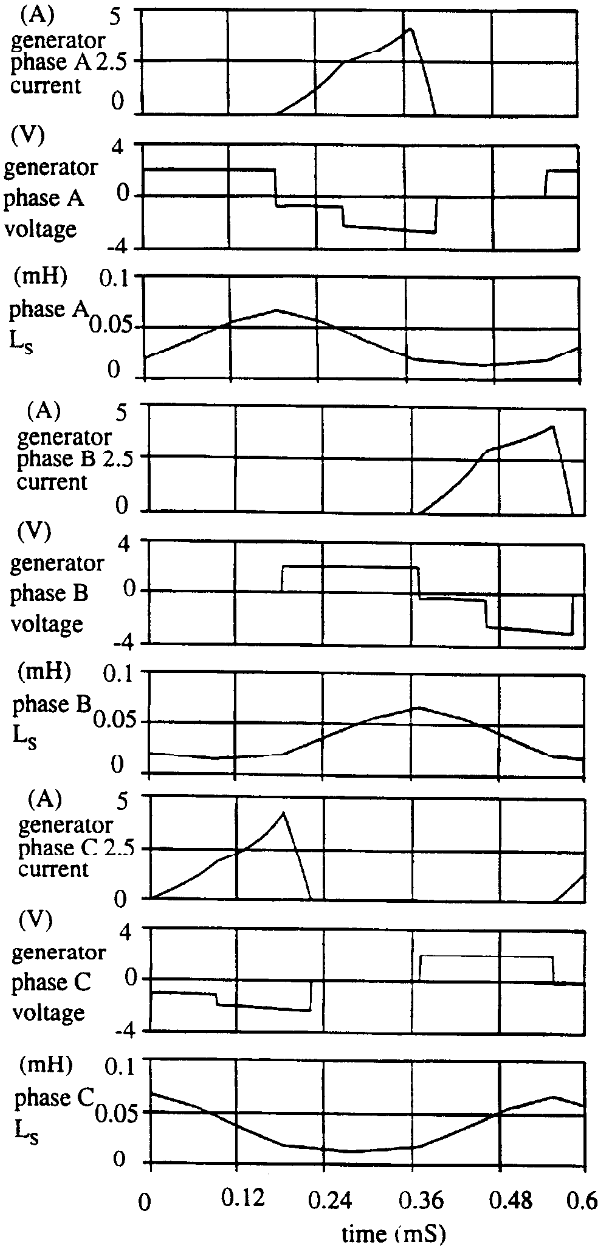


Fig. 12 One cycle of the operation at the start of the voltage build up[operation. The induced voltage is 2 volts at 27,000 rpm. The waveforms from top to bottom; the generator phase A current, voltage and self inductance, the generator phase B current, voltage and self inductance, and the phase C generator current, voltage and self inductance.

IGBTs are turned on and the phase A current starts flowing. The capacitor energy is consumed while the phase A current increases until the phase A IGBTs are turned off at about 0.28 msec. Then the current direction in the phase A windings is changed and the generated energy flows into the capacitor until the phase A current is reduced to zero at about t = 0.41 msec. The phase B operates in the same manner as the other two phases and the simulation results show that the capacitor voltage is successfully increased after the one cycle of the voltage build up operation. With an induced voltage of 1.45 V the capacitor voltage remains unchanged near 0 volts. The charging operation does not work properly with an induced voltage of 1.35 V.

Figure 14 shows the same items of the waveforms as Fig. 13 for 50 msec until the capacitor voltage is charged up to the rated voltage of 270 V. The simulation results, which include the practical effect of device losses, demonstrate that an induced voltage of 2 volts is enough to build the capacitor voltage up to the rated voltage, which suggests that the core length of the doubly salient permanent magnet machine can be roughly 6 % of the core length of the variable reluctance generator.

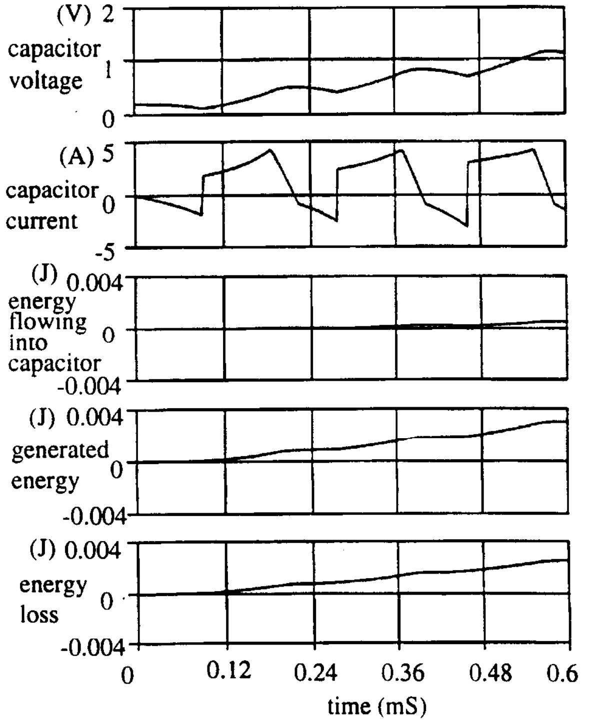


Fig. 13 One cycle of the operation at the start showing that the capacitor voltage is gradually built up after the completion of the charging operation where the capacitor is charged up with the induced voltage of the PM part of the machine. The induced voltage is 2 volts at 27,000 rpm. The waveforms from top to bottom; the capacitor voltage, the capacitor current, the energy flowing into the capacitor, the generated energy and the energy loss.

A simulation result of the self excited variable reluctance generator during continuous 30 kW generating operation is shown in Fig. 15. Torque pulsations arising from the presence of the magnets have been determined to be neglibigle.

VI. CONCLUSIONS

It was the purpose of this paper to present the use of permanent magnets for the purpose of self exciting a variable reluctance generator. An arrangement of permanent magnets in the extended stator core was assumed. A converter configuration, which is the identical power converter configuration used for variable reluctance generators, can be used for a self excited variable reluctance generator. The variable reluctance generator was analyzed with a finite element analysis program to obtain the magnetic flux in the stator poles per unit core length and the machine parameters including saturation. A simulation program was developed to determine the required induced voltage of a doubly salient permanent magnet machine, where the generator system is able to charge the capacitor up to the rated dc voltage with

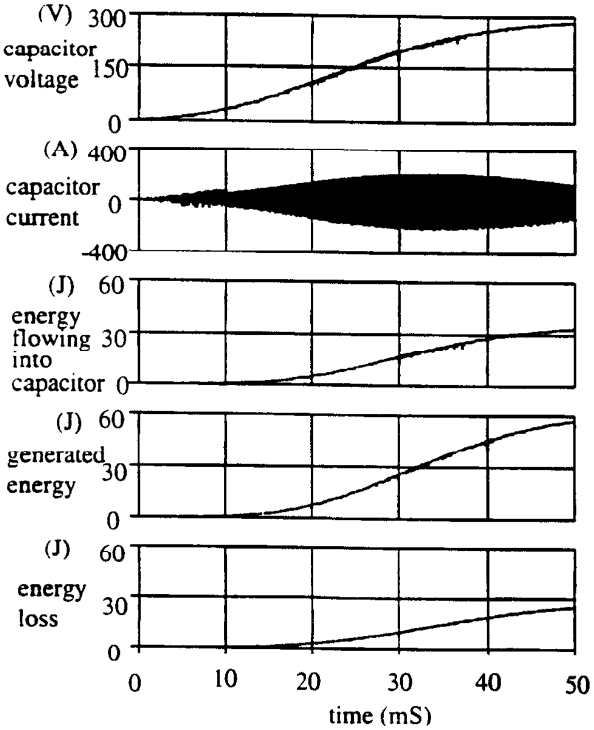


Fig. 14 The voltage build up operation showing that the capacitor voltage is increasing from nearly zero to the rated voltage of 270 V. The induced voltage of the permanent magnet part of the machine is 2 volts at 27,000 rpm. The waveforms from top to bottom; the capacitor voltage, the capacitor current, the energy flowing into the capacitor, the generated energy and the energy loss.

the charging process and the voltage build up operation. The required core length of the doubly salient permanent magnet machine for a specific induced voltage can be estimated with the results from the finite element analysis study.

With the doubly salient permanent magnet machine having a 10 % of the core length of the variable reluctance generator the estimated induced voltage is about 3.5 volts peak at the rotor speed of 27,000 rpm, which was estimated from the finite element analysis study. The simulation results, which include the losses, demonstrate that an induced voltage of 2 volts is sufficient to build the capacitor voltage up to the rated voltage, which suggests that the core length of the doubly salient permanent magnet machine need be roughly only 6 % of the core length of the variable reluctance generator. This amount of PM flux could possibly be obtained by simply fastening a magnet to the sides of each pole in the end winding region, making expensive redesign not necessary.

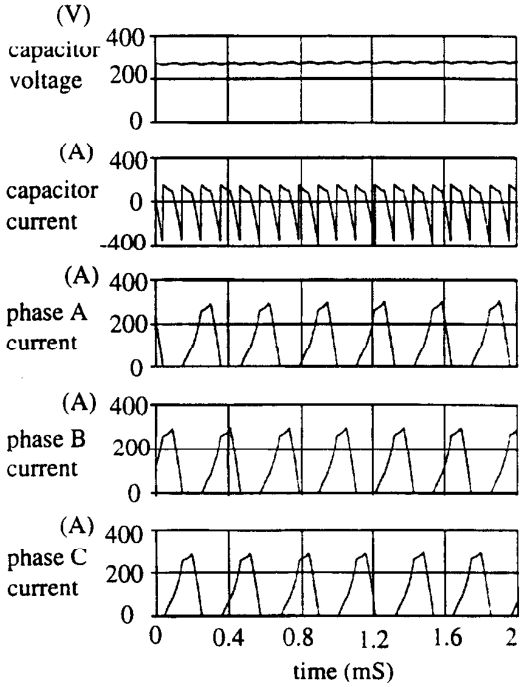


Fig. 15 Simulation result of the self excited variable reluctance generator during 30 kW generating operation. The waveforms from top to bottom; the capacitor voltage, the capacitor current, the three phase generator currents.

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