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A New Two Phase Bidirectional Hybrid Switched Reluctance Motor/Field-Assisted Generator

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Abstract: The switched reluctance motor is a simple and robust machine, which has found application over a wide power and speed ranges in different shapes and geometries. This study introduces a new two phase hybrid configuration for a switched reluctance motor/field assisted generator. The proposed novel motor/generator consists of two magnetically independent stator and rotor sets (layers), where each stator set includes four salient poles with windings wrapped around them, while the rotor comprises of two salient poles. There is a stationary reel, which has the field coils wrapped around it and is placed between the two-stator sets. The two sets are connected independently in the motor mode of operation. In this connection the poles in each layer can have both North and South Pole configurations. In the generator mode, the stator poles in one set can have either north or south pole configuration and the stator poles in the other set (layer) have the opposite pole arrangement. In this format, the developed magnetic field from the stator poles goes to the rotor poles after that to the rotor shaft and then completes its path via the motor/generator housing. To evaluate the motor performance, two types of analysis, namely, the numerical technique and the experimental study have been utilized. In the numerical analysis, the finite element analysis is employed, where as in the experimental study, a proto-type motor has been built and tested.

Key words: Switched reluctance motor, SRM, reluctance motor/generator, hybrid motor

INTRODUCTION

The switched reluctance motor (SR motor) has been extensively investigated and developed in the past four decades by several research organizations with results that are more promising than those obtained in the earlier study (Torkaman and Afjei, 2008). Although, this motor invented over 60 years ago, but it did not realize its full potential until the modern era of power electronics and computer-aided electromagnetic design.

Switched reluctance motors have been used extensively in clocks and phonograph turntables before but nowadays, they have been employed in many different industrial applications (Emadi, 2001). The motor development has matured to the point that its performance has been raised to levels competitive with that of DC and variable speed AC motors in such way that its impact is now becoming evident in the industry (Krishnan, 2001).

Due to the increasing demand for higher power and less fuel consumption in cars, the concept of starter-generator integrated to the flywheel has been investigated over the past several years. It is intended to provide the starter for the thermal engine and the generator for charging the car battery and supplying the on board equipment. Significant enhancement of vehicle driving performance and improvements in fuel economy and exhaust emissions can be established by the introduction of integrated starter-generator in hybrid vehicles. The application of electrical machines and drives systems in all-electric and hybrid-electric vehicles has been widely reported in recent years (Rahman *et al*., 2000; Emadi, 2001).

Switched Reluctance Generator (SRG) is an attractive solution for worldwide increasing demand of electrical energy. It is low cost, fault tolerant with a rugged structure and operates with high efficiency over a wide speed range. Merits of using SRG have been proved for some applications like starter/generator for gas turbine of aircrafts (MacMinn and Sember, 1989; Ferreira *et al*., 1995), windmill generator (Mueller, 1999; Cardenas *et al*., 1995) and as an alternator for automotive applications (Fahimi *et al*., 2004; Boldea *et al*., 2004). In principle of operation of SRG has been presented and the necessity for closed loop control is proved (Radun, 1994). In order to produce torque in all 360° rotor position for a two

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phase switched reluctance motor one must utilize different configurations for either stator pole or rotor pole geometry. In a new two phase switched reluctance motor utilizing a governor for the control of excitation has been presented by Afjei *et al*. (2007). Finally, a PM-assisted reluctance synchronous motor/generator (PM-RSM) for mild hybrid vehicles has been presented by Boldea *et al*. (2004).

This study presents construction, numerical analysis, experimental results of a new type of two phase hybrid switched reluctance motor/generator.

MOTOR/GENERATOR DESCRIPTION

The proposed novel motor/generator consists of two magnetically dependent stator and rotor sets (layers), where each stator set includes four salient poles with windings wrapped around them while, the rotor comprises of two salient poles. Every stator and rotor pole arcs are 45 and 47°, respectively. The two layers are exactly symmetrical with respect to a plane perpendicular to the middle of the motor shaft. This is a two phase motor/generator; therefore, each layer consists of four stator poles and two rotor poles, respectively. In the generating mode the coil windings in each layer are such that the stator poles gain either North or South Pole configuration. In the motoring operation each layer operates independently, but in sequence with each other. In another words, each layer consist of a four by two reluctance motor configuration sharing common shaft which operating in sequence. There is a stationary reel, which has the field coils wrapped around it and is placed between the two-stator sets. This reel has a rotating cylindrical core, which guides the magnetic field. The magnetic flux produced by the coils travels through the guide and shaft to the rotor and then to the stator poles and finally closes itself through the motor housing. Therefore, one set of rotor poles is magnetically north and the other set is magnetically South. In this motor, the magnetic field has been induced to the rotor without using any brushes. A cut view of the motor/generator is shown in Fig. 1.

In order to get a better view of the motor/generator configuration, the complete motor/generator assembly is shown in Fig. 2.

There are two stators and rotors sections placed on both sides of the field coil assembly which has the rotor shaft as its main core and two front/end caps plus the motor housing. A set of photo interrupters are also place in the back of the motor for the detection of rotor position. Two types of analysis namely numerical and experimental have been performed.

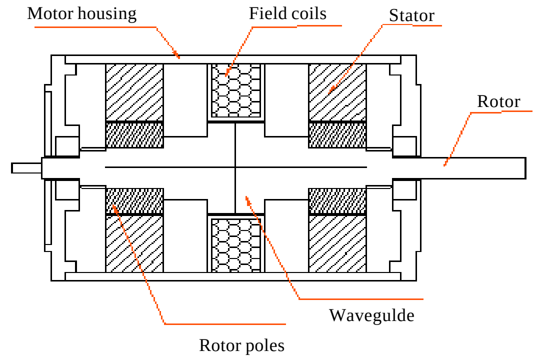

Fig. 1: A cut view of the motor/generator

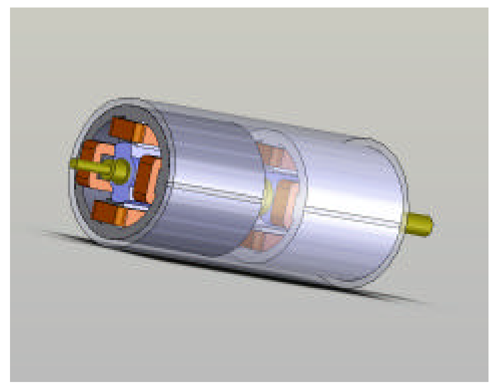

Fig. 2: The complete motor/generator assembly

NUMERICAL ANALYSIS

The design of the motor becomes complicated due to complex geometry and material saturation. The reluctance variation of the motor has an important role on the performance; hence an accurate knowledge of the flux distribution inside the motor for different excitation currents and rotor positions is essential for the prediction of motor performance. The motor can be highly saturated under normal operating conditions. To evaluate properly the motor design and performance a reliable model is required. The finite-element technique can be conveniently used to obtain the magnetic vector potential values throughout the motor in the presence of complex magnetic circuit geometry and nonlinear properties of the magnetic materials. These vector potential values can be processed to obtain the field distribution, torque and flux leakage.

The field analysis has been performed using a Magnet CAD package (2007), which is based on the variational energy minimization technique to solve for the magnetic vector potential. The partial differential equation for the magnetic vector potential is given by:

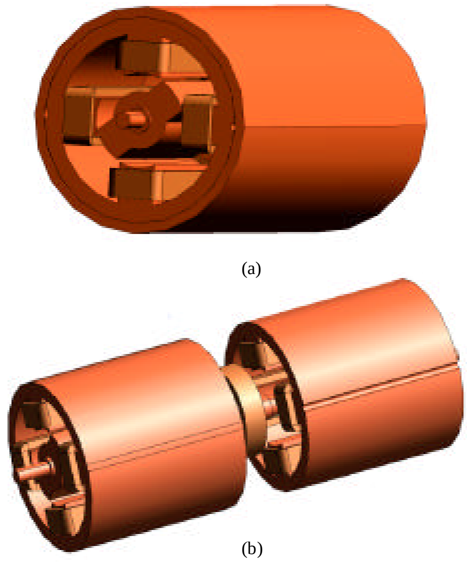

Fig. 3: 3-D view of motor/generator, (a) with housing and (b) without housing

$$-\frac{\partial}{\partial x}(\gamma\frac{\partial A}{\partial x})-\frac{\partial}{\partial y}(\gamma\frac{\partial A}{\partial y})-\frac{\partial}{\partial z}(\gamma\frac{\partial A}{\partial z})=J \quad (1)$$

where, A is the magnetic vector potential.

In the variational method (Ritz) the solution to Eq. 1 obtained by minimizing the following functional:

$$F(A)=\frac{1}{2}\iiint_{\Omega}[\gamma(\frac{\partial A}{\partial x})^2+\gamma(\frac{\partial A}{\partial y})^2+\gamma(\frac{\partial A}{\partial z})^2]d\Omega-\iiint_{\Omega}JAd\Omega \quad (2)$$

where, Ω is the problem region of integration.

In the finite element analysis second order triangular elements with dense meshes at places where the variation of fields are greater have been used.

The motor/generator with and without the housing used in the numerical analysis are shown in Fig. 3a, b. The 3-D field analysis has been performed using a commercial finite element package (2007), which is based on the variational energy minimization technique to solve for the magnetic vector potential.

The stator and rotor cores are made up of M-27 non-oriented silicon steel laminations with the following static B-H curve shown in Fig. 4.

Figure 5a-c show the magnetic field for non-aligned when the machine operates as a motor when each layer is operating independently.

Figure 6a-c show the magnetic field for aligned case when the machine operates as a motor and each layer is operating independently.

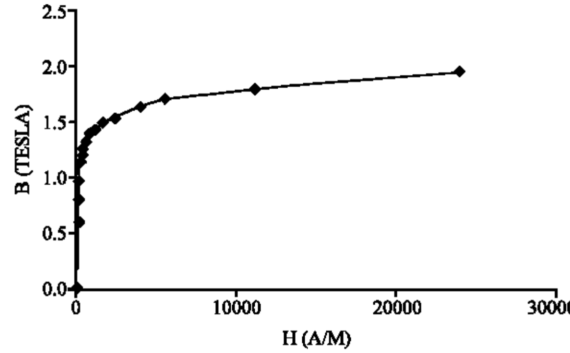

Fig. 4: Magnetization curve for M-27 non-oriented silicon steel sheet

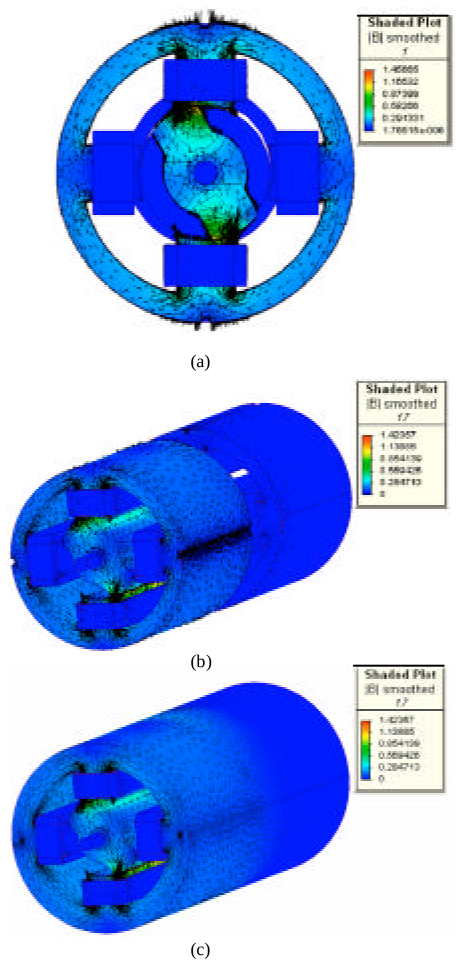

Fig. 5: 3-D magnetic field densities for non-aligned case

The plot of static torque versus rotor positions developed by the hybrid reluctance motor/generator is shown in Fig. 7. In Fig. 7, 0 and 45° are considered as completely unaligned aligned cases, respectively.

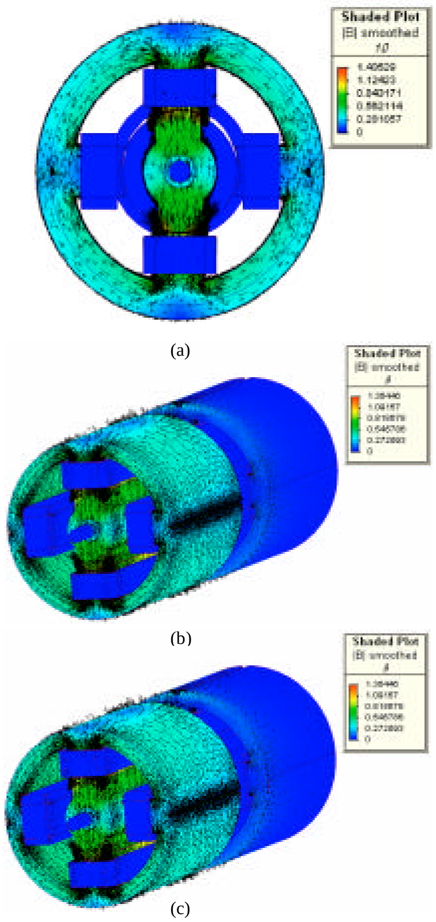

Fig. 6: 3-D magnetic field densities for aligned case

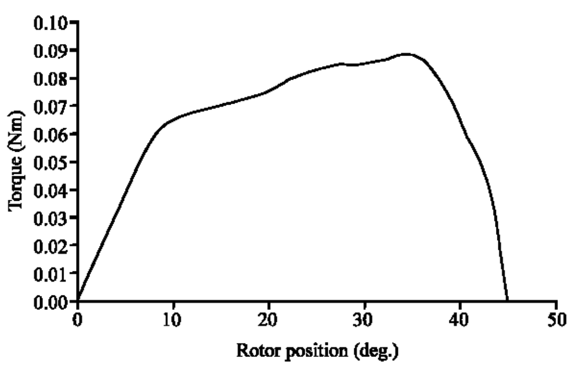

Fig. 7: Static torque versus rotor positions

EXPERIMENTAL RESULTS

The motor has been fabricated and tested for performance and functionality in the laboratory. Figure 8 shows the novel motor/generator fabricated in the laboratory.

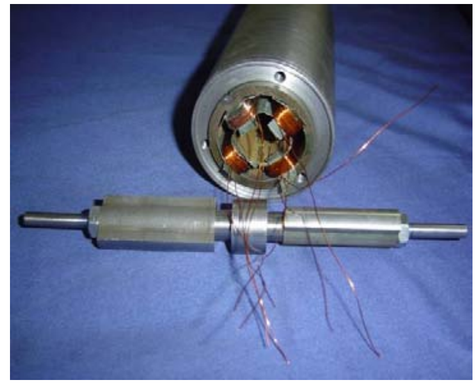

Fig. 8: The actual motor/generator

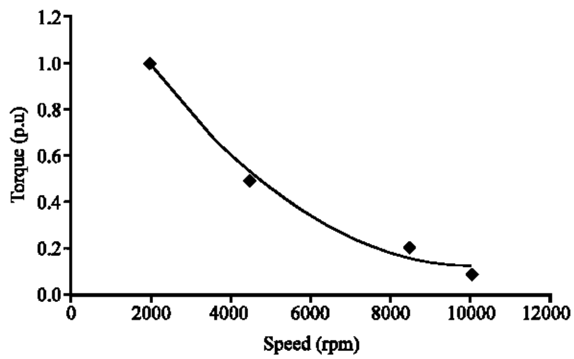

Fig. 9: Torque versus speed

The static torque of the motor was obtained by blocking the motor at different angle. The average static torque for a rated current of 3 (A) was measured to be about 7 (N. cm) over the stator pole arc (0 to 45°). It suddenly went to zero at the start of stator to rotor complete overlap. It was observed that the static torque shows lower value than computed which is expected, because the silicon steel sheet material used to build the motor is not quite what was used for the numerical analysis. Using a motor generator assembly, the dynamic torque for the motor versus speed has been measured by loading the motor. The torque-speed characteristic of the motor is shown in Fig. 9. The power curve fitting has been used for the data points. The torque-speed characteristics of the motor are like a series DC motor. Figure 10 shows the torque versus current under different loads.

The torque is proportional to the square of motor current which resembles the DC series motor (Fig. 10).

Figure 11 shows a set of opto-couplers with slotted disc as shaft position sensor is installed on the back of the motor in order to synchronize the proper firing of each phase transistor.

There are four opto-couplers, two for each layer and a slotted disc with two 45° openings, since each stator arc is 45°.

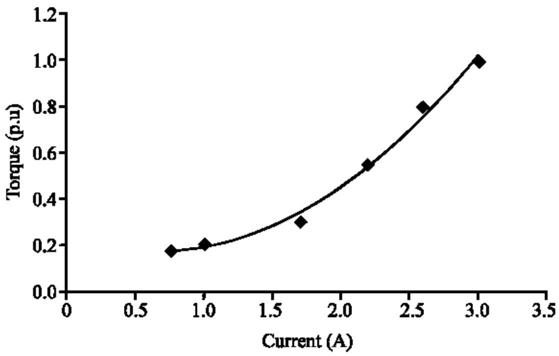

Fig. 10: Torque versus current

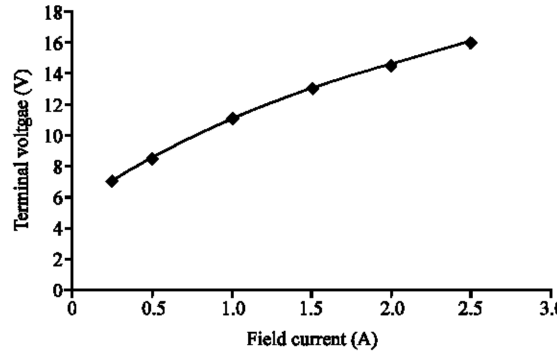

Fig. 13: Generator terminal voltage vs. field current

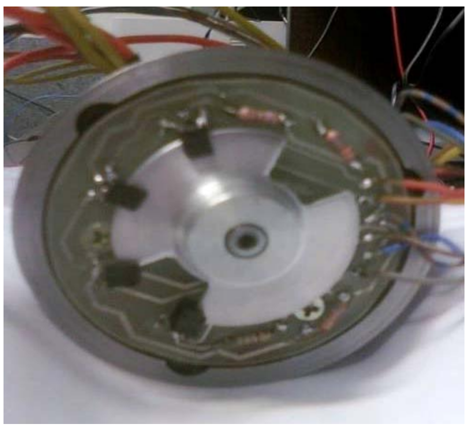

Fig. 11: Direct shaft position sensors

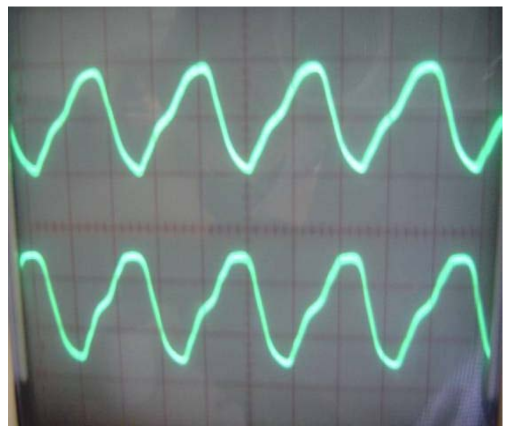

Fig. 14: Output voltages for two consecutive phases

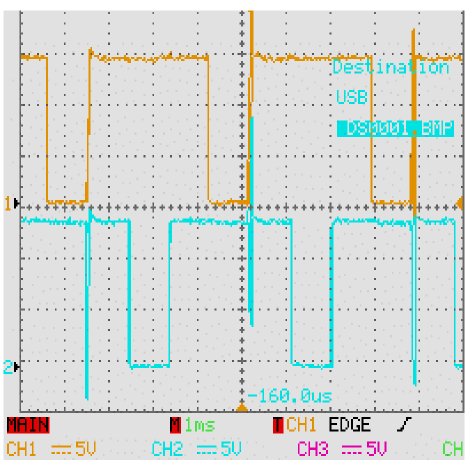

Fig. 12: The output signals from the photo-interrupters

Figure 12 shows the output signals coming from the photo-interrupters mounted on the back of the motor.

There are eight 45° pulses produced by the motor shaft position sensors and each pulse appears 4 times in one rotation.

In the generator mode, the shaft of the motor/generator machine is connected to a motor to act as a prime mover also the coil windings are set in such a way that the stator coils producing north poles in one layer and south poles in the other layer. The speed of the motor kept constant for various field currents, the resulting terminal voltage is shown in Fig. 13.

In Fig. 12 and 13, curve fitting (power) has been used for better presentation of the data points.

The actual output voltages for two consecutive phases are also shown in Fig. 14.

The phase shift is clearly shown in Fig. 14. The voltages have harmonics which are due to the shape of the stator and rotor poles as well as saturation inside them.

CONCLUSION

In this study, a novel two phase hybrid motor/generator was fabricated in the laboratory. Some of the motor parameters numerically computed and experimentally measured and tested. The main objective of this study namely, introduction of a new motor/generator configuration with durability has been achieved. The experimental analysis shows the functionality of the motor/generator in its new configuration, meaning, it has the ability and the potential of becoming a motor potentially be used in hybrid vehicle.

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