DESIGN IMPROVEMENTS OF 12 SLOT-14 POLE HYBRID EXCITATION FLUX SWITCHING MOTOR WITH 1.0KG PERMANENT MAGNET FOR HYBRID ELECTRIC VEHICLES

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For my beloved husband, Mr Mohd Rizwan Bin Mohd Rashid, my father, Mr Ahmad Mazlan bin Yahaya and my mother Mrs Habsah Bin Jaffar, thank you for the support, encouragement and spiritual. Also thank you to my supervisor, Dr Erwan Bin Sulaiman for the guidance, opinion and advices.

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ABSTRACT

Flux switching machine (FSMs) is a new class of brushless motor used in the automotive industry and have been developed in recent years. The FSMs can be divided into three groups which are permanent magnet flux switching machine (PMFSM), field excitation flux switching machine (FEFSM) and hybrid excitation flux switching machine (HEFSM). Among these three groups, HEFSM has several attractive features and offers the advantages of robust rotor structure together with variable flux control capabilities. These advantages make this machine more attractive to apply for high-speed motor drive system. This project is a design improvements of 12 slot- 14 pole hybrid excitation flux switching machine (HEFSM) with 1.0 kg permanent magnet (PM) for hybrid electric vehicles(HEVs). The design target of maximum torque is 333Nm, a maximum power of more than 123kW, and a maximum power density of more than 3.5kW/kg. The performance of the proposed machine on the initial design and improvements design are analysed based on 2-D Finite element analysis (FEA). The final results prove that the final design HEFSM is able to keep the maximum torque when compared to the initial design HEFSM.

ABSTRAK

Motor Pensuisan Fluks (FSMs) adalah motor berkelas yang digunakan dalam industri automotif yang baru dan telah dibangunkan dalam tahun kebelakangan. FSMs ini boleh dibahagikan kepada tiga kumpulan iaitu Motor Pensuisan Fluks Magnet Kekal (PMFSM), motor pensuisan fluks pengujaan medan (FEFSM) dan motor pensuisan fluks pengujaan hybrid (HEFSM). Antara ketiga-tiga kumpulan ini, HEFSM mempunyai beberapa ciri-ciri yang menarik dan menawarkan kelebihan struktur rotor teguh bersama dengan keupayaan kawalan pembolehubah sentiasa berubah-ubah. Kelebihan ini menjadikan mesin ini lebih menarik untuk diaplikasikan pada sistem pacuan motor yang berkelajuan tinggi. Projek ini adalah penambahbaikan kepada reka bentuk 12 slot-14 pole motor pensuisan fluks pengujaan hybrid (HEFSM) dengan magnet kekal 1.0 kg (PM) untuk pengangkutan elektrik hybrid (HEVs). Sasaran reka bentuk adalah tork maksimum adalah 333Nm, kuasa maksimum lebih daripada 123kW, dan ketumpatan kuasa maksimum lebih daripada 3.5kW / kg. Prestasi mesin yang dicadangkan ini untuk reka bentuk awal dan rekabentuk penambahbaikan akan dianalisis menggunakan 2-D finite element analisis (FEA). Keputusan akhir menunjukkan bahawa rekabentuk penambahbaikan dapat menjana tork maksimum yang lebih tinggi berbanding rekabentuk awal.

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LIST OF SYMBOLS AND ABBREVIATIONS

BRICs	Brazil, Russia, India, China and South Africa
EV	Electric Vehicles
FEC	Field Excitation Coil
FEFSM	Field Excitation Flux Switching Machine
FSM	Flux-switching Machine
FSPM	Flux-switching permanent magnet
HEFSM	Hybrid Excitation Flux Switching Motor
HEV	Hybrid Electric Vehicles
ICE	Internal Combustion Engine
IM	Induction Motor
IPMSM	Interior Permanent Magnet Synchronous Motor
kW	Kilo- Watt
mm	Milimeter
Nm	Newton metre
PM	Permanent Magnet
PMFSM	Permanent Magnet Flux Switching Machine
r/min	Revolutions Per Minute

CHAPTER 1

INTRODUCTION

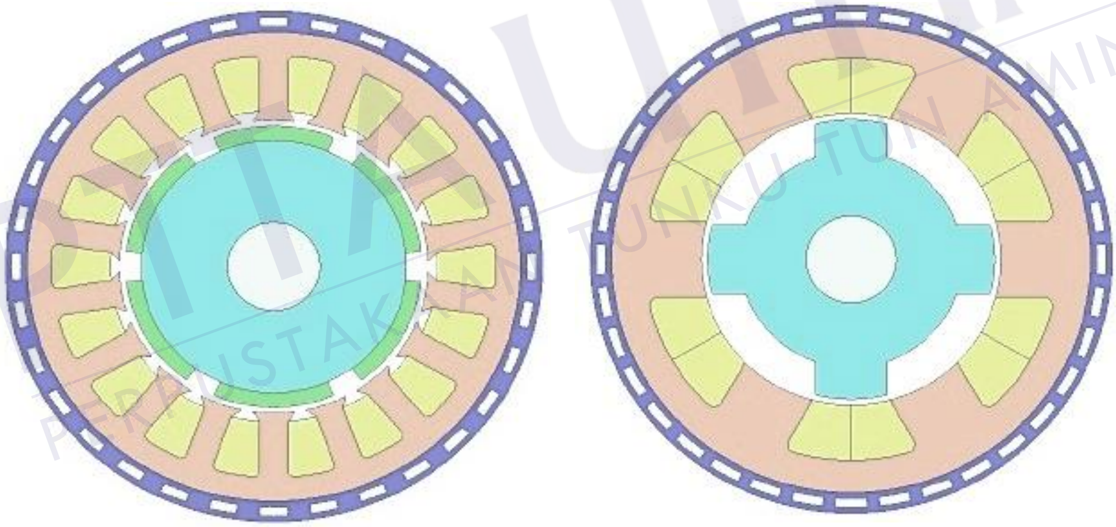
This chapter introduces the idea and concept of the project. It consists of project background and the overview of the project.

1.1 Project Background

Conventional internal combustion engine (ICE) was equipped in vehicles and have been used as a personal transportation for over 100 years. As demand of the private vehicles are also increasing due to the rates of world population. This trend will only intensify with the catching up of developing countries like BRICs [1]. The main problems due to these demands are related to emissions, fuel economy and global warming. Also the prices of fossil fuels keep rising. The greenhouse effect, also known as global warming, is an issue that all people have to face. This matter encouraged people to look at EV’s as a possible alternative mode of transportation as well as the cost and limitations supply of gasoline products.

Electric vehicles have been existence for a very long time. Electric vehicles give very low acoustic noise and zero emissions. The propulsion system for electric vehicles consists of batteries, electric motors with drives, and transmission gears to wheels.

At present, the major types of electric motors under serious consideration for HEVs as well as for EVs are the dc motor, the induction motor (IM), the permanent magnet synchronous motor (PMSM), and the switched reluctance motor (SRM). Based on the exhaustive review on state of the art of electric-propulsion systems, it is observed that investigations on the cage IMs and the PMSMs are highly dominant, whereas those on dc motors are decreasing but SRMs are gaining much interest. Due to the large torque capability and high torque (power) density, Flux-switching permanent magnet (FSPM) machines have attracted considerable attention in recent years, as well as compact and robust structure since both the locations of magnets and armature windings are located in stator instead of rotor as those in the conventional rotor-PM machines [3].



a) b)

Figure 1.1: Cross sections of traction motors (a) PM brushless motor (b) switch reluctance motor

This project deals with a design optimization of hybrid excitation flux switching motor (HEFSM) with 0.4kg permanent magnet. Among various types of HEFSSM, the machine with both permanent magnet (PM) and field excitation coil (FEC) on the stator has the advantages of robust rotor structure together with variable flux control capabilities that make this machine becoming more attractive to apply for high-speed motor drive systems.

However, for solely PMs excited machines, it is a traditional contradiction between the requests of high torque capability under the base speed (constant torque region) and wide speed operation above the base speed (constant power region). Hence, hybrid-excitation flux-switching machines (HEFSM) are proposed in which the magnet dimensions were reduced to save room for the introduced field excitation coil (FEC) windings. It is obvious that with variable dc FEC, the air gap field of HEFSM can be easily controlled and is favorable for Electric Vehicle (EV) applications [4].

1.2 Problem statement

With the issue of the global warming become an important issue in the 21st century, it concerns about environmental protection and energy conservation where carbon dioxide (CO2) gas emissions should be reduced to maintain the air quality. With the advent of more stringent regulations related to emissions, fuel economy, and global warming, as well as energy resource constraints, electric, hybrid, and fuel-cell vehicles have attracted increasing attention from vehicle manufactures, governments, and consumers. The demand toward vehicles for personal transportation has increased due to the increase of world population. To maintain and develop these energy consuming technologies, availability of sustainable energy sources and their effective utilization through efficiency improvements are of paramount importance. This increase has mainly come from new demands for personal-use vehicles powered by conventional internal combustion engines (ICEs) [1]. Government agencies and organizations have developed more stringent standards for fuel consumption and emissions due to the environmental problems.

Oil consumption of the transportation sector has grown at a higher rate than any other sector in these decades. The prices of oil also continue increase dramatically while tougher regulations and policies on permitted exhaust gasses are being instituted in major cities of the world. These related issues are compelling vehicle manufacturers to come up with fuel efficient vehicles that called hybrid electric vehicles. Electric (battery) vehicles exist for a long time and give very low acoustic noise and zero emissions. One of the most valuable achievements in power electronics is to introduce degree of freedom to variable frequency from the fixed value of the generated electrical power supplies. Over 60% of the generated energy is consumed by electric motors. Variable speed drive, which regulates the speed of the motor by controlling the frequency, can significantly reduce the energy consumption, particularly in heavy-duty systems. Thus, improvements in efficiency of the drive systems are the most effective measures to reduce primary energy consumption, and thereby reduce CO2 gas emissions which cause global warming [5-6].

The complex management of power distribution which required for hybrid electric vehicle (HEV) with two power sources of engine and battery is not needed because of the power source of HEV is only battery. In addition, most of commercial HEV used single motor and transmission gears coupled to the wheels. This system composed of many components and lead to transmission losses and also less efficiency and reliability. To enable HEV to directly compete with gasoline vehicles, an electric motor installed on HEV aims to pursue high-efficiency, high power and torque density, high controllability, wide speed range and maintenance-free operation, thus reducing the gas emissions. [7].

To meet this challenge, many automotive companies have been commercializing HEV, in which IPMSM using rare-earth magnet has been employed as their main traction drives. This is due to the restriction of motor size to ensure enough passenger space and the limitation of motor weight to reduce fuel consumption [7]. Although the torque density of each motor has been hardly changed, a reduction gear has enabled to elevate the axle torque necessary for propelling the large vehicles such as RX400h and GS450h [7]. From this trend, IPMSM design tends to be difficult because all PMs used in IPMSM are on the rotor part and hence, to ensure the mechanical strength of rotor relies on the number of bridges and rib thickness between PMs. Therefore, this researches and developments on a new machine with high power density, robust rotor structure for high-speed operation, and with no or less-rare-earth magnet machines would be very important [7].

1.3 Objectives

The objectives of this project are:

i) To design improvements of 12 slot-14 pole hybrid excitation flux switching motor synchronous machine (HEFSSM) with 1.0kg permanent magnet

ii) To analyze performances of the design motor under no load, load and torque speed.

iii) To improve the initial design of 12 Slot-14 Pole until the performances are achieved.

1.4 Scopes

The scopes of the project are:

i) Design by using software JMAG Designer version 13.0

ii) The outer diameter, the motor stack length, the shaft radius and the air gap of the main part of the machine design being 264mm, 70mm, 30mm and 0.8mm.

iii) Electrical restriction to field excitation current density(J_e), armature current density (J_a) and the limit of the current density is set to the maximum of 30 A_{rms}/mm^2 for armature winding and 30 A/mm^2 for FEC. The armature coil current (I_a) is set to $360A/mm^2$.

CHAPTER 2

OVERVIEW OF FLUX SWITCHING MACHINES (FSMs)

2.1 Introduction

Flux switching machine is a new class of brushless motor as an alternative to the permanent magnet brushed motor used in the automotive industry. It is the combination of switch reluctance machine (SRM) and synchronous machine. This new flux switching motor is a very simple motor to manufacture and coupled with a power electronic controller and requiring only two power semiconductor switches. It has the potential to be extremely low cost in high volume applications. The advantages of this machine are high-power density and relative high efficiency in a smaller and lighter package. Another advantage is the simplicity of the rotor, which allows for easy manufacture and attainment of relatively high speeds in operation. The shape of the rotor is designed to present a variable reluctance to the windings on the stator as it rotates, modulating the flux in defined sections of the stator to produce bipolar AC flux linkages of the armature windings. The FSM incorporates the features of a conventional switched reluctance (SR) machine and a conventional dc machine.

2.2 Classifications of Flux Switching Machine (FSM)

The FSMs can be divided into three groups which are permanent magnet flux switching machine (PMFSM), field excitation flux switching machine (FEFSM) and hybrid excitation flux switching machine (HEFSM). PMFSM and FEFSM has only PM and field excitation coil (FEC) as their main flux sources. HEFSM combines both PM and FEC as main flux sources. Figure 2.1 below, illustrates the classifications of FSMs.

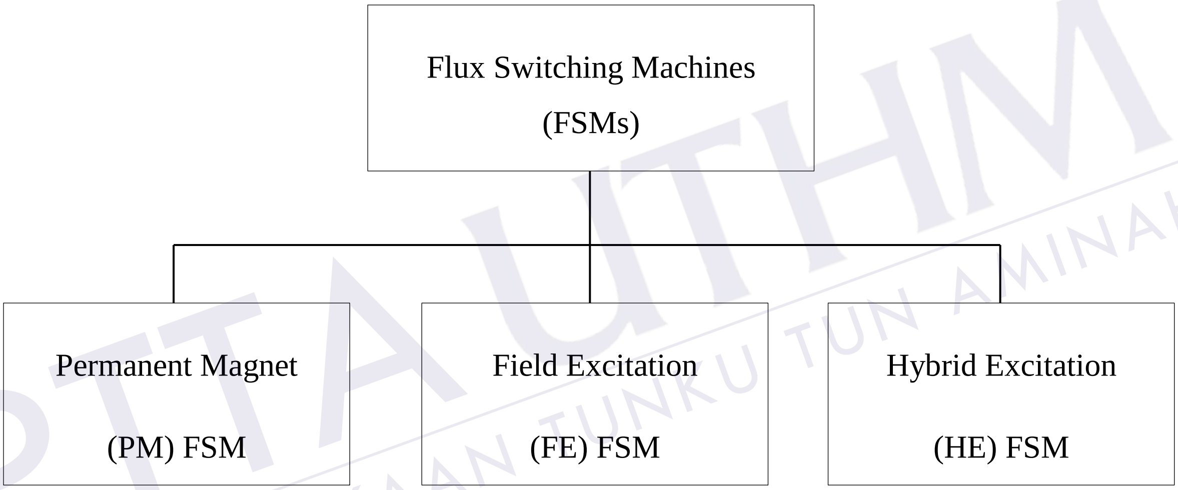


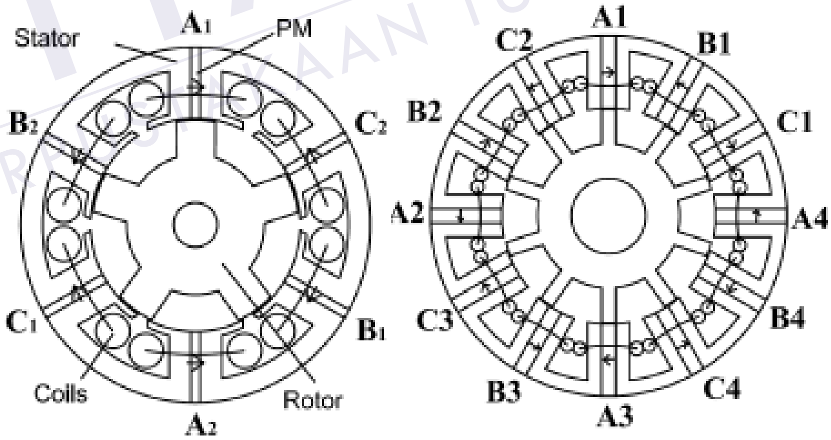
Figure 2.1: Classification of flux switching machine (FSMs)

2.3 Permanent Magnet Flux Switching Machine (PMFSM)

Development of Permanent Magnet Flux Switching Machines (PMFSM) for electric vehicle applications has gained popularity. The principle of PMFSM has been studied for several decades. Both permanent magnets and armature windings are located in the stator in PMFSM and a robust rotor similar to that of Switched Reluctance Machines (SRM) is employed. The permanent magnet flux switching (PMFS) machine is a less common type of PM machines comprising a passive and robust salient-pole rotor and a complex salient-pole stator with armature windings and permanent magnets.

Figure 2.2 shows a typical 6S-5P PMFSM and 12S-10P PMFSM. The concentrated windings employed in the PMFSM are also similar to those in the SR motor. In the PMFSM machine a concentrated coil is wound around two adjacent teeth with a piece of permanent magnet (PM) between them, and the two teeth and the magnet form a stator pole. This leads to low copper consumption and low copper loss due to the short end-windings. The magnets are tangentially magnetized, with the opposite direction in the adjacent magnets. Therefore, the number of stator poles must be even, and also must be integral times 3 for the 3-pole PMFSM.

The stator armature winding consists of concentrated coils and each coil being wound around the stator tooth formed by two adjacent laminated segments and a magnet. In the same figure, all armature coil phases such as A1, B1, C1, A2, B2 and C2 have the same winding configuration and are placed in the stator core to form 12 slots of windings. The slot area is reduced when the magnets are moved from the rotor to the stator, it is easier to dissipate the heat from the stator and the temperature rise in the magnet can be controlled by proper cooling system.



a) 6S- 5P b) 12S- 10P

Figure 2.2: 3-phase PMFSMs

The general operating principle of the PMFSM is illustrated in Fig. 2.3, where the black arrows show the flux line of PM as an example. The PM flux which is linked in the coil goes out of the coil and into the rotor tooth in figure 2.3 (a) then the flux-linkage corresponds to one polarity. The PM flux goes out of the rotor tooth and into the stator tooth when the rotor moves forward to the direction in Fig. 2.3 (b), keeping the same amount of flux-linkage whilst reversing the polarity. Consequently, as the rotor moves, the flux-linkage in the windings will change periodically, and back-EMF will be induced. Both the PM flux-linkage and back-EMF can be sinusoidal versus the rotor position as long as the machine is properly designed, thus it can be driven in the blushless ac (BLAC) mode.

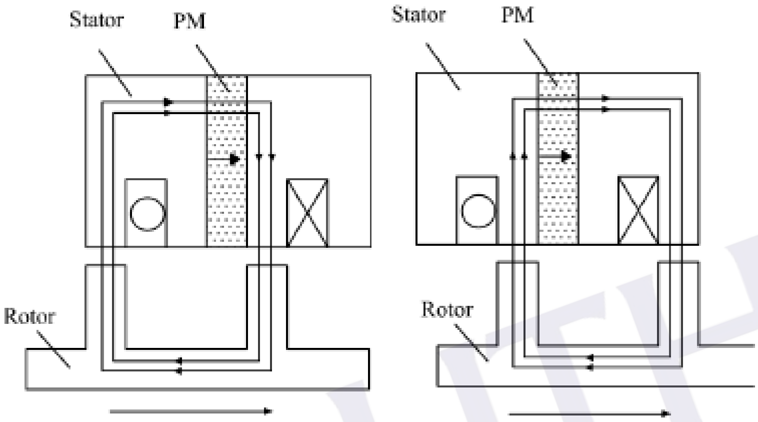
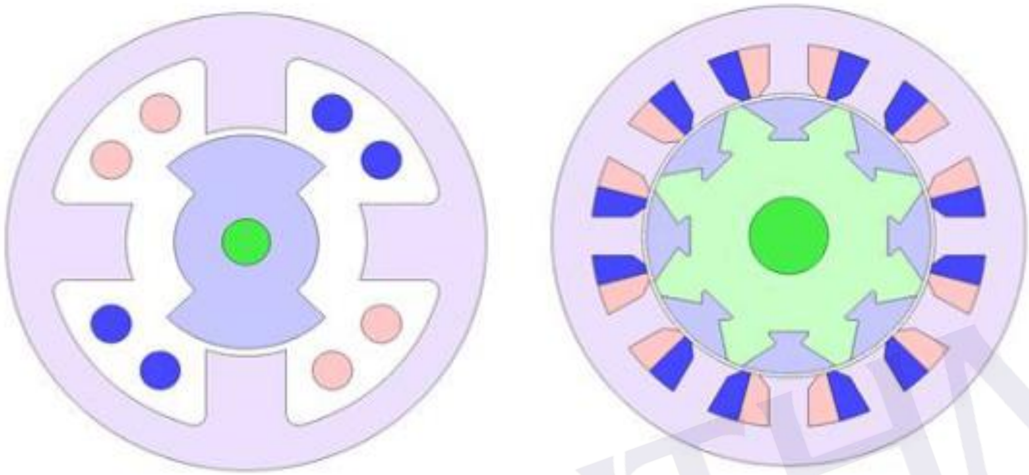


Figure 2.3: Operation principle of PMFSM

The problem of such kind of machine is the rotor mechanical strength which needs to be considered if the machine is applied for high speed applications. In addition, the summary of various types of PMFSMs are also discussed in [8].

2.4 Field Excitation Flux Switching Machine (FEFSM)

The PM excitation on the stator of conventional PMFSMs can be replaced by DC FEC to form FEFSMs. Various types of FEFSM are shown in figure 2.4. The machine consists of only field excitation coil (FEC) and armature coil allocated on the stator part. The rotor consists of only single piece iron, becoming more robust and more suitable for high speed operation. The concept of the FEFSM involves changing the polarity of the flux linking with the armature coil windings, with respect to the rotor position. Both armature coil and FEC windings are placed in the stator which overlapped each other as seen in a figure. The novelty of the invention is that the single-phase ac configuration could be realized in the armature windings by deployment of DC FEC and armature winding, to give the required flux orientation for rotation. The torque is produced by the variable mutual inductance of the windings.



(a) (b)

Figure 2.4: (a) 1-phase 4S-2P FEFSM (b) 3-phase 12S-8P

The term flux switching is to describe machines in which the stator tooth flux switches polarity following the motion of a salient pole rotor. All excitation sources are located on the stator with the armature coils and FECs allocated to alternate stator teeth. In the 12Slot-10Pole machine, the FECs produce six north poles interspersed between six south poles. The three-phase armature coils are accommodated in the 12 slots for each 1/4 stator body periodically. The fluxes generated by mmf of FECs link with the armature coil alternately as the rotor rotates. For the rotor rotation through 1/10 of a revolution, the flux linkage of the armature has one periodic cycle and thus, the frequency of back-emf induced in the armature coil becomes ten times of the mechanical rotational frequency.

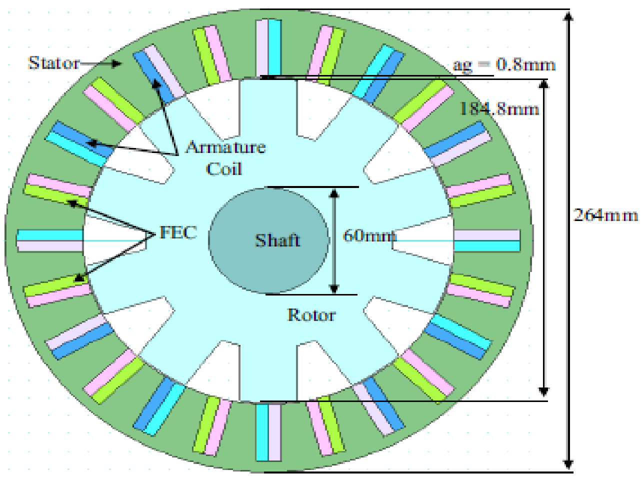


Figure 2.5: 12S-10P FEFSM

The operating principle of the FEFSM is illustrated in Figure 2.6. The direction of the FEC fluxes into the rotor shown in Fig. 2.6 (a) and (b) while Fig. 2.6 (c) and (d) illustrate the direction of FEC fluxes into the stator which produces a complete one cycle flux. The flux linkage of FEC switches its polarity by following the movement of salient pole rotor which creates the term “flux switching” similar as PMFSM. Each reversal of armature current shown by the transition between Fig. 2.6(a) and (b), will cause the stator flux to switch between the alternate stator teeth. The flux does not rotate but shifts clockwise and counterclockwise with each armature-current reversal. With rotor inertia and appropriate timing of the armature current reversal, the reluctance rotor can rotate continuously at a speed controlled by the armature current frequency. The armature winding requires an alternating current reversing in polarity in synchronism with the rotor position. The cost of the power electronic controller must be as low as possible for automotive applications.

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