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FEATURE
TECHNOLOGIES

Electric Vehicles and Axial Flux Permanent Magnet Motor Propulsion Systems

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I. Introduction

Overview

Recent years have shown a resurgence in electric vehicle drive research and development. This trend has been stimulated by various factors including rising fossil fuel costs and environmental concerns. New developments in basic technologies, such as improved permanent magnets, switching transistors and storage batteries (although these remain a weak point in modern electric vehicles), have contributed to recent developments in electric vehicle propulsion motors [1]. Several novel motor configurations have been investigated by various groups and organizations. In addition, new technology has allowed motor types, such as variable reluctance stepping motors and brushless DC motors, previously not suitable for use in electric vehicles, to be adapted for use as electric vehicle propulsion systems.

In addition to providing a brief history of the electric vehicle, the goal of this paper is to give a short overview of recent developments in electric vehicle propulsion systems with an emphasis on a particular class of motors, namely the variable reluctance axial flux permanent magnet motor.

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A Brief History of the Electric Vehicle

The brushed DC motor has been the mainstay of EV propulsion for close to 100 years. In the early part of the 20th century, both electric and fossil fuel vehicles were in development. Early electric vehicles used simple DC motors, lead-acid batteries and rheostat speed controls. Due mainly to the relatively low power densities of early electric storage batteries compared to that of fossil fuels, electric vehicles began to fall out of favor. By 1915 the rate of development of the internal combustion engine vehicle was proceeding more rapidly than that of the electric vehicle. The internal combustion engine vehicle quickly outpaced the electric vehicle in power, top speed and range. By the 1920s, electric vehicle technology for small vehicles was almost completely abandoned.

The early 1960's saw a resurgence in electric vehicle development. Although the internal combustion engine vehicle remained almost completely dominant in the market place, several companies began developing and building prototype electric vehicles. While the brushed DC motor continued to be used in electric vehicle propulsion, this period saw the implementation of several new motor types not available to engineers in the early part of the century. Variable frequency AC induction motors have been used in prototype vehicles since the resurgence of the electric vehicle, and in production electric vehicles since the late 1980's [2]. General Motors used AC induction motors in several of its prototype electric vehicles in the 1960's. The first production line electric vehicles, the General Motors EV1 and its predecessor the Impact, both used 3-phase induction motors.

The period from the late 1980's to the present represents a second resurgence for electric vehicle development. In the last decade several major automobile companies, including General Motors, Honda, Nissan, Daimler-Chrysler and others, have offered electric vehicles for sale as fleet vehicles and to the general public. In addition, various dedicated electric vehicle companies, such as Solar Vehicles Inc. and Green Motor Works, have appeared on the scene. Numerous companies selling electric vehicle components and gas-to-electric vehicle conversion plans have also sprung up.

Although it seems that the electric vehicle still hasn't caught the public's eye, the electric vehicle is here to stay. In recent years, large auto companies have allocated significant research and development funds to electric vehicles. For example, General Motors has invested billions of dollars in electric vehicle development in the last few years. In Europe and Asia, pure electric and hybrid electric vehicles are already on the road. The U.S. has lagged behind somewhat, with electric vehicles from the big auto companies only available for lease or as fleet vehicles in a few states including California, Arizona and New York. At the time of the writing of this article, both Toyota and Honda have electric vehicles in production. These vehicles will be shipped to dealers in the U.S. in December 1999 and January 2000, and will be for sale to the general public. Figure 1 shows the Honda EV Plus, now available through dealers nation wide in the US.

Figure 1. The Honda EV Plus.

New and Emerging Electric Vehicle Propulsion Systems

In recent years many new motor topologies have been proposed for use in electric vehicles. Some of these new motor types have been used in production electric vehicles while others remain in the prototype and development stages. As mentioned above, the variable phase induction motor has been used since the 1960's and continues to be the motor of choice for the major electric vehicle developers (GM, Ford and Daimler-Chrysler) in the U.S. market [3]. In the last ten years several other motor types have been researched and/or used for electric vehicle propulsion. These include the permanent magnet synchronous AC machine, the brushless DC motor, and the variable reluctance motor. In contrast, the Japanese companies, Honda, Toyota and Nissan, all use brushless DC motors in their electric vehicles. EMB Inc. has recently offered a line of electric motorcycles, which utilize variable reluctance brushless DC motor drive systems. In addition, implementation of electric vehicle drives based on several more esoteric motor topologies, such as the hybrid induction motor and the permanent magnet hysteresis hybrid synchronous motor, have been proposed.

One interesting and promising new motor topology is the axial flux permanent magnet DC machine [4]. A particular configuration of this class of motors, the axial flux variable reluctance permanent magnet disc motor, will be considered in more detail in the next section of this paper.

II. The Axial Flux Variable Reluctance Permanent Magnet Disc Motor

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A General Overview of Variable Reluctance Motor Function and Structure

The basic means of torque development in a variable reluctance motor is magnetic attraction between electromagnetic coils, usually on the stator, and iron or permanent magnets on the rotor. When a stator coil is excited with electric current, magnetic flux is induced. The induced flux flows through the core of the excited coil, across the stator-rotor air gap, and through one or more static flux paths on the rotor, thus producing magnetic attraction between the stator and the rotor. As the rotor turns, the air-gap portion of the flux path changes, thus the name "variable reluctance".

One can also describe force development in variable reluctance motors in terms of the law of conservation of energy. In a magnetic system, a force will be generated that tends to reduce the reluctance of any flux path to a minimum. When a flux producing coil is excited, a directed force is generated that tends to move the rotor to a position that minimizes the variable part of the flux path (in this case, the air gap), thus causing rotational torque (depending on the initial position of the rotor). Figure 2 shows a typical 3-phase six stator coil four rotor pole variable reluctance motor layout.

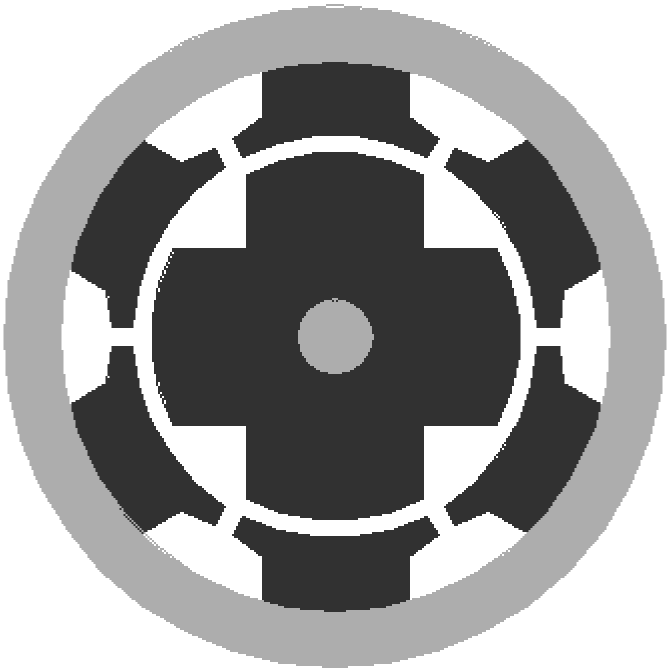

Figure 2. Cross sectional view of a six coil four pole variable reluctance motor.

A Specific Motor Topology

For purposes of illustration and explanation, we will consider a particular motor configuration, the axial flux variable reluctance permanent magnet disc motor, in more detail. For the remainder of this article, the term axial flux disc motor will be used to refer to this particular class of motors. The reader should note that in the broader context of motor design, the term axial flux disc motor describes a much larger class of motors, including various types of brushless DC and synchronous motors.

The motor described below has been prototyped for purposes of demonstration and control research in the Advanced Diagnosis and Control (ADAC) lab at North Carolina State University, and is shown in Figure 3. This motor has four permanent magnet rotor poles and seven stator phases. Each stator phase consists of two coils to make a total of 14 stator poles.

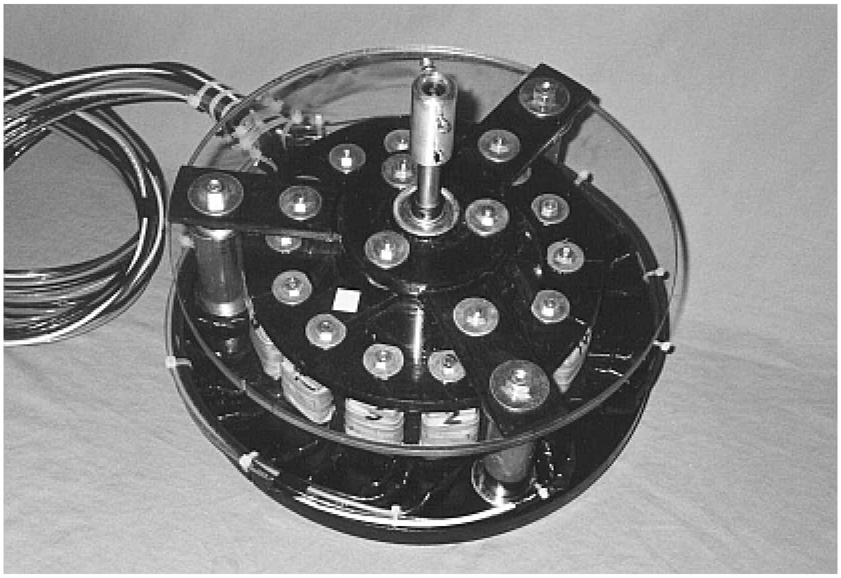

Figure 3. The ADAC axial flux disc motor.

The motor has wound coils on the stator and permanent magnets on the rotor. In this motor design, the phrase "Axial Flux" indicates that the stator coils and rotor poles are arranged so that the magnetic flux paths have components that are parallel to the axis of the rotor. The rotor is a disc with permanent magnets set into the edge of the disc so that each pole of every magnet is oriented toward one or the other face of the disc. Similarly, the stator coils are arranged to induce north and south poles oriented axially as to attract (or repel) a pair of rotor poles. Note that the term "pole" actually refers to a set of north and south poles from a single permanent magnet.

Figure 4 shows a schematic representation of the axial flux disc motor described above. Note that the rotor 'disc' in this case has a relatively small radius. Motors of this type can be made to have much wider disc rotors (resulting in higher torque) without significantly increasing overall motor weight. Two stator coils and two rotor permanent magnets have been shaded in Figure 4 to emphasize the torque generation relationship between the stator and the rotor.

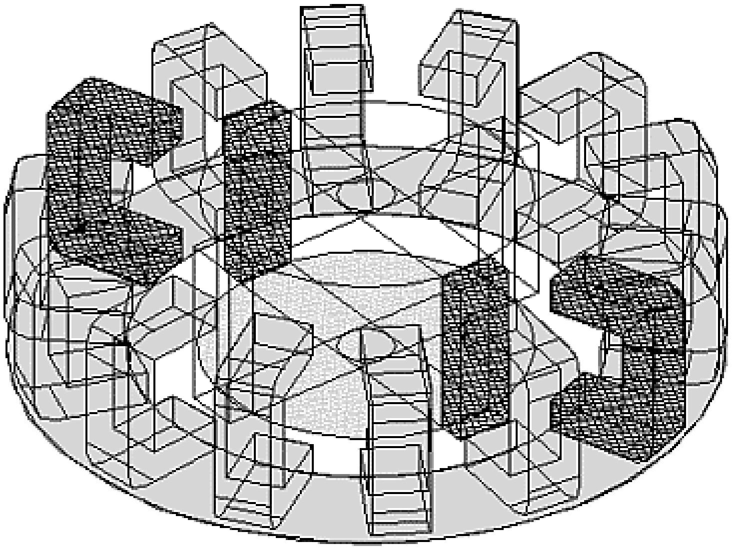

Figure 4. Drawing of the axial flux disc motor.

Unlike traditional variable reluctance motor arrangements, it should be emphasized that magnetic flux does not flow through the center of the rotor, nor does it flow circumferentially around the stator during motor operation. Flux generated by a stator coil flows axially through the stator coil core, then radially across the (upper) air gap, then axially through one or more rotor permanent magnets, and then back across the (lower) air gap to the originating stator coil. Motors of this configuration exhibit a high degree of flux path isolation. There is no low reluctance (iron) path between neighboring stator coils.

Modes of Operation

Motors of the configuration described above can be operated in several modes, including as a stepping motor, as a brushless DC motor (in conjunction with a rotor position sensor), and as a synchronous AC motor.

To operate this type of motor as a stepping motor, the stator coils are switched on and off in a set pattern that causes the rotor to “step” forward as the switching pattern proceeds.

Operation as a brushless DC motor requires the addition of a rotor position sensor. Often, Hall effect sensors are used for this purpose. Using position information from the sensor(s), the motor can be electronically commutated and driven as a DC motor via power switching devices such as MOSFETs [5].

To drive the motor as an AC motor, each coil must be fed with a differentially phased sinusoidal current. The number of coil sets per rotor pole determines the required number of current phases.

Advantages and Disadvantages of the Axial Flux Disc Motor

Compared to traditional motor configurations, axial flux disc motors have very short iron flux paths. Minimizing the iron flux path length results in a reduction in core losses (hystereses and eddy current losses). No eddy current losses within a permanent magnet are associated with flux generated by that permanent magnet. Thus the use of permanent magnets in the rotor also contributes to a reduction in flux path related losses. In addition, because permanent magnets produce magnetic flux, the torque to weight ratio of a permanent magnet rotor motor is higher than that of its iron rotor counterpart. Flux does not flow radially through the rotor, so the iron used in traditional rotor flux paths can be eliminated altogether. This motor configuration also provides for flux path isolation, which significantly reduces coil to coil induced inductance and associated losses. This flux path isolation structure also allows for a large degree of freedom in the choice of control strategy. Because of its light weight and high efficiency, this type of motor lends itself to use in electric vehicles, mobile electric equipment of various types, and many other applications.

The axial flux disc motor requires a more sophisticated control strategy than that of the brushed DC motor. A rotor position sensor is required in order to achieve efficient high speed control. This type of motor generally requires micro-processor based control for efficient power utilization. Also, since the stator contains many distinct core units and axially oriented windings, manufacturing complexity is increased.

III. Multi-Motor and Direct Wheel Drive Systems in Electric Vehicles

General Description

Direct wheel drive systems consist of a motor drive coupled directly to a driven wheel without any intervening gear or suspension linkage. As a result, there is a direct one to one correspondence between the rotation of the motor drive and that of the driven wheel. This arrangement simplifies the drive train considerably but alters the suspension characteristics of the vehicle. In a conventional drive system (electric or internal combustion), the only unsprung mass in the vehicle are the wheels and a small portion of the drive train. Generally, the drive motor(s) in a direct wheel drive system are part of the vehicle’s unsprung mass. Most electric motors and all internal combustion engines are too heavy to be removed from the body of the vehicle and incorporated into one or more of the drive wheels. In order for an electric motor to be suitable for use in a direct wheel drive system, it must have a relatively low mass and a high torque to mass ratio. In addition, direct wheel drive motors must have physical dimensions that are amenable to location near or in a drive wheel. Because of these constraints, various configurations of brushless permanent magnet DC motors and permanent magnet variable reluctance motors have been shown to be good candidates for direct wheel drive systems. The axial flux disc configuration allows for the incorporation of the motor directly into the hub of a driven wheel [4].

In the 1990’s new technologies, such as the development of powerful rare earth permanent magnets and advances in power switching electronics, have made the production of light weight high torque motors feasible [4].

Some Examples of Direct Wheel Drive Systems in Electric Vehicles

Recent years have seen the development of numerous direct wheel drive prototype vehicles. One of the earlier (1994) examples of a functional direct wheel drive electric vehicle was the Di-Elettrica [6], a motor scooter with a direct drive rear wheel. The Di-Elettrica was powered by a slotless axial flux permanent magnet DC motor with a single disc shaped stator sandwiched between two permanent magnet disc rotors. The motor was mounted inside the rim of the scooter’s drive wheel.

Eastham and Gair et al. describe a motor arrangement in which the stator of a permanent magnet disc motor is attached to the sprung body of the vehicle, while the rotor is attached to the unsprung drive wheel shaft [7]. This arrangement further reduces the unsprung mass of the vehicle, but requires a relatively complicated and dynamic control strategy to accommodate motor torque fluctuations due to constant and variable rotor-stator misalignment associated with vehicle suspension movement.

Motors have been specially designed for direct in-wheel use. Chen and Tseng and others describe permanent magnet motors designed and optimized for placement in the hub of an electric vehicle drive wheel [8].

The Four Direct Wheel Drive Electric Vehicle

One of the most promising direct wheel drive configurations for electric vehicles is the four in-wheel drive electric vehicle [9]. Figure 5 shows a four direct wheel drive electric vehicle arrangement. Incorporating a motor in each wheel increases the number of drive motors in the vehicle, thus decreasing the required power and mass of each individual drive motor. Four in-wheel drive vehicles require a distributed control system that can deliver the appropriate control to each individual drive motor. Although this may at first seem like a drawback, it should be noted that conventional four wheel drive systems also require a relatively complex control system to regulate the performance of the drive train. In addition, a modern conventional four wheel drive train and transmission system is quite complex mechanically and very expensive to manufacture. The complexity required to implement control in an electric four in-wheel drive system can be reduced to programming a micro-controller chip.

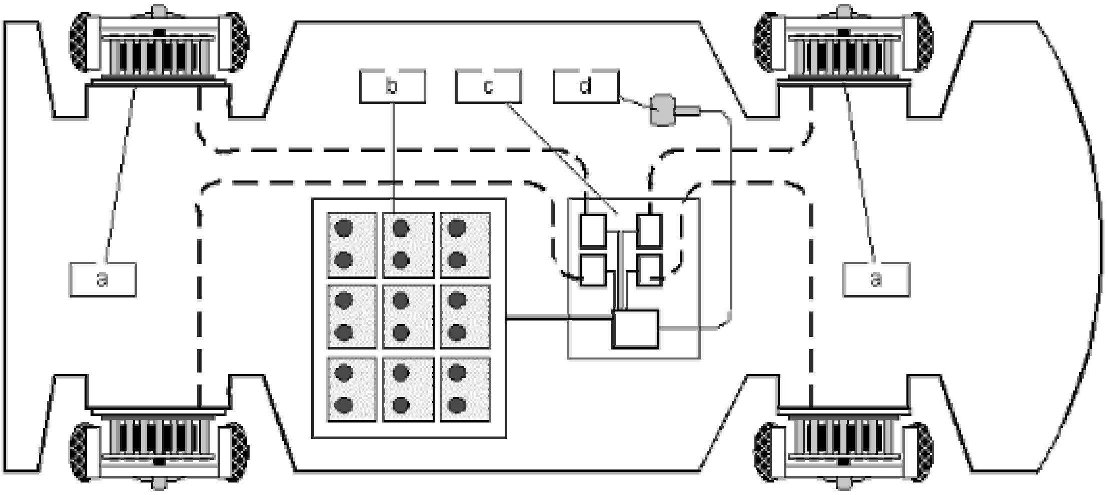

Figure 5. A four direct wheel drive arrangement showing motor and controller locations.

a) Each wheel has a disc motor mounted inside its hub.
b) Battery pack.
c) System controller.
d) Accelerator pedal.

IV. Closing Remarks

Challenges and opportunities for the future

The field of electric motor fault detection has generally received attention in the context of industrial applications. The working environment of electric motors used for electric vehicle drive applications is significantly different than that seen by typical industrial motors. In the coming era of hybrid electric, fuel cell electric, and pure electric vehicles, the field of motor fault detection in the context of electric vehicles will receive much greater attention.

Direct in-wheel drive systems offer opportunities for the development and implementation of dynamic fault detection and accommodation systems [10]. Multi-motor drive systems will require the continued development and application of distributed control technology.

New application specific motor topologies will continue to be developed. The line between motor design and motor control is becoming less distinct. As computer and power electronics technologies continue to advance, motor designs that take advantage of new control options are becoming more common. This blending of mechanical electrical design and control technology will offer new opportunities for motor designers, technology experts and control theorists to work together to develop more robust and efficient electric vehicle drive systems.

Acknowledgments

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References

[1] C.C. Chan, K.T. Chau, 'An Overview of Power Electronics in Electric Vehicles', IEEE Transactions on Industrial Electronics, vol. 44, no.1 pp. 3-9, 1997.

[2] K. Rajashekara, 'History of Electric Vehicles In General Motors', IEEE Transactions on Industrial Applications, vol. 30, no. 4, pp. 897-904, 1993.

[3] M.E. Hanson, 'A New Era Begins: Report on NAEVI 98' Conference', http://evworld.com, Digital Revolution, 1998

[4] F. Profumo, Z. Zhang, A. Tenconi, 'Axial Flux Machine Drives: A New Viable Solution for Electric Vehicles', IEEE Transactions on Industrial Electronics, vol. 44, no.1 pp. 39-45, 1997.

[5] J.R. Hendershot Jr., T.E. Miller, Design of Brushless Permanent Magnet Motors, Claredon Press, 1994.

[6] F. Caricchi et al, 'Compact Wheel Drive for EVs', IEEE Industrial Applications Magazine, Nov/Dec, pp. 25-32, 1996

[7] J.F. Eastham et al., 'Disc Motor with Reduced Unsprung Mass for Direct EV Wheel Drive', Proceedings of the IEEE International Symposium on Industrial Electronics, Athens, Greece, July 10-14, pp. 596-573, 1995.

[8] G.H. Chen and K.J. Tseng, 'Design of a Permanent-magnet Direct-driven Wheel Motor Drive for Electric Vehicles', Record of the IEEE PESC, June 23-27, pp.1933-1939, 1996.

[9] M. Terashima et al., 'Novel Motors and Controllers for High-performance Electric Vehicles with Four Wheel Motors', Transactions on Industrial Electronics, vol. 44, no.1 pp. 28-36, 1997.

[10] S. Altug, M.-Y. Chow, H.J. Trussell, 'Fuzzy Inference Systems Implemented on Neural Architectures for Motor Fault Detection and Diagnosis', IEEE Transactions on Industrial Electronics, vol. 46, no. 6, 1999.

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