Application of Permanent Magnet Synchronous Machines in Automotive Steering Systems

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Abstract - Several of the conventional hydraulic systems in an automobile are now being replaced by more reliable and energy efficient electromechanical systems. Developments in the brushless permanent magnet machine and in the power and control electronics are the key factors responsible for this transformation. These applications brought out some performance challenges associated with the brushless machines. This paper will focus on these challenges to be able to use these machines in such applications. In terms of replacing hydraulic systems with electromechanical systems, steering system is leading the way in automobiles. Currently, steering systems using Electro-hydraulically assisted systems and Electrically assisted (Electromechanical) systems are in the market. Though the Electrically assisted power steering has several advantages over other systems, certain performance and cost challenges delayed the penetration of such systems in to the market.

Keywords: automotive steering systems, electromechanical systems, brushless permanent magnet machine, electrically assisted power steering

1. Introduction

Since the introduction of the first automotive steering system in early 1900's, they have gone through several technological evolutions. Application of electronically controlled systems into steering application is the latest in this evolution. Recent advances in power electronics, control electronics, computing capability and machine design are all responsible for this transformation. The need for higher fuel efficiency and environmentally friendly vehicles is also fuelling the new evolution into the electromechanical systems.

Brushless permanent magnet machines are ideal for high performance applications due to several advantages such as high power density. However, several of the technical and commercial challenges associated with these machines need to be resolved before it fully penetrates the automotive drive applications. This paper discusses some of the future generation steering systems and some of the issues and challenges in using permanent magnet motor drives in such applications.

2. Assisted steering systems

The steering system in automobile converts driver's rotational input at the steering wheel or hand wheel into a change in the steering angle of the vehicle's road wheels to control the direction of motion. In earlier steering systems, the driver provided the required torque to steer the vehicle. As the vehicle is growing bigger in size and weight, the driver is unable to provide sufficient torque to steer the vehicle. In such cases additional mechanism to assist the driver is needed.

Traditionally, the power assist is obtained by hydraulic means, which was introduced around the 1950s. A hydraulic pump along with belt and pulley arrangement driven by the vehicle engine, pumps high-pressure fluid to move a piston in the steering gear assembly to assist the driver. The direction of movement is controlled by a valve mechanism. The hydraulically assisted system has an assist characteristic, which is independent of the vehicle speed. The variable speed-effort characteristic is obtained by using electronically controlled valve mechanisms or by electromagnetically controlled systems such as Magna Steer^{TM}[1]. The hydraulically assisted steering system provides exceptionally good steering feel characteristics. But, it has several disadvantages such as; a) low fuel economy due to the continuously running pump, b) end of life environmental issues, due to the hydraulic fluid and the hoses, c) increased vehicle tuning time and vehicle assembly time, d) increased engine accessories and e) the engine dependency on the assist.

Developments in power and control electronics and in electric machines led to the development of electrically assisted steering. The electrically assisted steering is developed to overcome the drawbacks associated with the hydraulic assisted steering systems.

2.1 Electro-Hydraulic Power Steering

Unlike the conventional hydraulic power steering, in the Electro-hydraulic power steering, the pump is driven by an

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electric motor. This system addresses the issues of engine dependency and engine accessories. It also provides with reduced fuel consumption as the pump speed is independent of the engine speed and the speed could be controlled to reduce the losses. These systems draw a continuous current of the order of few amperes from the battery to support mostly the hydraulic losses. During the steering maneuver depending on the vehicle size, the peak current drawn may be as high as 100 amperes from a 12V power system.

2.2 Electric Power Steering

In an electric power steering system, the assist to the driver is provided by an electric motor. An electric motor with a gear reduction mechanism is coupled to the main steering path to provide the assist. In Fig. 1, the assist mechanism is coupled to the steering path at the column (column assist). The assist could also be provided at the pinion (pinion assist) or even at the rack (rack assist). A block diagram of the system is shown in Fig. 2. The required motor torque can be written as

$$T_m = \frac{(T_L - T_D)}{\eta\, n} \tag{1}$$

where, T_D is the driver input torque, η is the efficiency of conversion, n is the gear ratio between the column and the motor, and T_L is the total load torque at the column. In addition, the motor speed ω_m and the steering wheel speed ω_s are related by

$$\omega_m = n\,\omega_s \tag{2}$$

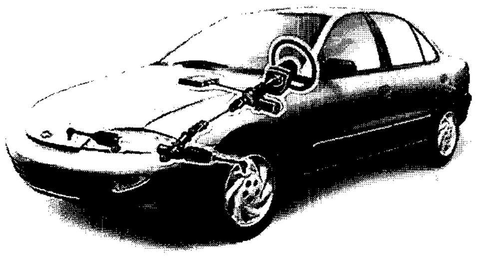

Fig. 1 Implementation of an electric power steering system

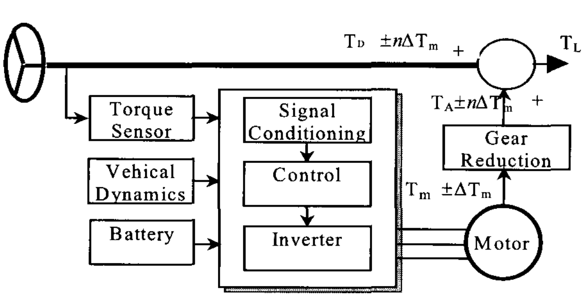

Fig. 2 Block diagram of an electric power steering system.

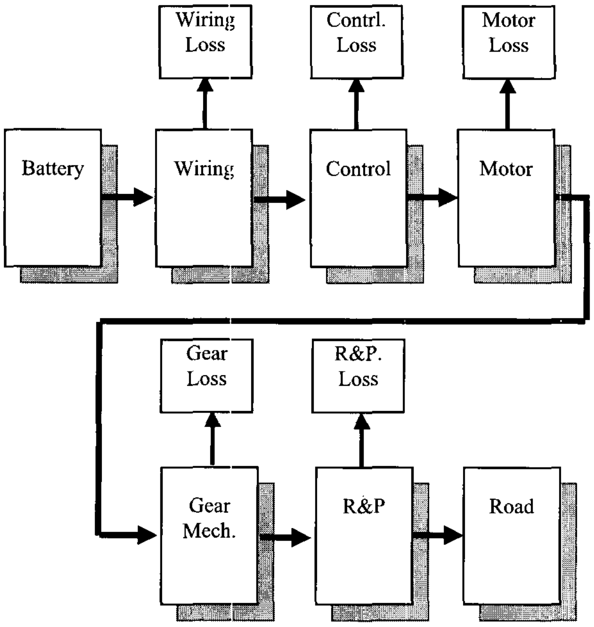

Fig. 3 Power flow in an electric power steering system.

Fig. 3 shows the power flow and losses in a typical electric power steering system. The power source for an automotive application is usually the battery with a nominal voltage of 12V. The maximum current draw allowed from the battery is usually about 75 -100 A, depending on the vehicle type and the manufacturer. This automatically places a limit on the input power (=12 x 75 = 900 W peak power). Based on this input power limitation, the designer has to allocate the efficiencies to the system components in order to get the required output power, which can vary depending on the vehicle steering loads, which in turn depends on the gross vehicle weight. Usually the overall system cost and efficiency is balanced with tradeoffs between the different components(i.e. gear reduction mechanism, electronic controller, motor and wiring harness).

The electric power steering is an on demand system. This results in an improved fuel economy to the vehicle. The system takes very little current to support the control electronics when the vehicle is not in a steering maneuver. In a steering maneuver, the battery current could reach up to 100A. Heavier vehicles will require higher current. This limits the usage of electric power steering for smaller vehicles, as the available battery current is limited. Also due to the engine independent nature, the steering assist will be provided even with the engine stalled as long as the battery power is present. It also reduces the engine accessories making it simpler to package. Another advantage of the electric power steering system is in the ease of tunability of the steering feel. The assist as a function of the vehicle speed can be easily programmed using software. The vehicle tuning time substantially reduced compared to a hydraulic power steering system [2]

3. Advanced steering systems

Steering systems have moved from just providing directional control, to also providing added comfort and enhanced vehicle stability. The introduction of electric power steering also allowed other modes of vehicle control. Recently, several systems such as four wheel steering were introduced in the market, which enabled better vehicle controllability.

3.1 Four Wheel Steering

The addition of steering capability to the rear wheels provides the vehicle with much more control options. The four-wheel steering introduced in trucks and sport utility vehicles allows for better vehicle maneuverability [3]. The advantages are obvious when the vehicle is used for tailoring and during parking. At low vehicle speeds, the rear wheels are in phase opposition to the front wheels and at higher vehicle speeds they are in phase with each other.

3.2 Active Front Steering Systems

Future steering systems will integrate other functions such as braking, throttle, suspension etc, to improve the vehicle stability and control. To accomplish this, there has to be some level of decoupling between the driver and the road wheels. Active front steering systems uses a differential arrangement to be able to control the road wheels either by the driver or by the motor.

3.3 Steer by Wire

Steer by wire system gives complete mechanical decoupling of the driver to the road wheel by eliminating all mechanical linkages between the steering wheel and the road wheel [4]. The sensors and control along with the drive motors precisely position the road wheels at the desired position. Such systems will require fault tolerant communication and control schemes. This system will require actuators to actuate the road wheels and to provide feedback to the driver.

4. Motors in assisted steering

Performance requirements and cost are primary drivers in technology selection for automotive applications [5]. Several motor technologies are viable for assisted steering applications. Inherently the nature of the steering application puts some stringent requirements to be met by the motor drive system. As new technologies are introduced, the balancing of the performance and cost becomes a significant challenge. Some of the major performance issues, besides the necessary speed and torque requirements, are discussed in this section.

4.1 Audible Noise

Audible noise is an important factor from the environmental and vehicular technology point of view. Quieter motors are always desired, especially for steering applications, since in some systems the noise can be heard in the passenger compartment. The noise requirements are very challenging, as it is not just the motor but the driven system has to be quiet enough to be acceptable. Sinusoidal type back-emf permanent magnet motors has definite advantage over other motor technologies.

4.2 Torque Ripple

Any torque ripple present in the developed motor torque (ΔT_m) will be amplified by the gear reduction mechanism as shown in Fig. 2. Since the motor is directly coupled to the steering wheel hence, the ripple constraint is more stringent. Also it is due to the impact it has on the tactile feel for the driver. Thus, the motor should provide sufficient torque with minimum torque ripple. Torque ripple may also contribute to the acoustic noise. Certain noise frequency may stimulate resonance with the driven system causing unacceptable audible noise.

4.3 Response Time

Response time is a key factor for safety critical applications such as steering, brakes, etc. During the transient response, the motor must be able to meet the system requirements. A motor with high torque to inertia ratio has definite advantage in this case. Permanent magnet motors have clear advantage since they can be designed for high torque density.

4.4 Fault-tolerance

For safety critical applications, the motor technology has to be fault-tolerant. For future steering systems such as steer by wire, not only the detection of the fault, but also prediction of potential faults will be important. Switched reluctance motor has definite advantages over other motor technologies.

4.5 Size and weight

As more and more features are introduced in the automobile, space becomes a premium. Thus, the torque density and reduced size of the motor become more important. Any additional weight added will adversely affect the fuel economy of the vehicle and thus the motor weight has to be minimized. Permanent magnet motors have better solution for such challenges.

5. Permanent magnet machines

Permanent magnet synchronous motors have been found most attractive for steering application due to its various attractive features such as low torque ripple, low acoustic noise and high torque density. These machines are ideal for torque ripple sensitive applications. These machines allow the incorporation of phase advancing or field weakening mode, thus allowing the operation over a wide speed range.

To achieve torque ripple levels of less than 1% requires critical care in the design of motor and controller. Parasitic torque ripple still exists even in a sinusoidal PM motor drive due to limitations in machine design and controller implementation. From a machine design standpoint, a sinusoidal back EMF requires a sinusoidal distribution of magnet flux or windings. Due to limitations in magnetization and in the practicality of sinusoidal winding distribution, harmonics in the back EMF, and thus their associated torque ripple, are unavoidable. Also, the interaction between the magnets and the slots of a slotted machine produces a non-uniform magnetic force, resulting in cogging torque. In addition, torque ripple can still be produced by magnetic asymmetry, such as that due to rotor eccentricity and magnetic circuit saturation.

5.1 Cogging Torque

In a simple way, the cogging torque in a PM machine can be considered as the summation of the interactions of each edge of the rotor magnets with the slot openings. Considering each of them independently, the cogging torque can be expressed as

$$T_{cog} = \sum_{k=1}^{\infty} T_{ck} \cos kQ\theta \qquad (3)$$

where k is the order of the cogging harmonics, Q is the number of slots, T_{ck} is the amplitude of the cogging torque component at k^{th} cogging frequency. The cogging torque components are denoted as the cycles per mechanical revolution (CPMR), which ideally depends on the number of slots and poles. For a rotor with identical magnet poles equally spaced around the rotor with ideal soft iron, the CPMR is computed as

$$CPMR = LCM(Q, P) \qquad (4)$$

where LCM stands for least common multiple. The number of cogging cycles F per slot pitch is defined as

$$F = CPMR/Q \qquad (5)$$

Higher value of F is preferable as the cogging torque with high CPMR exhibits low peak amplitude. Example of such slot/pole combination of 3-phase motors include 15/4, 21/4, 27/4, 27/6, 9/8, 18/8, 27/8, 12/10 etc. From cogging torque perspective, fractional slot per pole machines are better than integral slot per pole machines since they exhibits higher value of F. In reality, due to the irregularities in magnet dimension, location, and magnetization pattern and due to rotor eccentricity the value of F may be equal to unity i.e. the CPMR becomes equal to the slot number even for a fractional slot per pole machine [6].

There exist several techniques for reducing the cogging torque at the expense of added complexity and some reduction of output torque. Practically, it does not completely eliminate the problem due to manufacturing tolerances and variations [6]. Skewed and step-skewed magnets, dummy slots are popular practices for reducing cogging torque. Fig. 4 shows the skewed and step-skewed magnets for reducing cogging torque. Figs. 5-6 shows the cogging torque plot for a 27-slot 6-pole sinusoidal back-emf machine for skewed and step-skewed arc magnets.

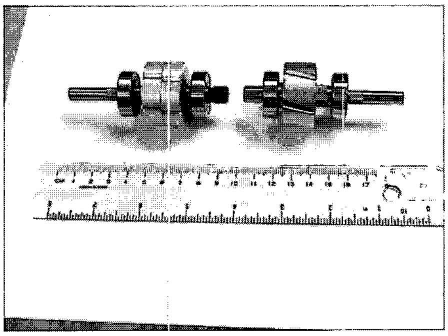

Fig. 4 Cogging torque reduction using step-skewed and skewed arc magnets.

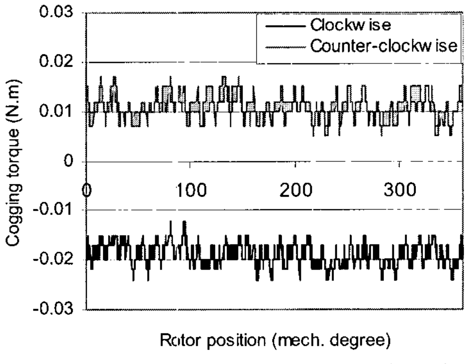

Fig. 5 Cogging torque of the test motor using skewed arc magnets.

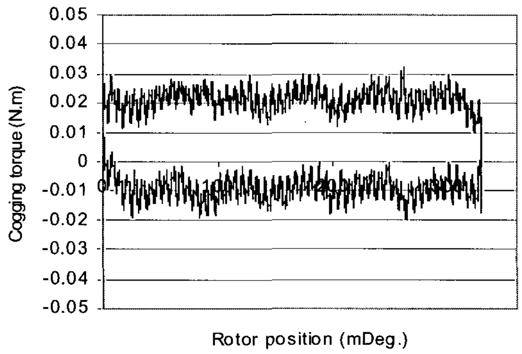

Fig. 6 Cogging torque of the test motor using step-skewed arc magnets.

5.2 Harmonics in the Induced EMF

For sinusoidal back-emf machines, the harmonics in the induced emfs are critical for minimizing torque ripple. The harmonic contents are dictated by the airgap flux density distribution and stator mmf's. The magnet shapes and magnetization pattern have direct influence on the induced emf. Furthermore, both amplitude and shape of the back-emf and the stator mmf's in machines are determined by the winding arrangements and general machine geometry. These configurations in turn are dictated by optimum use of space and materials in the machine. Hence, the winding configuration has also direct influence on the harmonic contents. For 3-phase sinusoidal type back-emf machines, slot/pole combination dictates the winding arrangement. Though fractional-pitch winding reduces the machine back-emf constant, it helps to decrease the harmonic content in the back-emf waveform and in the mmf distribution. Besides, it shortens the end connections too.

Table 1 gives the induced emf harmonics when either the stator slots or rotor magnets are skewed by a selected angle. θ_s is the angle of skew in electrical degrees. In addition to reducing the cogging torque, skewing also minimizes the induced emf harmonics and thus the torque ripple for sinusoidally excited machines. But for trapezoidal back emf type machines skewing may have adverse effect on torque ripple. Depending on the type of machine, appropriate ripple minimization technique must be used.

Table 1 Induced voltage harmonics with square wave rotor flux density with stator slots or rotor magnet skewing by θ_s degrees

Machine Type	θ_s (deg)	V1	V5/V1	V7/V1	V11/V1	V13/V1
9-S 6-P	60	2.11	4.00%	2.04%	0.83%	0.59%
27-S 6-P	20	2.39	2.61%	0.71%	0.29%	0.39%
27-S 6-P	40	2.36	1.70%	0.25%	0.10%	0.25%
18-S 6-P-FP	60	2.43	4.00%	2.04%	0.83%	0.59%
24-S 4-P-FP	30	2.43	4.00%	2.04%	0.83%	0.59%
24-S 4-P-SP	30	2.35	1.07%	0.55%	0.83%	0.59%

Assuming the back-emf consists of only fundamental, 5th and 7th harmonics and the phase currents are balanced and sinusoidal, the expression for the electromagnetic torque can be written as

$$\begin{aligned} T_e &= \frac{P}{\omega_m} = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \\ &= \frac{3}{2\omega_m} E_m I_m \cos\varphi - \frac{3}{2\omega_m} E_{m5} I_m \cos(6\omega_e t + \varphi) \\ &+ \frac{3}{2\omega_m} E_{m7} I_m \cos(6\omega_e t - \varphi) \end{aligned} \qquad (6)$$

where E_m and I_m are the peak amplitude of the fundamental component of the phase voltage and phase current, respectively. E_{m5} and E_{m7} are the peak amplitudes of the 5th and 7th harmonic components of the phase voltage, respectively. ω_m and ω_e are the mechanical and electrical speed, respectively in rad./sec and φ is the angle by which current leads the back-emf. As shown in (6), the instantaneous electromagnetic torque has 6th order ripple per electrical cycle due to the 5th and 7th harmonic contents in the back-emf. Fig. 7 shows the developed torque over half electrical cycle at 72A. The plot shows 6th order ripple in one electrical cycle. The 18th order cogging torque ripple is also visible due to the straight arc magnets used in the simulation.

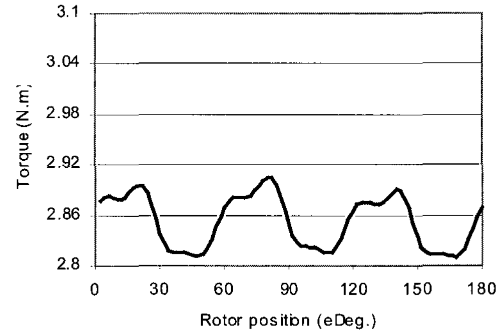

Fig. 7 Developed torque at 72A using non-linear steel characteristics.

5.3 Effect of Saturation

For high performance applications, saturation of the magnetic circuit should be avoided as much as possible. Increased electrical loading causes more saturation, which in turn is responsible for increased torque ripple and torque non-linearity with current. Less magnetic loading keeps the magnet cost lower. Increased stack length with smaller number of turns (low ampere-turn) yield high performance motor with low torque ripple and high torque linearity. Basically, a design optimization between cost and performance is necessary.

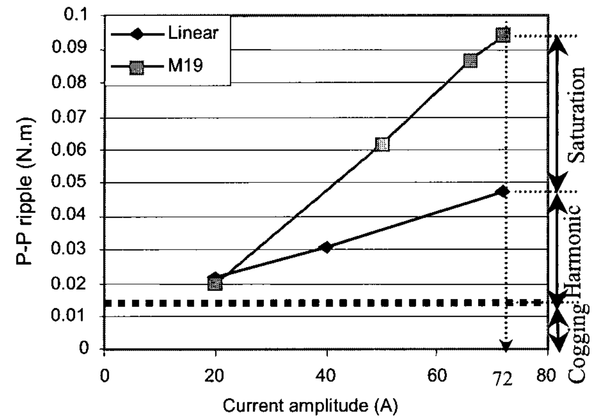

Fig. 8 Peak-to-peak ripple with varying current amplitude.

Fig. 8 is an attempt to quantify the various sources of torque ripple in the sample machine considered in the analysis and tests. The cogging torque shown is calculated with no current in the stator and is assumed constant irrespective of current. The P-P cogging torque was found to be 15.6 mN.m using FE analysis. The difference in torque ripple where linear steel is used and cogging torque is assumed to be due to the harmonic contents in the induced emf. Similarly, the difference in torque ripple using nonlinear and linear steel is attributed due to the saturation. The torque linearity decreases with current due to saturation, resulting in lower output torque.

5.4 Controller Induced Torque Ripple

From a controller design standpoint, there still exist tremendous challenges in providing a pure sinusoidal current waveform to the machine [7]. In practice, the motor controller has to be built using either an analog or digital circuitry. Due to advantages in flexibility and implementation offered by a digital control system, most of the motor controllers built today are in digital format using a processor or some form of a digital circuit.

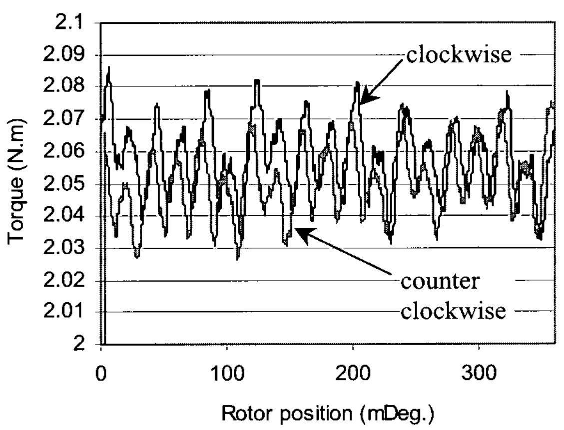

Fig. 9 Measured torque at 50A for the test motor.

The experimental plot in Fig. 9 showed other ripple components besides 6th and 18th order ripples. The other ripple frequencies are contributed from the electronic controller. The controller induced torque ripple components are 1st, 2nd and 3rd per electrical revolution as reported in [7]. 1st order ripple is caused by FET non-linearites, 2nd order ripple is due to phase imbalance and 3rd and 6th order ripples are due to switching dead time.

6. Conclusions

Permanent magnet brushless machines are playing a vital role in the conversion of hydraulic steering systems to electro mechanical systems. Several of the performance challenges associated with this machine for such applications are being addressed. As the cost of electronics is coming down and the capabilities are increasing with time, brushless motor-based systems will become increasingly attractive for automotive applications

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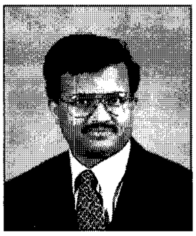

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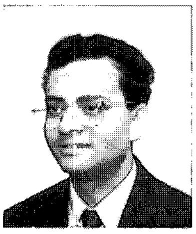

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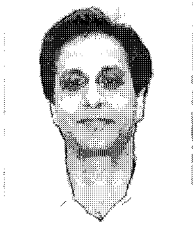

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