

# MOTOR DRIVE SELECTION FOR AUTOMOTIVE APPLICATIONS

**James M. Kokernak**

Advanced Energy Conversion  
31 Ontario Street  
Cohoes, NY 12047

**David A. Torrey**

Department of Electric Power Engineering  
Rensselaer Polytechnic Institute  
110 Eighth Street  
Troy, NY 12180-3590

## ABSTRACT

This paper considers the design of two specific adjustable speed drives based on brushless dc and switched-reluctance motor technologies for the same automotive power steering application. This application is used to provide an overall approach to assessing the relative merits of application-specific brushless dc and switched-reluctance motor drives. Some of the issues addressed include the identification of an appropriate motor technology based on speed requirements, thermal specifications and failure modes. The paper will also include careful examination of the excitation requirements of each motor under various modes of operation, and the effect of those requirements on the inverter design and the vehicle's electrical system. Special attention is paid to semiconductor selection and cost minimization of the inverter. The paper shows that each motor technology has advantages that make it attractive for certain applications. Those advantages may be in cost or electromechanical performance, and there is no clear winner for all automotive applications currently under consideration.

## 1. INTRODUCTION

The trend in the automotive industry is to replace mechanically actuated systems with systems based on electric motor technology. The traditional dc motor, while rich with history, is not suitable for many of these adjustable speed applications. The impetus for moving away from the brushed dc motor results from the wear associated with the brushes, the lower overall power density, and the EMI problems that can be associated with commutator arcing. This arcing can become more serious as application requirements move from sub-fractional horsepower to transient integral horsepower. Given the low system voltage, the resulting inductive motor currents that must be interrupted by the commutator can be quite large.

The (figurative) explosion of power electronics components that target the automotive industry (i.e. low voltage, high current semiconductors) has motivated the automakers and original equipment manufacturers to consider higher performance motor technologies with the expectation that high volume and improved fuel economy will bring value to their products. Few applications have seen broad acceptance at the 12-V level, primarily because the load currents (which are often transient) can be quite high. While the electric motors can often be sized for their nominal usage, and overloaded in transient situations, the same is generally not true for the power electronics. This requirement that the electronics be sized for peak power requirements results in expensive systems, much to the dismay of the automakers.

In an effort to find some balance between the projected electrical demands of a typical automobile and touch-potential safety, the move toward a 42-V platform has been proposed. While this voltage does provide some relief from the 12-V headaches, such as large conductors and inherent voltage drops across semiconductors, it is by no means a complete solution for the motor and power electronics designer. While the challenges are likely not insurmountable, the first two production hybrid electric vehicles to be sold in this country, the Toyota Prius and the Honda Insight, are not examples of low-voltage technology.

This paper highlights some of the difficulties associated with designing an electric motor drive for a power steering system. The motor specifications, which have been distilled from the automaker's performance requirements and the existing mechanical system, are presented. The process of evaluating a brushless dc motor and a switched-reluctance motor for this application is reviewed, attempting to shed some light on the issues associated with motor selection.

## **2. Why SRM and BLDC Technology**

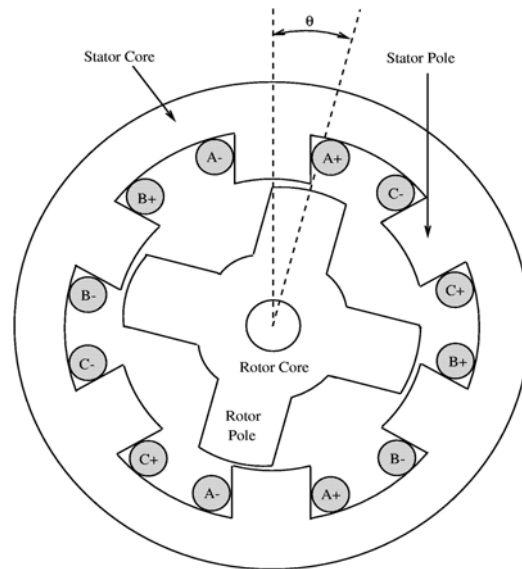
Both the brushless dc (BLDC) and switched-reluctance motors (SRM) have some barriers to market penetration. Unlike the traditional induction motor, the brushless dc motor has permanent magnets that are susceptible to high temperature complications. The BLDC motor also raises concerns about failure modes. The switched-reluctance motor is generally believed to be noisy and have high torque ripple. As a result, often the well-understood and traditionally robust induction motor is force-fit into many automotive applications. The situation is one to be expected: there is a wealth of knowledge available for this mature technology. While the induction motor has proved to be an excellent performer in many industrial applications, the performance margins that the automotive industry are demanding require that other motor types (in addition to the two presented here) be pulled up the technology curve rather quickly. The induction motor is ill-suited for most automotive applications because of the difficulties associated with extracting heat from the rotor, efficiency problems over a wide speed range if high slip is required, long end-turns, and a more expensive manufacturing process due to the distribution of windings. While the induction motor will find some automotive applications, the authors believe that lighter and more suitable candidates will ultimately replace its deployment. The BLDC and SRM technologies presented here represent two of those potential candidates. Standard references for the SRM are [1-2] and the references therein. The BLDC motor is discussed extensively in [1,3-4] and the references therein.

### **2.1 The Switched-reluctance Motor**

Power electronic technology has made the SRM an attractive choice for many applications. The SRM is a doubly-salient, singly excited synchronous motor. The rotor and stator are comprised of stacked iron laminations with copper windings on the stator, as shown in Fig. 1. The motor is excited with a power electronic inverter that energizes appropriate phases based on shaft position. The excitation of a phase creates a magnetic field that attracts the nearest rotor pole to the excited stator pole in an attempt to minimize the reluctance path through the rotor. The excitation is performed in a sequence that steps the rotor around.

The SRM is similar in structure to the stepping motor, but it is operated in a manner that allows for smooth rotation. Because there are no permanent magnets or windings on the rotor, all of the torque developed in the SRM is reluctance torque. While the SRM is simple in principle, it is rather difficult to design and develop performance predictions. This is due to the nonlinear magnetic characteristics of the motor under normally saturated operation. In [5,6], modeling processes are outlined for the conventional SRM.

There are several advantages of the conventional SRM over other types of motors. Manufacturing is relatively straightforward due to the concentrated windings around the stator poles as opposed to distributed in the induction motor. There are no windings or permanent magnets on the rotor. The simplicity of construction and lack of costly permanent magnets imply that the SRM would be much less expensive to produce in the quantities that dc or induction motors currently enjoy.



**Figure 1: A switched-reluctance motor with 6 stator poles and 4 rotor poles.**

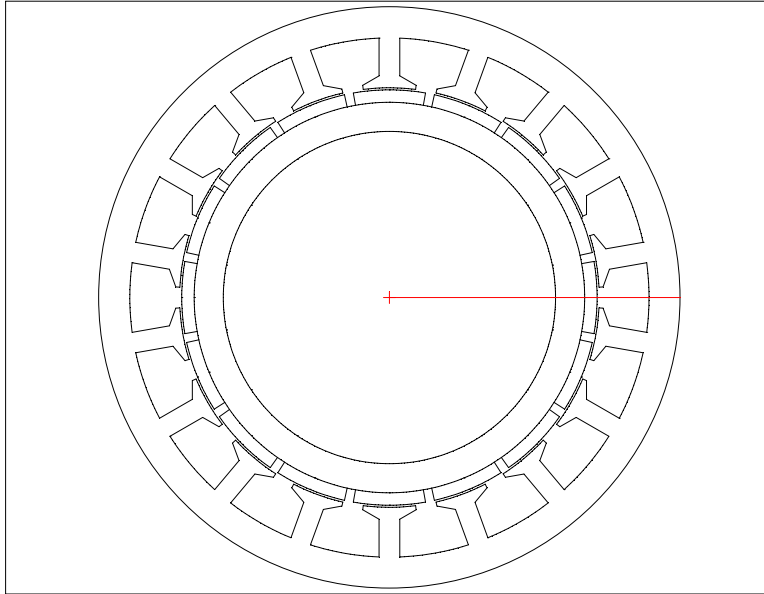
## 2.2 The Brushless Dc Motor

The brushless dc motor is also comprised of stacked steel laminations on the stator. Traditionally, the stator resembles that of an induction motor, however the windings can be configured so that they are not distributed. The rotor on the brushless dc motor can take many forms, but all have permanent magnets in some form. Depending on the size of the motor, these magnets can be a full-ring magnet, spoke, embedded, etc. The magnet configuration is tied closely to the performance and manufacturing logistics of the permanent magnet material. Figure 2 shows the cross-section of the BLDC motor considered for the power steering application.

In motors of less than 1.5-kW rating, the presence of permanent magnets can significantly increase the power density of the motor. The energy density of permanent magnets can easily exceed that of a copper winding when space is tight. This suggests that the BLDC motor should enjoy an advantage. Consideration of speed range, however, suggests that as the speed range increases, the permanent magnets may become something of a liability unless provisions are made to weaken the field. Field weakening in the BLDC motor is sometimes attempted through phase advance of the current waveform, but this tends to introduce substantial torque ripple.

## 3. A Power Steering Specification

Based on required rack performance, steering wheel input and a mechanical power balance between the motor output and the steering rack output, a motor requirement can be developed.



**Figure 2: A BLDC motor with three phases and 16 poles.**

**System Specification:**

DC bus voltage: 9-19-V range;  
12-V nominal

The motor drive system should not draw more than 80-A from the dc bus when operated at 14.4-V. The inverter efficiency can be assumed to be 93%. The motor may be driven by a trapezoidal or sinusoidal drive.

**Required Motor Torque-Speed Characteristics:**

Table 1 outlines the required performance points for the power steering motor. The 5.0-Nm points represent the predicted maximum torque for the application. The 7.0-Nm is a safety margin to account for losses in the mechanical interface between the electric motor and the tires. The required no load speed for the motor is 4500-rpm. Because the duty is transient in nature, the time requirements are provided to help minimize the size of the motor by not designing to tolerate steady-state performance under these conditions.

**Table 1: Require performance points for the power steering application.**

Torque (Nm)	Motor Speed (rpm)	Required Duty (seconds)	Motor Power (W)
7.0	0	5	0
7.0	500	5	366
5.0	280	240	147
5.0	1550	1.4	811
3.0	3170	22	996

### 3.1 The SRM Candidate

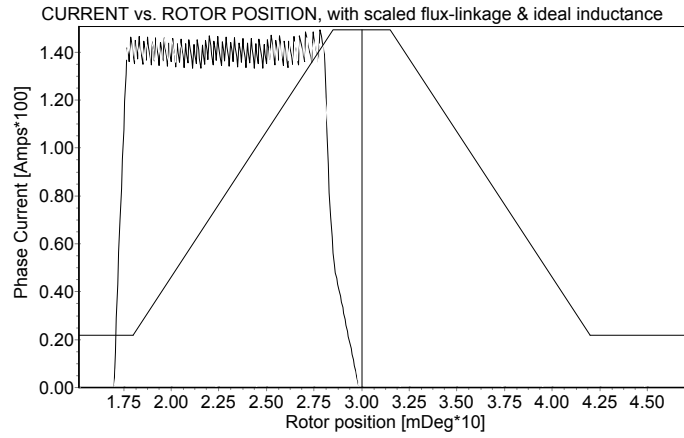
From Table 1 it is seen that the maximum power output from the motor is about 1-kW. Given that the SRM operates in a constant torque region below base speed, and a constant power region above base speed, it is necessary to determine the shaft speed associated with 1-kW at 7.0-Nm. This base speed point is a key design point and defines the torque-speed profile for the motor and is given by  $143\text{-rad/sec} = 1364\text{-rpm} = 1000\text{-W} / 7.0\text{-Nm}$ . If the SRM is capable of producing 7.0-Nm at this speed, then it will satisfy all other points in Table 1. To accomplish this from 14.4-V and 80-A is quite challenging. The available battery power is 1152-W and the peak shaft power is 1-kW. The required system efficiency to accomplish this power and satisfy the battery current requirement is 86.8%. This requires both the motor and power electronics to have efficiencies in the range of 93%. Selecting a base speed significantly above the 1364-rpm could result in excessive phase currents, adding cost to the inverter.

A four-phase switched-reluctance motor has been designed for this application. Table 2 summarizes the performance achieved at the specified points. Base speed has been selected between 1600 and 1800-rpm. It should be noted that while certain points in the design do exceed the battery current requirement, those points are well outside of the envelope of expected torque required by the system. Recall that the 5.0-Nm is the expected maximum torque. The two operating points at 5.0-Nm demonstrate battery currents below the specified level. In the event that there are static friction issues that require 7.0-Nm to break free, battery currents in excess of 80-A should be expected transiently unless the duration is so short that inverter bus capacitors can supply the additional energy.

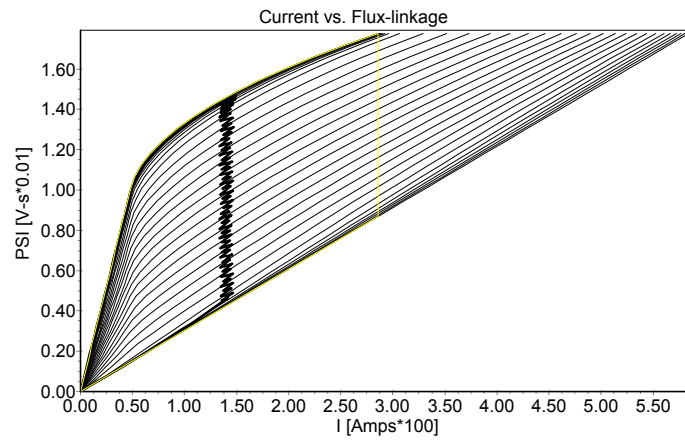
**Table 2: Design performance for SRM motor.**

Speed (rpm)	Torque (Nm)	Phase Current (A)	Battery Current (A)
280	7.4	140	40.3
1550	7.8	140	142.4
3170	3.8	v.c.	125.2
280	5.1	100	26.8
1550	5.1	105	72.4

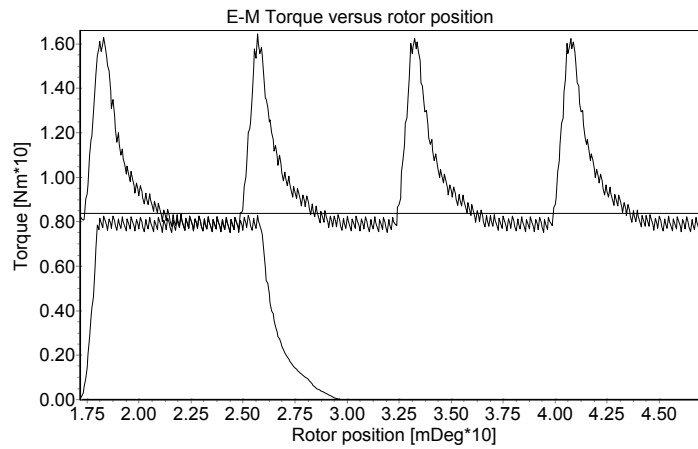
Figures 3-5 show typical examples of motor phase current versus phase inductance below base speed, the energy conversion cycle and the achievable torque, respectively. Note that while the total torque appears to be high in ripple, the ripple is a result of phase overlap. A certain amount of current shaping during phase overlap can achieve satisfactory torque performance.



**Figure 3: Phase current and phase inductance for motor operation below base speed.**



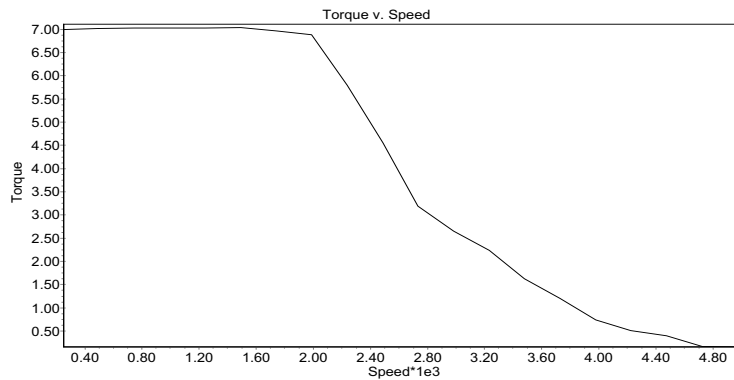
**Figure 4: Typical energy conversion cycle for the power steering SRM operating below base speed.**



**Figure 5: Aggregate torque production for all phases above the torque contribution of a single phase.**

### 3.2 The Brushless Dc Candidate

A three-phase brushless dc motor was designed for this application as well. A primary difference between the SRM and BLDC motors is their behavior at high speeds. The SRM is reasonably good at behaving as a constant power motor above base speed. The brushless dc motor, on the other hand, often loses power output capability rapidly as the speed increases. As a result, the design must carefully evaluate points beyond base speed to make sure that they fall within the actual torque speed envelope of the motor. Figure 6 shows the torque speed curve for the brushless dc motor designed here. Notice that the base speed (point where torque demonstrates a rapid drop from 7.0-Nm), is extended out to more than 2000-rpm. This is necessary to ensure that the motor meets the no load speed requirement and that 3.0-Nm can be achieved at 3170-rpm. It should be noted that the brushless dc motor and switched-reluctance motors considered here have the same active stack length and outer diameters. Performance was evaluated at the same points as demonstrated on the SRM to provide some basis for comparison. The points are summarized in Table 3. The most noticeable difference between the two motors is the required phase current to produce the required torque. The back emf created by the permanent magnet limits the ability to shape phase currents. To improve high-speed performance, this BLDC motor is designed with a full slot skew that produces back emf waveforms that are nearly sinusoidal. As a result, the inverter will excite the motor with 3-phase sinusoidal currents. A sample of these phase currents is shown in Figure 7; the resulting torque is shown in Figure 8.



**Figure 6: The torque-speed characteristic for the brushless dc motor.**

**Table 3: Brushless dc motor performance at selected operating points.**

Speed (rpm)	Torque (Nm)	Phase Current (A)	Battery Current (A)
280	7.0	325	51.5
1550	7.0	325	106.2
3170	3.1	150.	89.1
280	5.2	240	41.8
1550	5.2	240	77.8

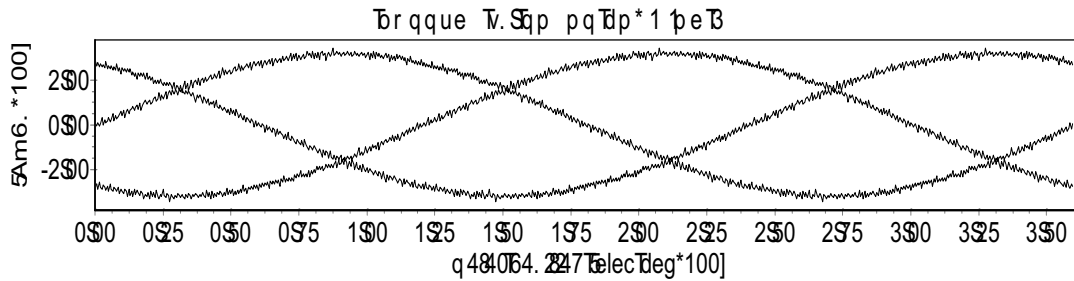


Figure 7: Sinusoidal phase currents for the design brushless dc motor at 500 rpm.

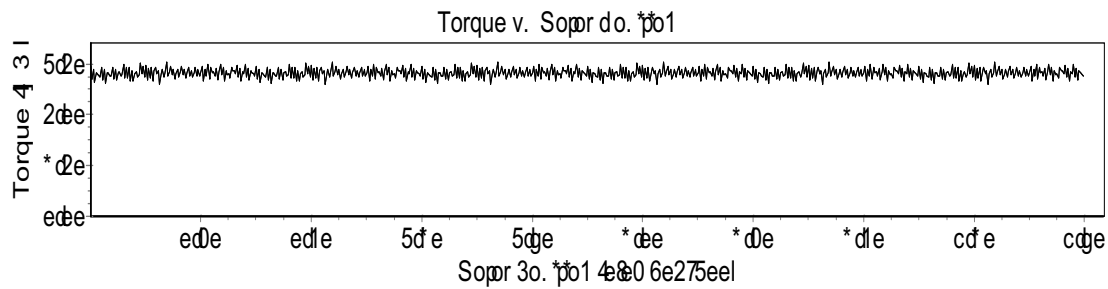


Figure 8: Resulting torque for sinusoidally excited brushless dc motor.

#### 4. Motor Selection and Power Electronics

The previous sections suggest that the SRM and the BLDC motors can provide comparable electromagnetic performance over the intended duty of the motor. There are, however, differences in motor control and the cost of the electronics that must be carefully considered in an application that is extremely cost sensitive. It would appear at the outset that the BLDC has an advantage over the SRM because of the lower number of phases. Consideration of the currents that must be supported by the switches shows that the BLDC inverter would be significantly more expensive than the SRM inverter: the BLDC motor has six switches that must support 325-A while the SRM has eight switches that must support 140-A. Even taking into account the penalty for discrete diodes in the SRM inverter, the SRM inverter would require less silicon than that of the BLDC. This is before consideration of any one of a number of SRM inverter topologies that support operation with five controllable switches (the number of phases plus one). Inverter costs favor the SRM.

Manufacturing costs favor the SRM. The BLDC design is based on using rare earth NdFeB permanent magnets; these magnets are expensive. Use of lower quality magnets will exacerbate the current requirements. The performance of any magnets is a concern with the BLDC motor, particularly in an automotive environment where extreme ambient temperatures cause significant variation in magnet strength. The SRM typically uses a smaller airgap than the BLDC motor, but the cost of the magnet more than compensates for this. Relative to both motor and inverter cost considerations, the SRM appears to have an advantage over the BLDC motor in this application.

## 5. Summary

This paper has discussed the design of a BLDC motor and an SRM for the same automotive application. Each motor is able to meet the electromechanical specifications in the same physical size, with the BLDC offering slightly higher efficiency. The BLDC motor, however, requires substantially higher phase currents than the SRM in order to cover the entire operating range. This is because of the penalty paid by the BLDC motor in servicing a broad speed range. For the application discussed here where the torque speed characteristic is that of a constant power application, the SRM appears to enjoy excitation advantages over the BLDC motor. These excitation advantages play into a reduced inverter cost which, when coupled with reduced motor cost, favors the SRM in this application.

It is important to recognize that the SRM is not better than the BLDC motor in all applications. Each application demands careful matching of the electromechanical requirements to the inherent characteristics of the electric motor. The best match between motor and load characteristics will generally yield the lowest cost drive.

## 6. References

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- [6] D. A. Torrey, X.-M. Niu, and E. J. Unkauf, "Analytic modeling of variable-reluctance machine magnetization characteristics," *IEE Proceedings-Electric Power Applications*, Vol. 142, pp. 14-22, 1995.