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Candidates of Motor Drives for 48V Automotive Applications

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Abstract—**In automotive systems, reliability and cost are paramount for the success of electrical drive systems. Considering the interior permanent magnet motor, the cost of the rare-earth permanent magnet is becoming a big concern. In this paper, the switched reluctance motor, variable flux reluctance motor and synchronous reluctance motor are analyzed and compared as candidates for the 48V automotive applications. A recommendation is given for the selection of the motor drives.**

1. Introduction

Future vehicle electrification needs more electric power to manage more functions, such as electro-mechanical valves, direct electrically driven engine water pump, assisted electrical power steering, etc. As a result, medium power electrical motors are required to assist the main traction drive train. A voltage level of 48V is suitable for such a motor drive considering the safety regulation.

Interior permanent magnet motor (IPM) is commonly considered as a candidate for automotive applications. However, the price rise of the rare-earth permanent magnet tends to restrict the use of the IPM in large scale. Therefore, the utilization of the rare-earth-free motor drive is desired. As a result, the adoption of the switched reluctance motor (SRM) is investigated by researchers and is compared with IPM. Additionally, the current analysis of the variable flux reluctance motor (VFRM) and synchronous reluctance motor (SynRM) also shows a bright prospect. This paper reviews the aforementioned motor drives considering the power electronic circuit, the motor itself and the control algorithm. Finally, the paper is concluded with a summary on the overall performance of different motor drives.

2. MOTOR DRIVE COMPARISON

Interior permanent magnet motor is used by a lot of automakers due to its high efficiency at nominal speeds, high power density, flux-weakening capability and easy cooling. However, the efficiency of the motor decreases in higher speed range since an extra magnetization current is required to suppress the flux. Moreover, at high demagnetization current, there is the risk of magnet demagnetization.

Switched reluctance motor is more and more appealing to researchers as the rival of IPM [1]. It has robust and simple rotor structure, utilizes low cost material and is tolerant towards hostile environment. However, shortcomings of this motor drive are also obvious, for example, it needs complex profiling of phase current waveforms at low speed, requires non-standard power electronic module, demands large DC-link capacitor, generates large acoustic noise, etc.

Three-phase variable flux reluctance motor has been proposed as another candidate recently. [2]- [3] It has simple and robust stator and rotor structures as the SRM. It is concluded in [2] that the VFRM can produce higher output power in flux weakening region compared to IPM while generating lower acoustic noise compared to SRM. Moreover, the conventional three-phase inverter is applicable for this motor, which makes it a competitive option for automotive application.

The synchronous reluctance motor is considered as another competitor. [4] This kind of motor has a shortcoming of the low power factor (with a radially laminated structure). Different methods have been presented to overcome this, such as injecting direct capacitance through an auxiliary winding [5] and adding permanent magnets in the rotor flux barriers [6].

The features of the motor drives from the literature are elaborated in the following, as well as the simulation and analysis for the representatives of the motors.

2.1. Switched reluctance motor

In this subsection, an SRM is analyzed specifically for the aforementioned shortcomings with some possible solutions. To ensure the position-independent starting capability of the machine, it is favorable to have at least four phases in the SRM. It is well known that if the phase windings in SRM are excited by pure square wave current, the torque ripple is large. Therefore, current profiling method is used to smooth the torque and it works effectively for relatively low speed operation [7]. In high speed operation, the SRM may be operated in the continuous conduction mode since the current has to be increased fast enough to reach the desired average torque.

An 8/6 SRM is simulated using the finite element analysis (FEA) for obtaining the flux-current-position character-

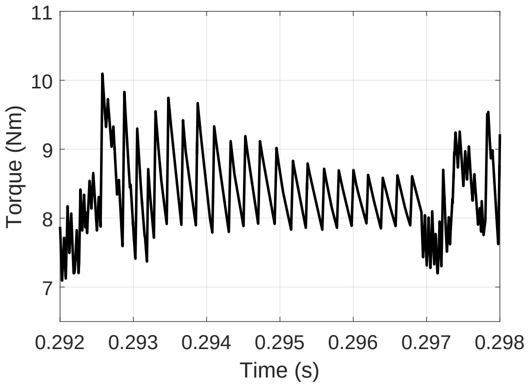

Figure 1. Torque ripple of the SRM by using the torque sharing function when rotational speed is 50 rad/s.

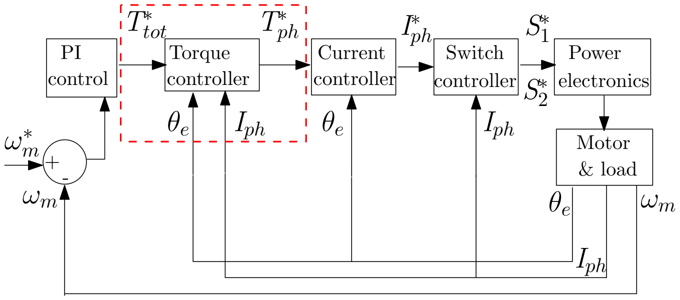

Figure 2. Torque ripple for different number of turns using the same torquse sharing function when rotational speed is 50 rad/s.

istic and torque-current-position characteristic. A Simulink model composed of control, power electronic circuit and motor represented by differential equations is created. For low speed operation, torque sharing function is used [8]- [9], as a result, an example of the torque is shown in Figure 1. As can be seen, the torque ripple is around 30%.

For higher speed operation, the torque sharing function is not applicable anymore since the actual phase current is not able to follow the desired current profile. Instead, a speed control is used as shown in Figure 2. T^*_{tot} in the figure represents the drive reference torque and T^*_{ph} represents the desired torque of the incoming phase. During commutation, T^*_{ph} is calculated as a difference between T^*_{tot} and the torque of the outgoing phase that is calculated in the 'Torque controller' block. Turn-on and turn-off angles are tuned in this stage to increase the speed.

To further increase the working envelope, the SRM starts to work in continuous conduction mode. One feasible method in this stage is to control switch S_2 in Figure 3(a) using the control method shown in Figure 3(b). The typical profile of the phase current is shown in Figure 3(c).

In [10], it introduces the feasibility of using merely the bus line current sensor for controlling the SRM, however, if the SRM works in the CCM, a current sensor is required for each phase.

The motor structure of the SRM is simple, however, the intrinsic low *kW/kVA* ratio of the motor leads to a high demand on the power electronic components, such as the DC-link capacitor. Different methods for the minimization of the capacitor size have been reported, including sinusoidal current injection [11], control algorithm for the elimination of bus line current [12]- [13], etc. However, the torque density may decrease using these methods.

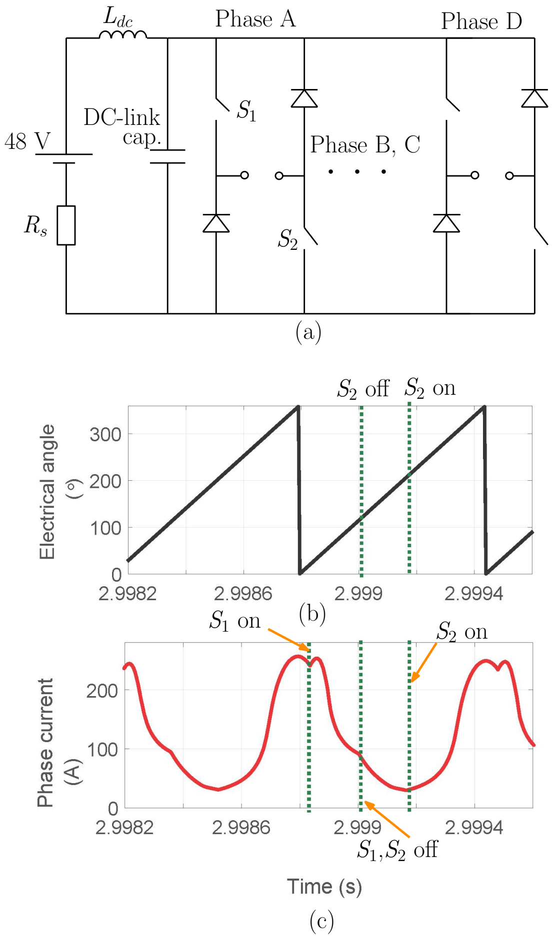

Figure 3. (a) Power electronic circuit of the SRM drive, (b) the control algorithm of S_2 and (c) the current profile of phase A at 15000 rpm.

Another drawback of the SRM is the large acoustic noise, which is dominantly caused by the radial vibration. An effective method for reducing the noise is introduced in [14] using two-step switching during commutation, other method, such as using sinusoidal bipolar excitation [11], is also investigated.

2.2. Variable flux reluctance motor

Another rare-earth-free candidate for the 48V automotive application is the VFRM. There are a lot of stator and rotor combinations for this kind of motor. The self and mutual inductances of the field and armature windings are simulated in FEA and are shown in Figure 4. For 6 stator poles, the fundamental component of the back-emf with 5 rotor poles is the highest at the same field current, as well

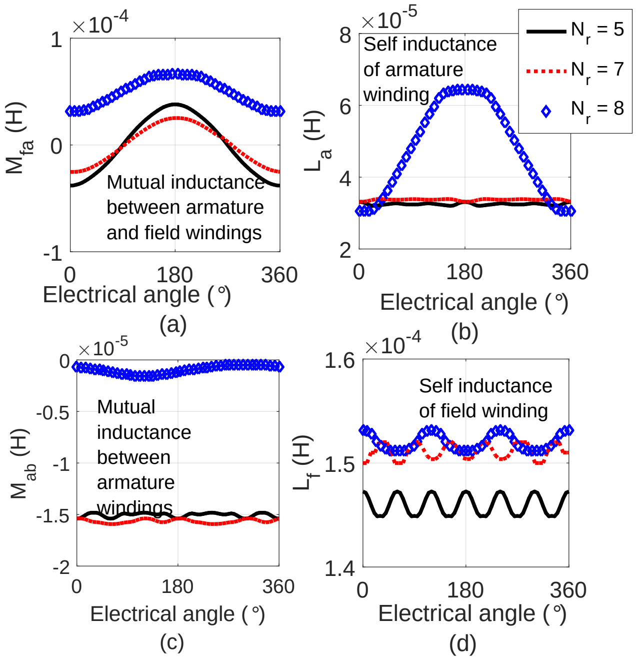

Figure 4. (a) The mutual inductance, M_{fa}, between the armature and field windings (b) the self inductance, L_a of the armature winding (c) the mutual inductance, M_{ab}, between armature windings and (d) the self inductance, L_f of the field winding (N_r is the number of rotor poles).

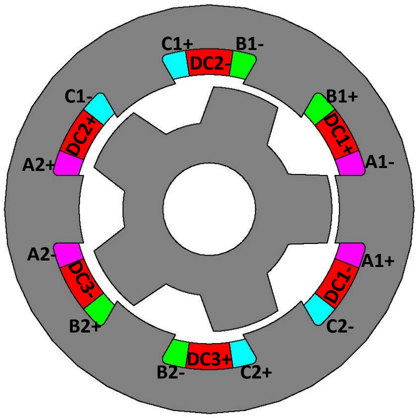

Figure 5. The motor configuration of the 6/5 VFRM.

as the highest torque density [16]. Therefore, only the 6/5 VFRM, shown in Figure 5, is analyzed in this paper.

The self inductance of the armature winding L_a, the mutual inductance between the armature windings M_{aa} and the self inductance of the field winding L_f are almost constant as shown in Figure 4. The ideal expressions of the inductance in a 6/5 motor is [17]

$$
\begin{aligned}
L_a &= L_0 + L_2 cos 2\theta + ...,\\
M_{ab} &= -L_0/2 + L_2 cos(2\theta + 4\pi/3) + ...
\end{aligned}
\tag{1}
$$

where L_0, L_2 are the DC component and second harmonic of L_a, and M_{ab} is the mutual inductance between phase A and B. L_d and L_q are

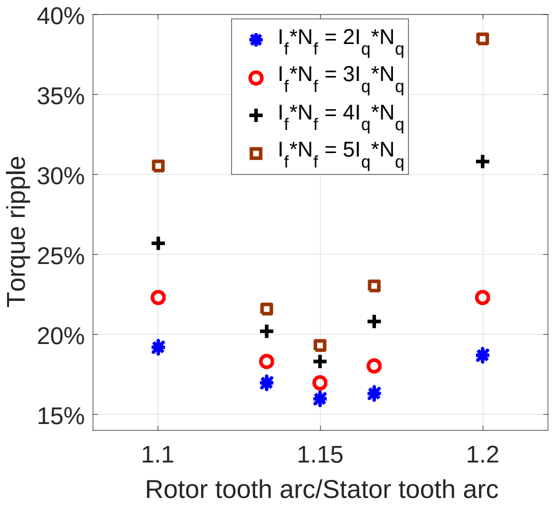

Figure 6. Torque ripple for different motor parameters and currents (N_f and N_{ph} are the number of turns for the field winding and phase winding, respectively).

$$
\begin{aligned}
L_d &= \frac{3}{2}L_0 + \frac{3}{2}L_2,\\
L_q &= \frac{3}{2}L_0 - \frac{3}{2}L_2
\end{aligned}
\tag{2}
$$

As can be seen in Figure 4(b), harmonics in L_a are small, as a consequence, L_d and L_q are close when saturation and leakage of the end winding are neglected. This is also verified by simulating L_d and L_q using 2D FEA, namely injecting I_d and I_q respectively, and calculate the inductances as [18],

$$
\begin{aligned}
L_d &= \frac{\Psi_d}{I_d},\\
L_q &= \frac{\Psi_q}{I_q},\\
\Psi_d &= \frac{2}{3}(\Psi_a - \frac{1}{2}\Psi_b - \frac{1}{2}\Psi_c),\\
\Psi_q &= \frac{1}{\sqrt{3}}(\Psi_b - \Psi_c)
\end{aligned}
\tag{3}
$$

The torque and voltage expression is

$$
\begin{aligned}
\begin{bmatrix} U_d \\ U_q \end{bmatrix} &= \begin{bmatrix} R_s & -\omega_e L_q \\ \omega_e L_d & R_s, \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \omega_e M_{fa} I_f \begin{bmatrix} 0 \\ 1 \end{bmatrix},\\
T &= \omega_e M_{fa} I_f I_q + (L_d - L_q) I_d I_q
\end{aligned}
\tag{4}
$$

where ω_e is the electric speed and I_f is the field current.

The torque ripple of the 6/5 VFRM is shown in Figure 6 for different field currents and rotor arcs. The ripple is calculated using

$$
T_{ripple} = \frac{T_{max} - T_{min}}{T_{mean}}
\tag{5}
$$

As can be seen, the torque ripple increases as the field current rises. However, the torque ripple caused by the

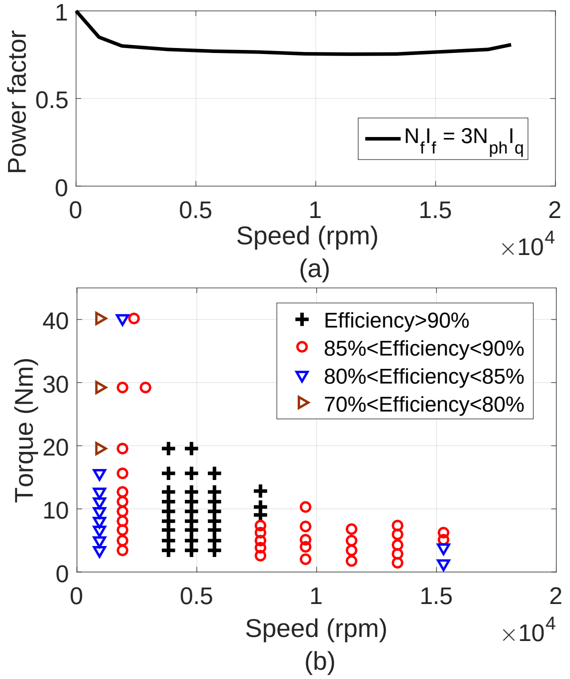

Figure 7. (a) Power factor and (b) efficiency of the 6/5 VFRM.

current fluctuation due to the small inductance in this low voltage application is not considered.

The efficiency and power factor for the 6/5 VFRM are shown in Figure 7. As can be seen, the power factor is relatively high in the overall working range and it can even be further increased by adjusting the ratio between the field current and armature current. However, Figure 7 shows only an indication, because the values are dependent on the control algorithm.

The torque density of the VFRM is relatively low as shown in [2], which is around 75% of the IPM. The acoustic noise of the VFRM is investigated in [19]. A much lower sound pressure level is generated by this motor compared to SRM, although they have similar stator and rotor structures.

2.3. Synchronous reluctance motor

In this subsection, the permanent-magnet-assisted SynRM is briefly introduced. The permanent magnet added in the rotor flux barriers of a conventional SynRM significantly improve the overall performance, such as the operational envelope, efficiency, power factor, etc. The influence of different types of magnets are analyzed and the results are compared with Prius IPM in [21]. By using the ferrite magnet, the torque-speed characteristic, torque density and the efficiency of the SynRM is competitive with Prius IPM. However, the overall power factor is still relatively low, especially in the high speed region based on the result in [21].

In the end, a summary of the performance for different motor drives is listed in TABLE 1. [22]- [23]

TABLE 1. COMPARISON OF THE MOTOR DRIVES.

Note: + good, − bad, ○ neutral.

	IPM	SRM	VFRM	SynRM	PMA-SynRM
Torque density	+	−	−	−	+
Motor efficiency	+	+	○	○	+
Motor cost	−	+	+	+	○
Demands on power electronics	+	−	○	+	+
Power factor	+	−	+	−	○
Controllability	○	−	○	○	○

3. Conclusion

This paper introduces the comparison between the switched reluctance motor, variable flux reluctance motor, synchronous reluctance motor and permanent magnet assisted synchronous reluctance motor. The strong points and the weakness of each motor drive are analyzed. The switched reluctance motor itself is cheap and robust, however, its low power factor leads to the demands on the large power electronic components, additionally, the high radial force results in large acoustic noise and torque ripple therefore needs complicated control algorithm. The variable flux reluctance motor has good performance for the aspects of power factor, however, the torque density is relatively low. The synchronous reluctance motor has the drawback of relatively low torque density and power factor compared to IPM, however, these are improved by the assisted magnets in the rotor.

The final selection of the motor drive should rely on the specific application and the most important concern in the design, such as the cost limit or the size, etc.

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