SWITCHED RELUCTANCE MOTOR CHARACTERISTICS: POTENTIAL FOR ELECTRIC VEHICLE APPLICATIONS

1. Introduction

Environmental concerns are motivating the international community to replace internal combustion engine vehicles with low/local zero – emission ones. Currently, the electrification of vehicular powertrains (both hybrid and pure electric) is considered the most effective solution for increasing energy efficiency and reducing greenhouse gas emissions in the automotive sector. In addition to areas as power electronics, control and energy storage systems, there has been a growing interest in traction motors (both optimized and new types), aiming to reach the high performance demanded by electric powertrains [1]. The torque & power speed characteristics of an electric drive suitable for electric vehicles (EV) is shown in Figure 1, where three different zones are marked: constant torque (Zone 1), constant power (Zone 2) and high speed with reduced power (Zone 3).

An electric machine for traction application must fulfil a set very demanding requirements. In addition to the lowest possible cost, they can be summarized as follows [1]:

- High efficiency in a wide range of speed (including regenerative braking);
- High torque and power density with fast dynamic response;
- High torque at low speeds (starting, acceleration, and hill climbing) and high power at high speeds – Figure 1;
- Wide constant power speed range (CPSR) – Figure 1;
- Operation in demanding conditions (e.g., frequent start/stop) and harsh environmental conditions (e.g., dust, water, cold, and hot temperatures);
- Intermittent overload capability;
- Ruggedness and robustness with low-frequency service and maintenance;
- High level of fault tolerance and safety, low acoustic noise and vibrations.

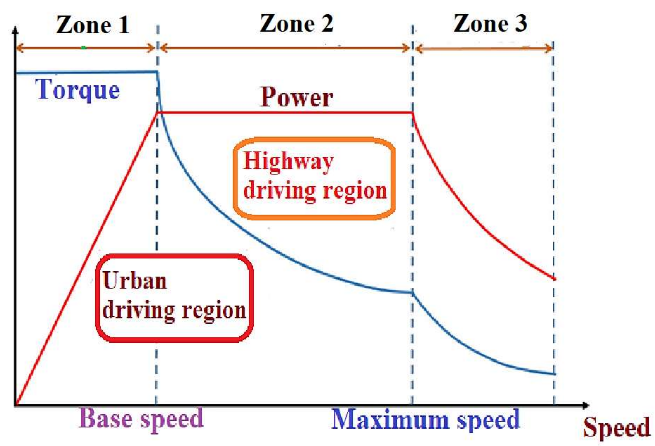


Figure 1. Torque & power vs speed characteristics of desired EV motor (adapted from [2])

So far, the majority of HEVs and BEVs traction drives have permanent magnet synchronous motor (PMSM), due to their high power, torque density and efficiency (reduced heating), as well as wide speed range (this is true for interior PMSM, where the magnets are located inside the rotor structure). However, high energy density permanent magnets (PM) combine rare-earth elements (e.g., Neodymium Iron Boron (NdFeB) and Samarium cobalt (SmCo)), which is a significant obstacle to PMSM drives widespread. The main reasons are the following ones [2], [3]:

- Around 50% of reserves are located in China;
- China controls most (85%) of the world's rare-earth PM production;
- Demand is growing for PM in green industries (e.g., wind generation and electric vehicles);
- Ecological impact of rare-earth extraction, mining, and refining processes;
- Cost of PM, since they constitute between 30-40 % of the total motor cost.

In addition, PM are also constrained by demagnetization effect due to strong armature reaction (this is notorious in high-speed range due to field weakening). Moreover, they are vulnerable to high temperatures, which can affect their performance in demanding driving conditions. This can cause increased expenses, premature deterioration, and reduced stability [2].

2. Rare-Earth (RE) Free Electric Motor for EV

Hence, significant efforts have been made in order to develop electric machines with reduced or even without PM. Currently, the most relevant candidates are induction motor (IM) drives, synchronous reluctance motor (SynRM) drives and switched reluctance motor (SRM) drives. Figure 2 shows a basic cross-section of these motors.

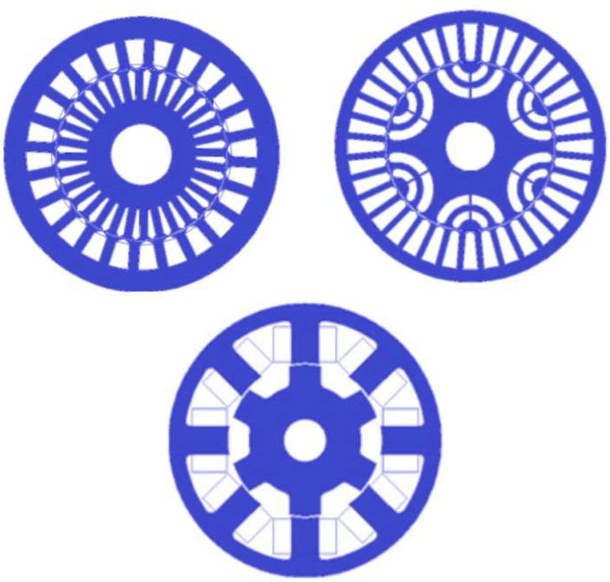


Figure 2. Cross-section view of: a) IM; b) SynRM and c) SRM [4]

IM are a natural option for EV, since they are reliable and require minimal maintenance actions. However, their choice is limited by low operating power factor and efficiency, corresponding to a low inverter usage factor resulting and high losses [5]. Also, low speed control is a difficult task [2], [6].

The main advantages of SynRM are high efficiency, small size, robustness, and fault tolerance. It is based on a magnetic anisotropic rotor to produce a reluctance torque, where PM are not required. Moreover, the rotor has no windings. Compared with IMs, SynRMs have higher torque density, higher efficiency, since there are no rotor Joules loss. When compared to SRM, SynRM has smoother low speed torque. Challenges for SynRM applications are manufacturing, controllability and low power factor [7].

Overall, compared to PMSMs, RE free motors have lower efficiency (particularly in low-speed range), torque density and power factor.

3. Switched Reluctance Motor (SRM)

SRM is a doubly salient electric machine able to develop a reluctance torque. The term "switched" is because the machine operation depends on power switching transistors.

Its low-cost robust and simple structure make SRM suitable for applications such as automotive, renewable energy and aerospace, particularly in high-speed range. Moreover, this machine is able to operate in harsh environments and has a high fault tolerance. Nonetheless, SRM drives need a non-conventional power converter type with specific control schemes [1], [8]. In Figure 3 is depicted the most usual converter architecture for SRM (asymmetric half-bridge), where the control unit is also represented.

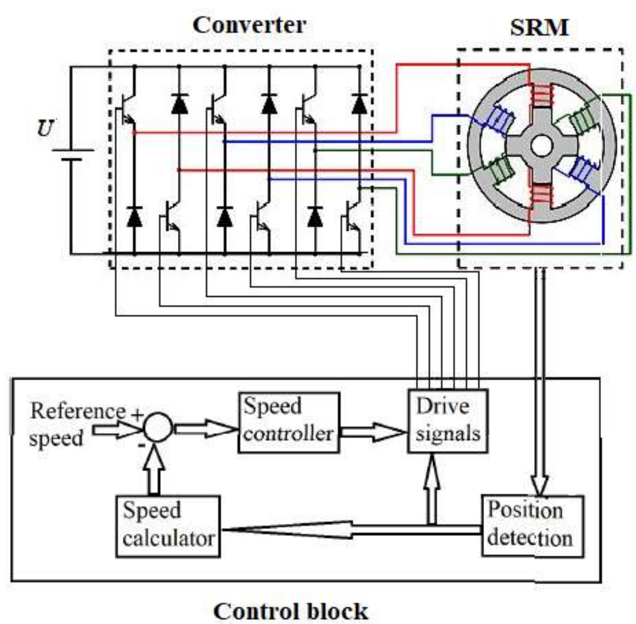


Figure 3. Three-phase 6/4 SRM drive (adapted from [2, 9])

Due to SRM double salient geometry and phase current pulse, its operation has intrinsic torque pulsation and noise. As stated before, its efficiency (low speed) and power density are lower than PM machines. Such limitations poses obstacles for EV, particularly in passenger vehicle since these applications are more performance oriented [1]. In spite this, SRM shows a significative potential for EV applications, including e-bike and e-scooter powertrains. It has a very wide constant power speed range and can actually reach high speeds, since the rotor has no windings or PM. In addition, its inertia is considerably low compared to other motor types.

3.1. SRM Constitution

The main attractive point of conventional SRM is its simple structure. The windings are of concentrated type, located around the stator poles and the rotor consists in a stack of laminations of ferromagnetic material, as depicted in Figure 4. From manufacturing point of view, SRM is easy to make. The windings can be simply inserted into the stator, whereas core laminations in conventional designs are made with stamping. Since the rotor has no windings, SRM colling is more effective since removing heat from the stator is easier. It should be noted windings are a significant source of heat in all electrical machines.

Another relevant SRM particularity is a small phase mutual inductance. In many applications it is considered null, i.e., each phase is magnetically decoupled from the others. This has a most relevant impact on the machine operation: since a phase fault has no influence in the others, SRM have a significant fault-tolerance capacity. As phase number increases, the impact of the faulted phase is smaller. However, in high-speed operation, currents in adjacent phases can overlapped for a significant portion of the conduction cycle. Therefore, the mutual flux linkages between phase windings can be most relevant, so their effects should be considered in those situations [8].

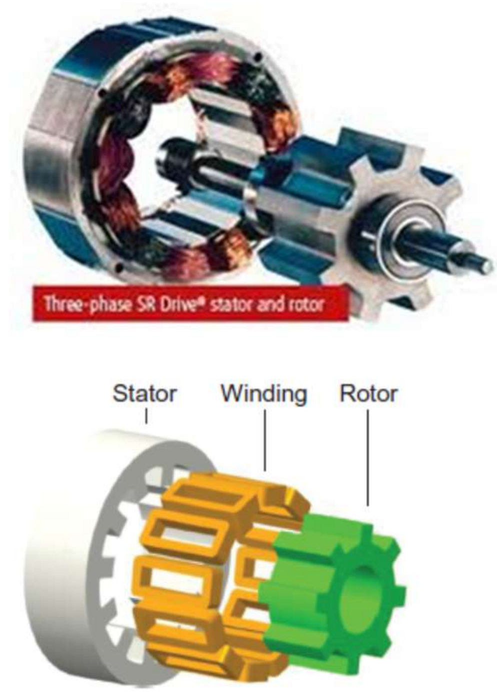


Figure 4. Structure of conventional SRM [10]

3.2. SRM Basic Control

SRM usually operates under high magnetic saturation with a complex flux dependency on rotor position and stator current. There are three basic control modes: current hysteresis mode (Figure 5-a)); voltage-PWM mode (Figure 5-b)); and single-pulse mode (Figure 5-c)). For low/medium speed range (below rated speed), the motor can be controlled either by current hysteresis control or voltage-PWM control. In the former phase current is kept in the reference value (Iref) within a given hysteresis band. For the latter each SRM phase is supplied with voltage-PWM with constant duty-cycle. In both cases, the turn-on (θo) and turn-off (θc) angles are kept constant, unless is intended to apply an optimization process (e.g., minimizing torque ripple, noise or losses). At high speeds, due to high back-electromotive force in stator phases, single-pulse control is used with the voltage at rated value. The conduction period (θo - θc) in then adapted to torque and speed requirements.

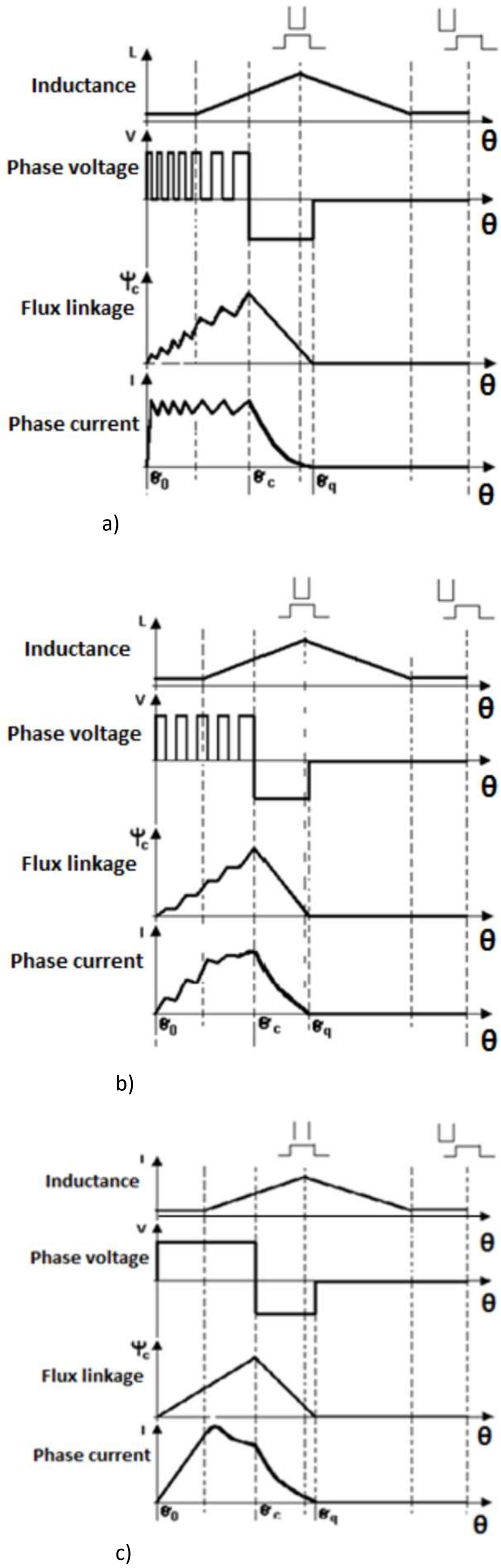


Figure 5. SRM operation modes: a) current hysteresis; b) voltage-PWM; c) single-pulse [4]

3.3. SRM Non-Conventional Configurations and Applications

In order to overcome the SRM main limitations (torque ripple, noise, low power density and low power factor), different research directions have been pursued, both in design and control. This section just enumerates some promising alternative SRM configurations, being far for presenting an exhaustive overview on this issue. There is also considerable ongoing research on SRM control methods, but this is not cover in this paper.

Recent research shows that multi-stack conventional SRM and multi-stack SRM with segmental stator or rotor are promising alternatives for reducing torque ripples, increase torque density and increase power factor. Other approaches as double stator and double-sided topologies also have been addressed. For further improvement, the insertion of magnets into the stator poles was also implemented, giving rise to a new class of hybrid machines that are being actively researched. A few examples are depicted in Figure 6.

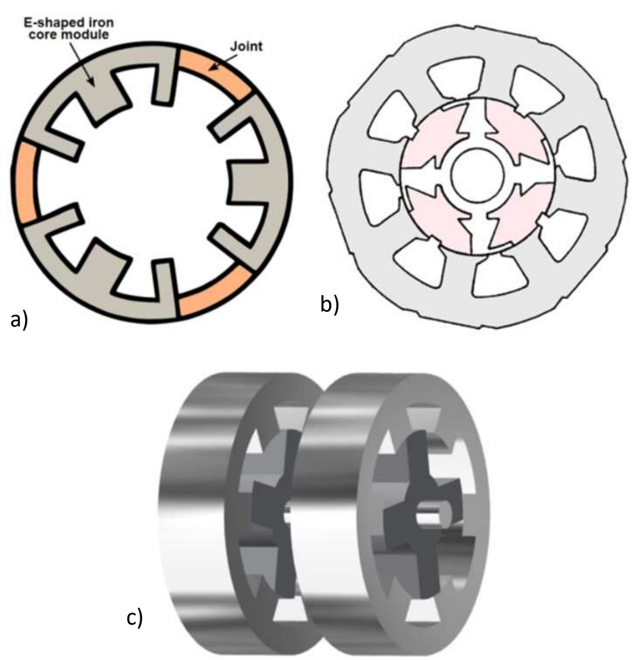
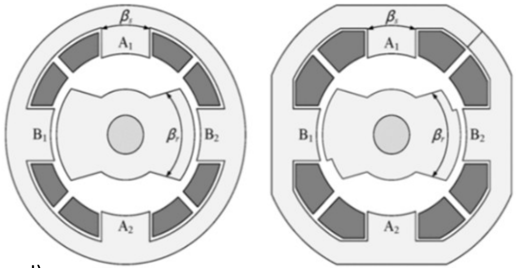
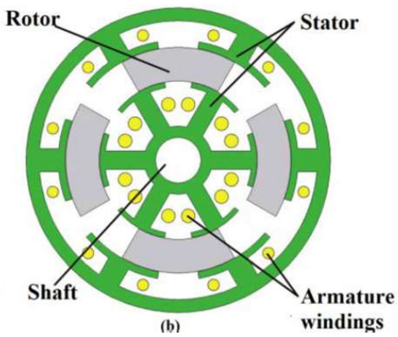


Figure 6 (part 1). Examples of non-conventional SRM – a) 9 poles (unsymmetric) modular SRM stator [11]; b) independent iron cores of a segmental rotor [11]; c) two-stack SRM. Torque ripple & vibrations are reduced [12]; starting torque is increased;



d)



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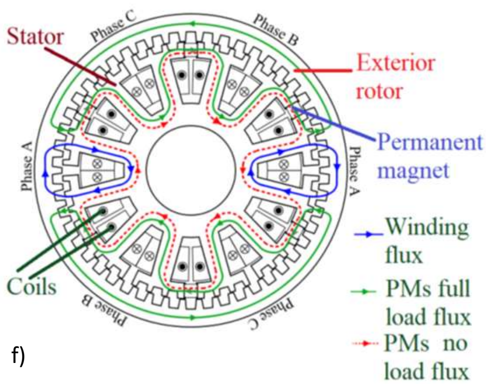

f)

Figure 6 (part 2). Examples of non-conventional SRM – d) non-uniform air gap for high torque & reduced torque ripple [2]; e) double stator switched reluctance motor (DS-SRM) to minimize radial forces [2]; f) exterior rotor with multiple teeth employing PMs improving the output power and torque [2]

Figures 7 shows some SRM for electric traction and HVAC applications, whereas in Figure 8 is depicted a prototype developed for hybrid electric vehicle. New opportunities for SRM applications are emerging. It should be pointed that non-conventional design may increase the production costs. This can be mitigated with optimized control methods.

a)

b)

c)

Figure 7. Actual windings in SRMs: (a) 24/16 traction SRM, (b) external-rotor e-bike SRM, and HVAC SRM

a)

b)

c)

d)

Figue 8. Prototype 24/16 SRM used as traction motor for HEV application: (a) rotor core, (b) stator-winding subassembely, (c) rotor-shaft subassembly, and (d) SRM assembly

4. Conclusions

Currently, interior PMSMs are still the first choice in the electric propulsion market. However, rare earth metals cost and supply chain restrictions are motivating an interest for electric machines without RE. SRMs are RE free machines with several advantages for EV, such as simple structure, a wide constant power region at high speed, fault tolerance, cost effective, and robust construction. However, high torque ripple and acoustic noise are their main limitations, in addition to specific power converters and control methods. Significant research progress has been done (and still is!) in order to mitigate torque ripple and noise, addressing both the SRM design and control methods. non-conventional structures may have a negative impact on the machine simplicity, cost and robustness. Therefore, optimizing the converter configuration and control methods (e.g., adopting machine learning techniques for real-time control) can minimize those impacts.

5. References

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