Switched Reluctance Motor: Research Trends and Overview

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(Invited)

***Abstract*—There has been a growing interest in switched reluctance motor (SRM) ever since the development of thyristor in 1956. The most appealing feature of SRM which attracts researchers over these years is its simple structure that incorporates concentrated windings on the stator poles and plain laminations of ferromagnetic material as a rotor. Due to this attributes, advances are being made rapidly with the consideration that SRM can be used as an alternative to DC motors and permanent magnet motors. The objective of this paper is to present an overview of the recent developments and a prediction of possible future advancements in SR Drives. Brief history, importance, innovations in structure and control, along with practical application examples are all discussed here to give a more in-depth comprehension of the motor.**

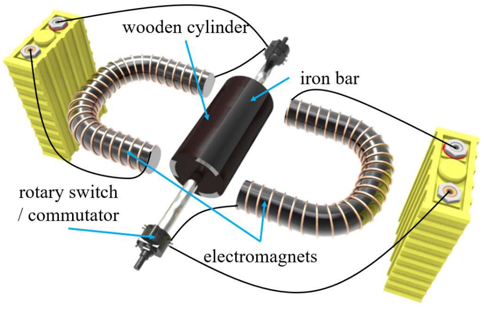
***Index Terms*—Switched Reluctance Motor (SRM), history, operating principle, SRM types, applications.**

I. INTRODUCTION

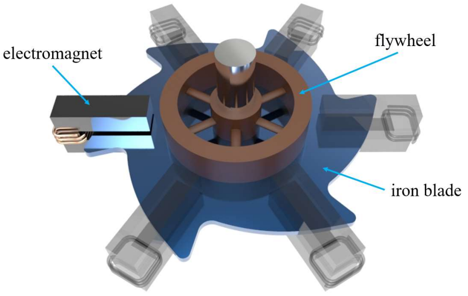
SWITCHED reluctance motor (SRM) is a doubly salient electric machine that relies on reluctance torque to rotate rather than electromagnetic torque, as indicated on the name. The term switched comes from the fact that the motor depends heavily on power switching transistors for its operation. This, however, was the factor that slowed the development of SRM since power electronics were not so advanced.

Robert Davidson invented the world's first electric locomotive for the Edinburgh-Glasgow railway line on 22nd September 1842 which was driven by a motor that he created in 1839 [1]. The structure of Davidson's motor was simple: there was a pair of horseshoe-shaped electromagnets each connected to either a rotary switch or commutator and a wooden cylinder with an odd number of iron bars on it, as shown in Fig. 1(a). By alternately turning the switches on and off, the iron bars will be pulled towards the corresponding electromagnets, thus creating a rotation. As primitive as it might be, this later became the fundamental principle of modern SRMs, which will be explained in detail in the next section. Although there were some problems such as a significantly large radial force when an iron bar gets aligned with an electromagnet that would detach it from its wooden frame and high eddy loss on the iron bars, Davidson's motor was functional and became one of the remarkable inventions throughout history.

There were a few variations of the early SRMs which rooted from the electromagnetic motor by Davidson, but the name itself did not arise to the public until 1969 when S. A. Nasar published his paper titled "D.C.-Switched Reluctance Motor" [2]. The rotor consisted of a single iron blade and there were six electromagnets which current us switched on and off according to the rotor position. This model slightly resembled the modern SRM as can be seen in Fig. 1(b) and it was introduced as a commutator-less DC motor emphasizing on the replacement of commutators with solid-state switching devices.



(a) Davidson's motor



(b) Nasar's DC-SRM

Fig. 1. Graphical illustrations of early SRMs

It was not until 1980 where Lawrenson both used the term switched reluctance motor and introduced the design principle of the now popular structure of SRM [3]. It was called the doubly-salient reluctance motor and the layout is shown in Fig. 2 with the symbol $\theta, \beta_s, \beta_r, g_i, d$ expressing rotor position, stator pole arc, rotor pole arc, intepolar air-gap (rotor pole height), and rotor diameter, respectively. Other key development points of SRM fundamentals are listed in order in Table I.

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The advancements of SRMs have been recorded in some literature such as [4] and [5]. However, there are not any works done to document the researches from year 2000 until now. This paper deals with the more recent and updated innovations which are followed by the prediction of SRM utilization in the future. The main idea and concept of each important research as of now are described along with the final results. To give a better understanding of the matter, the significance of SRM development is explained first in the next section, then motor types are described, and finally, prospective research topics are discussed.

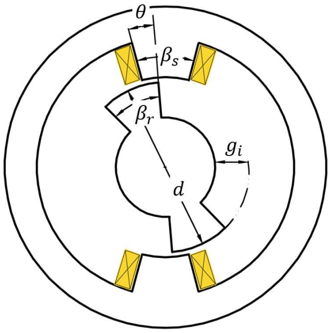


Fig. 2. Elements of a doubly-salient reluctance motor [3]

TABLE I
KEY MILESTONES OF SR DRIVE RESEARCH

Year	Developer	Research Topic
1839	Robert Davidson	Davidson's motor for electric locomotive: origin of SRM
1844	Charles Grafton Page	Axial engine: two solenoids switched by a commutator on the crankshaft to drive a flywheel
1933	British Navy	First bidirectional variable reluctance step motor used as a remote position repeater for compass and gun pointer indicator.
1956	General Electric Company	Development of thyristor
1962	Jean Jarret, et al.	Variable reluctance motor which core saturation is near maximum level to maintain high efficiency
1969	S. A. Nasar	First term usage of 'switched reluctance motor'
1972	B. D. Bedford	First patent of early SRM explaining about the structure of a brushless reluctance motor and its control circuit
1974	L. E. Unnewehr and W. H. Koch	Axial air-gap reluctance motor for variable speed applications
1976	J. V. Byrne	Saturable reluctance motors
1978	H. Bausch and B. Rieke	A 4-phase, thyristor-fed, double stack motor for vehicle propulsion
1980	P. J. Lawrenson et al.	Variable-speed switched reluctance motors: general foundation for the practical design of SRM
1983	Tasc Drives Ltd.	Oulton motor: first commercially available SR drive
1984	P.St.-J.R. French and W.F. Ray	Switched reluctance motor drives for rail traction
1986	T. J. E. Miller	SR drive operating without a shaft position sensor
1987	T. A. Lipo and J. C. Moreira	Coupled circuit model which allows mutual coupling between motor phases
1988	P. Materu and R. Krishnan	Estimation of switched reluctance motor losses

II. IMPORTANCE OF RESEARCH IN SRM

The main attractive point of SRM is its simple structure. The windings and/or, if needed, permanent magnets are located on the stator only and the rotor only consists of a stack of laminations of ferromagnetic material. Furthermore, the windings are that of the distributed type. From manufacturing point of view, SRM is practically easy to make. The windings can be simply inserted into the stator and core laminations in conventional designs are made with stamping. The placement of the coils which is a major source of heat during operation is also beneficial for cooling. However, there are several known drawbacks of SRM such as high torque ripple and acoustic noise, which are also the consequences of its geometry and these have become popular research topics.

Generally, a research can be described as a careful and detailed study to find an answer or solution into a problem or issue that motivated it. Literature regarding SRM usually are focused on performance improvement either from design [6-8] or control side [8-11]. Other than these subjects, there are some other motivational backgrounds which state the utmost important of SRM development, as explained below.

A. Demand for high-speed drives

The interests in high-speed machines are increasing in the last decade and the speed limit has been pushed further up to one million rpm which was claimed to be the world-record speed [12]. Power is a product of torque and angular speed whereas torque is proportional to rotor diameter and stack length. Therefore, three conclusions can be obtained from this:

- For the same output torque and volume, high-speed motors can produce higher output power, thus increasing the power density.
- For the same output power, high-speed motors can be made smaller, reducing its size and weight. Lightness and compactness are desirable factors, especially in automotive and transportation field.
- For the same output power, the small size and winding design of high-speed motor may improve efficiency.

High-speed motors are mainly used in direct-drive application. This also has its own merits such as: increased overall system efficiency due to the elimination of transmission gears/belts and higher reliability. Applications that take advantage of it are micro machineries, industrial spindles for grinding or drilling, spindles for dental surgery, air compressors, and vehicle turbochargers/superchargers. Fig. 3 shows the categorization of each application considering the output power and rotational speed.

SRM rotor has no windings or permanent magnets on it, so generally, the inertia is considerably low compared to other motor types. Based on this, most SRMs are used in high-speed application. Literature in [14] and [15] summarized the high-speed motor technologies and [16] specifically gave an outline about high-speed SRMs. The fastest SRM is recorded as a 100W 750,000 rpm 6/4 SRM which was designed for micro machine [17].

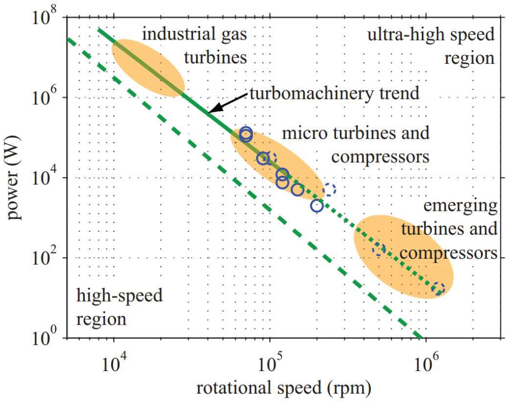


Fig. 3. Elements of a doubly-salient reluctance motor [13]

B. *Permanent magnet scarcity*

Permanent magnet motors are associated with high power density and efficiency. This is due to the fact that they do not require any energy to generate magnetic field. There are a lot of permanent magnet types, depending on the rare earth material (REM) synthesis made to create them. Although REMs are relatively abundant, discovered minable concentrations are mostly located in China, which provided over 95% of output in 2011 [18]. Therefore, there are some concerns over the availability of these materials as permanent magnet demands are increasing due to its wide usage and it has also been widely reported that the extraction and refinement of rare earth oxides is a potentially environmentally damaging process. Numerous government supported projects such as REACT (Rare Earth Alternatives in Critical Technologies) by ARPA-E in the US and rare-earth-free motor by NEDO (New Energy and Industrial Technology Development) in Japan.

The most popular element for permanent magnet is neodymium (Nd) and is also considered as the strongest, which means only a small piece of neodymium magnet is needed to produce a certain amount of magnetic field. Dysprosium (Dy) is usually added to the mix to increase coercive force. However, unlike what the name might suggest, REM is not exactly rare. Neodymium abundance in the Earth's crust is reported at about 38 mg/kg whereas dysprosium is much lower at about 5.2 mg/kg. It is the bulk production of the material by one single country which becomes the problem. Fig. 4 shows the annual magnet output in China from 1997 to 2015 [19].

This goes back to the previous section about demand high-speed drives which is usually fulfilled with permanent magnet motors. Even though neodymium is mostly used, the most abundant rare-earth element is cerium (Ce) and its price is 90% cheaper than neodymium. This can be a temporary solution to the current problem. However, a long-term answer can only be achieved by eliminating the dependency on permanent magnets. A study in [20] proposed an 18/12 SRM to compete with PMSM (permanent magnet synchronous motor) of the same size for electric vehicle traction. Furthermore, another possible benefit of removing permanent magnets is cost reduction, as shown in [21]. SRM researchers may invest more in low core loss core material which is expensive, but the overall cost is lower than that of PM motors.

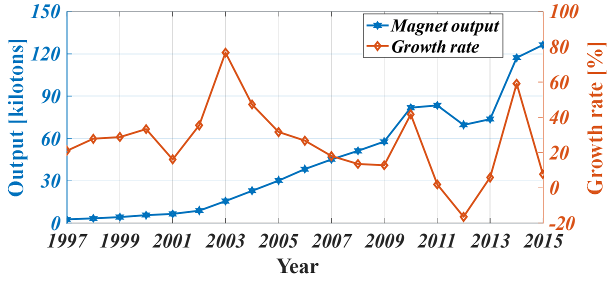


Fig. 4. Annual magnet output growth in China

III. Advancements in Design

Previously, the primitive designs of SRM were shown. In this section, some modified or altered structures of the motor are discussed and evaluated. Normally SRMs are known as free permanent magnet motors, but they might be added to the stator either to give an initial rotating position, increasing power density, etc., according to the application. This type of SRM is called hybrid. Outside the shown common SRM classification in Fig. 5 below, there are also other configurations such as double rotor or outer rotor types.

To produce an optimal design result, some trade-offs must be involved. There are a lot of possible options to achieve the required specifications. For example, for a given motor volume, an effort to increase torque by maximizing rotor outer diameter will result in a thinner stator yoke that will lead to full saturation. Experience plays a great role in determining which parameters should be subjects to change. This is why some engineers turn to evolutionary algorithms such as genetic algorithm (GA) and differential evolution (DE) or swarm intelligence, even neural networks to act as a second eye in designing electric machines as proposed in [22] or [23]. Due to the fast varieties of this kind of algorithms and that these are only means of designing which are not solely applied to SRM, the author does not discuss it further.

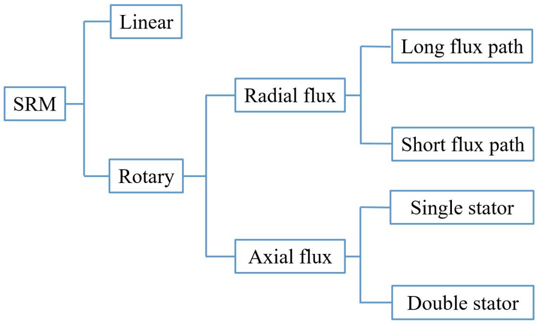


Fig. 5. SRM classification

A. *Rotor with ribs*

The salient poles of SRM rotor cause windage loss during rotation and even though it is not a major factor, this still contributes to the production of acoustic noise. Therefore, cylindrical rotor structure by implementing ribs connecting each rotor pole is adopted as shown in Fig. 6. The rib is saturated in [24] and the result shows that this method may be more appealing to high-speed application since it reduces efficiency in low-speed region. On the other side, a study in [25] gives a more comprehensive analysis by including displacement and stress investigation of the 0.2mm rib. This time, however, the efficiency improvement is higher in low-speed region. To be noted here, both motors were experimented at different rated speed. The former was already in an operating state from 15,000 to 40,000 rpm and the latter was from starting state 0 to 7500 rpm. Therefore, it can be concluded that the rib reduces windage loss in high-speed operation and static friction loss at startup.

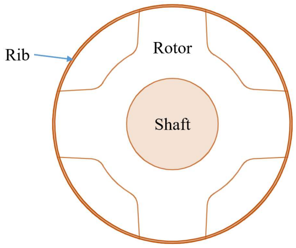


Fig. 6. Rotor with rib.

B. Non-uniform air-gap

The generated electric torque T_e in SRM can be described by using the equation below,

$$T_e = \frac{1}{2} i^2 \frac{dL(\theta, i)}{d\theta} \quad (1)$$

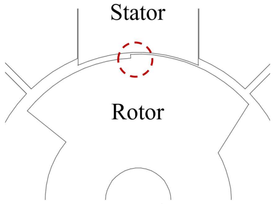
where i is phase current, θ is rotor position, and $L(\theta, i)$ can be calculated as,

$$L(\theta, i) = \frac{\lambda}{i} \quad (2)$$

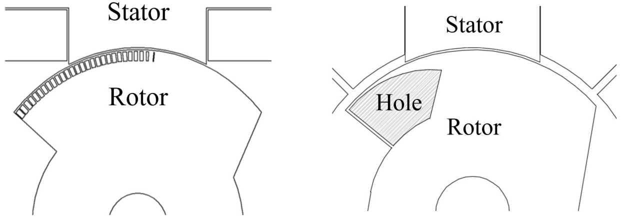
in which λ is phase flux linkage.

Based on the equations above, output torque can be altered if there are modifications that change flux linkage over air-gap. For this purpose, some rotor structures that create variable air-gap are reviewed in [26] and shown in Fig. 7.

These rotors are used to produce wider positive torque region and therefore higher average torque. One common disadvantage that they have is that they only can rotate in one predetermined direction. Moreover, saturated rotor and internal air-gap types suffer from less robustness than stepped rotor since they possess holes. On the other hand, stepped rotor has higher torque ripple due to the sudden change in the air-gap. Meanwhile, if variable air-gap stator structure is considered, it will create asymmetry which has the potential to increase radial force of stator teeth and thus, vibration.



(a) Stepped rotor



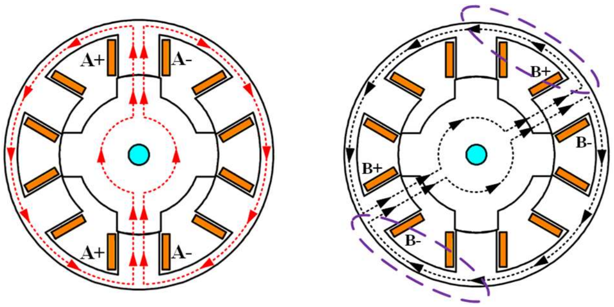
(b) Saturated rotor (c) Internal air-gap

Fig. 7. Variable air-gap rotor structures

C. Short flux path

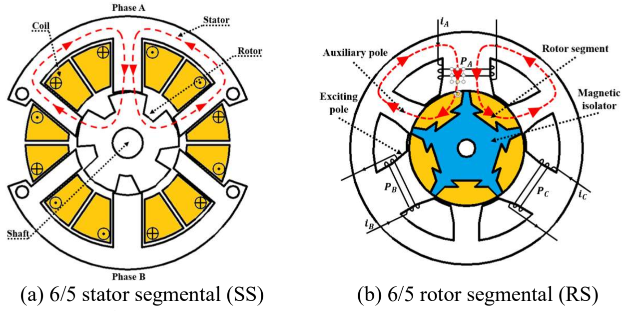
Conventional or basic SRMs implement long flux path where flux flow along the full circumference of stator back iron. This results in the flux reversal phenomena in which the flux direction of one phase excitation "clashes" with each other, as shown in Fig. 8. Flux reversal leads to an increased magneto-motive force (MMF) requirement and core loss, resulting in low electric utilization of the motor [27]. Therefore, structures adopting short flux path can be considered instead to improve performance, as summarized in [28].

Segmental SRMs can be categorized into two types: stator and rotor segmental. Stator segmental (SS) means that the stator core is divided into discontinued segments and the same goes for rotor segmental (RS) but with the rotor part. Fig. 9 shows 6/5 SRM in both SS and RS forms. For SS, the core can be cut into a C or E shape according to the pole numbers. On the other hand, RS achieved the short flux path by implementing both magnetic isolator to redirect flux and ferromagnetic materials. When designing SS, radial force has to be considered since it can create rotor unbalance that, at worst, can make it hit the stator during operation. Meanwhile, since RR adopt two materials, the motor has to be carefully manufactured to make sure the two do not separate during rotation, especially if it is used in high-speed region.



(a) Phase A excitation (b) Phase B excitation

Fig. 8. Flux reversal phenomena.



(a) 6/5 stator segmental (SS) (b) 6/5 rotor segmental (RS)

Fig. 9. Segmental SRMs

D. Bearingless SRM

The design process of electric machines, especially the high-speed ones, are not just about electromagnetic factors, but considerations on mechanical limitations are also necessary. For example, higher rotational speed means higher mechanical losses due to bearings and wrong selection of bearings will limit the maximum speed of a given motor. Common types of bearing such as roller and ball bearings may not even be suitable for high-speed operation, so noncontact types such as air foil and magnetic bearings are usually used. Motors with magnetic bearings can be categorized into maglev type along with bearingless motors.

The concept of bearingless SRM (BLSRM) is based on magnetic bearing principle. Generally, there are two kinds of winding: torque and suspension windings. As the name suggests, torque windings are responsible for torque generation and are excited accordingly as a regular SRM would whereas suspension windings are responsible for holding the rotor and shaft in the air, keeping them balanced. Fig. 10 shows the phase A of a 12/8 BLSRM with suspension force generation and Fig. 11 shows the corresponding inductance, torque, and force profiles. θ_1 and θ_3 mark the unaligned and aligned positions of the rotor. Phase excitation is turned off before aligned position so torque generation only happens between θ_1 and θ_2. Therefore, there is a torque dead zone from θ_2 to θ_3 where the next phase will be excited. Meanwhile, the suspending force is slowly increasing and reaches its max at aligned position and then slowly decreases accordingly. Other structures of BLSRM are reviewed in [29].

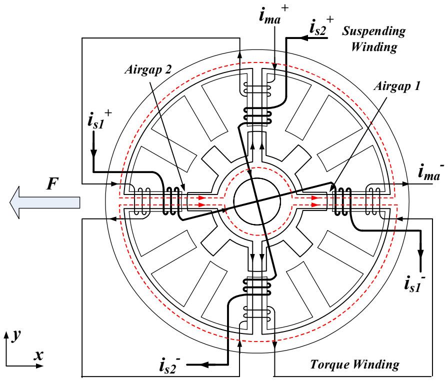


Fig. 10. Typical conventional BLSRM structure

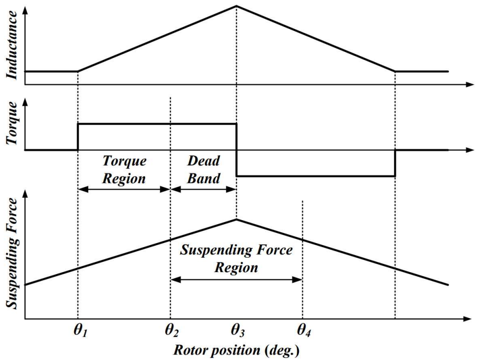


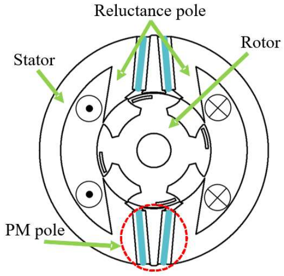
Fig. 11. Ideal inductance, torque and suspending force profiles

E. Hybrid SRM

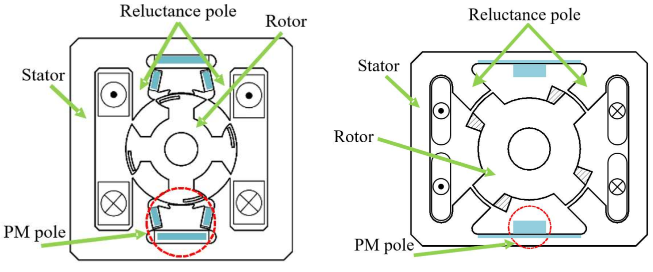
SRM is known as a permanent magnet-less motor which is one of its attractive features as explained before. However, there are some applications that require permanent magnet to be implemented, such as in a single-phase SRMs where the rotor has to be parked to give it a definite starting position.

Single-phase SRM has the least number of switches and can be considered economical converter-wise. However, conventional structure has a large torque dead zone occupying half of the electric cycle. This means high torque ripple and that if the rotor happens to stop in that area, it is unable to self-start. Due to these reasons, permanent magnets are often used in single-phase SRMs and they are often positioned to provide positive cogging torque or in other words, pull the rotor to maintain rotation as if there is phase excitation. Fig.12 shows variations of 4/4 hybrid SRM structures. In the v-shaped motor, the magnets are inserted in the middle of the stator in a concentrated manner as proposed in [30]. This construction is simple and easy to manufacture. However, it also weakens the stator since it cuts into segments instead of whole. The π-shaped motor also places the magnets in concentration, but it keeps the wholeness of stator [31]. The disadvantage of this structure is its complicated design and manufacture. Other variation is also proposed in [32] and it is called a Cyrano motor. Magnet-location-wise, even though it has to be inserted into stator core, it is relatively simpler than the previous two without sacrificing robustness. However, there is a rotor "nose" involved in the design which is not easy to manufacture that may increase the overall cost.

One important design point when designing a hybrid SRM other than permanent magnet placement is starting torque. There is a considerably high cogging torque due to the permanent magnets compared to conventional SRMs. The electromagnet torque produced by phase excitation has to be large enough to overcome cogging torque.



(a) v-shaped



(b) π-shaped (c) Cyrano type

Fig. 12. Hybrid SRM structure variations

IV. ADVANCEMENTS IN CONTROL

The operation of SRM is based on reluctance torque instead of continuous torque such as that in synchronous motors. This nature leads to high torque ripple and a highly nonlinear magnetization characteristic. The generation of torque depends on the switching action according to rotor position, which is why one of the common control of SRM is switching angle control where the engineer may choose appropriate turn on and off angles. Current controls such as soft/hard chopping and hysteresis are also frequently used. The characteristics of these methods are described in Table II. Generally, current control is applied in low-speed region where the current has enough time to rise to its maximum value, so it is controlled to adjust to desired performance. On the other hand, angle control is used for high-speed operation where the time is not enough for current to rise, which is why the on/off angle is controlled to allow more current flow. In this section, however, instead of the common methods, three advanced controls in SRM are chosen and a brief introduction of each is discussed.

TABLE II
COMMON SRM CONTROL METHODS

	Current control (low speed)	Angle control (high speed)
Concept	Back EMF < supply voltage Slow inductance increase rate Large current increase rate	Back EMF > supply voltage Fast inductance increase rate Low current increase rate
Explanation	Chopping → Loss due to switching action Conduction angle decrease → Higher torque ripple and acoustic noise In high-performance machine (low torque ripple), current overlap method is preferred	Excitation angle is moved forward to allow more current Conduction angle decrease → Higher torque ripple, reduced average torque Constant conduction angle → reduced torque ripple and lower acoustic noise

A. Direct torque control

It is well known that direct torque control (DTC) is an advanced control technology firstly developed for induction motor and is based on vector control. DTC is primarily applied to AC motors which magnetization characteristics are linear so conventional DTC cannot be just adopted to SRM in which phase excitations are independent to each other. The main idea of DTC is to select stator voltage vectors based on the rate of change of torque and flux, as shown in Fig. 13. Some researchers brought this concept to SRM in [33]. The amplitude of stator flux vector is set to be constant and torque can be controlled by increasing or decreasing stator flux. The structure of DTC for SRM incorporates both torque and stator flux hysteresis controls.

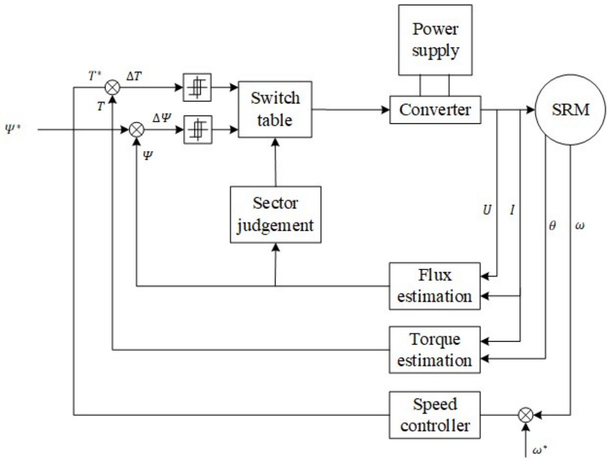


Fig. 13. Block diagram of conventional DTC

For a three-phase SRM with asymmetric half bridge converter, there are six voltage vectors available to be selected as illustrated in Fig. 14. The selection of voltage vectors complies with the rules in the table below where T and k indicates the phase torque and active phase.

TABLE III
VOLTAGE VECTOR SELECTION

T↑ λ↑	T↑ λ↓	T↓ λ↑	T↓ λ↓
V_{k+1}	V_{k+2}	V_{k-1}	V_{k-2}

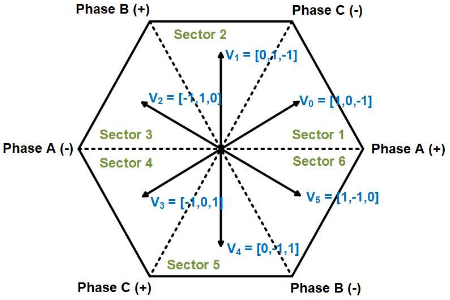


Fig. 14. Voltage vector selection for a 3-phase SRM

The advantages of DTC in SRM are:

- High precision torque feedback compared to conventional control strategies such as chopping current control. This opens possibilities for high-performance speed and position controller.
- Directly controlled torque which is simple to implement by using hysteresis controllers with no predetermined current information needed. This is if compared to other instantaneous torque control strategies, such as current-control-based torque sharing function and current profiling method, where torque-current transformation is required.
- Commutation strategy is also not needed and the same principle can be applied in any rotor position.

Meanwhile, the disadvantages are:

- SRM is generally singly excited and the excitation of additional phase together may generate negative phase torque and reduce total output. Therefore, a constant amplitude of flux vector does not have to be kept constant in SRM, unlike in induction motors [34].
- High phase current is required to generate constant flux which increases copper losses and reduces efficiency. This is achieved by longer phase conduction time. Moreover, the absence of current controller allows possibility for the current to exceed maximum allowed value.

B. Sensorless control

SRM depends heavily on rotor position information in order to correctly execute phase excitation. Mechanical position sensors such as rotary encoders, optical encoders, and hall sensors are widely used to give position feedback. However, this adds to overall volume and costs and malfunctions may reduce motor performance significantly which can often happen if the motor operates in harsh environment. Therefore, sensorless control method is developed to overcome these problems. The main idea of sensorless control in general is to use electrical parameters such as current, back-emf voltage, or inductance to estimate rotor position. An introduction to sensorless method in SRM has been provided in [35]. There are also methods using intelligent algorithms to predict rotor position such as in [36] where actual flux linkage is calculated from current and voltage in real time and fed into an artificial neural network or an adaptive neuro-fuzzy inference. Typically, there are four techniques to perform sensorless control in SRM: open-loop control, passive waveform detection, active probing, and state observer.

Conventional open-loop control of SRM deals with dwell angle which relies heavily on rotor position to synchronize with proper firing angle. Therefore, in sensorless open-loop method, commutation frequency is controlled. This put SRM at the same place as stepper motor where it runs at an exact synchronized speed due to numerous step angle and lack of damping. Also, there is no measurement of rotor position. Since there is no feedback involved in the control, in order to improve stability, an additional circuit can be incorporated. The open-loop method focuses on the variation of DC link current, as shown in [37], e.g. a sudden increase in DC-link current means there is an increase of load current. While this method can be considered low cost, the proposed controller has to be designed differently depending on the application and not suitable at those which load changes rapidly.

Passive waveform detection method is related to the maximum and minimum values of phase current when the rotor moves towards either aligned or unaligned position. Instantaneous emf changes according to the rotor position and by observing the effect of emf modulation on current waveform, the position can be estimated [38]. This technique was first developed for closed-loop operation of stepper motor.

The concept of active probing is presented in Fig. 15 where a rectangular wave voltage applied to the non-excited phase and excitation current waveforms are shown. Current pulse increases as phase inductance lowers and vice versa and at its maximum value at unaligned position. If the pulse falls below threshold, the position can be sensed and the transistor can be instantly turned on and off. The maximum value of the current pulse is given by (3),

$$i_{peak} = \frac{VT}{L(\theta)} \tag{3}$$

where T is the period of voltage pulse, V is excitation voltage, and $L(\theta)$ is inductance according to rotor position.

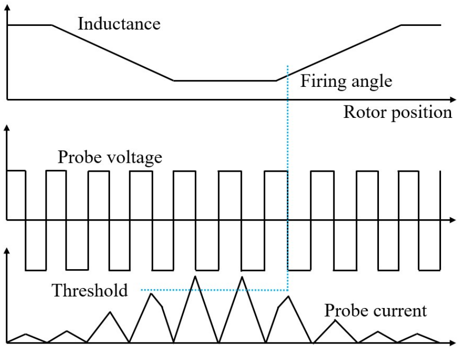


Fig. 15. Active probing method

Lumsdaine and Lang introduced state observers in [39]. The method is based on a mathematical model of a motor running in parallel with the actual drive. The measured voltage of the actual drive is connected to the model which calculates state variables such as rotor position and speed. Both researchers analyzed the stability and performance of the observer and experimentally proved it with 242 pole servo motors. The method gave accurate rotor position with a resolution of 1/15,000 revolution.

V. NOTABLE APPLICATIONS

The advantages of SRM does not only attract academic researchers but also industries. Most real-life applications are usually based on either the effort to use the drive to replace another type of motor in order to reduce cost and maintenance needs or high-speed requirement. In this section, four significant utilization of SRM that had been commercialized were chosen and discussed based on their category.

A. *Home appliance*

Sir James Dyson, a British inventor, revealed what was claimed as the fastest motor in the world which is a small switched reluctance motor in 2009 and it was considered a breakthrough at that time. As explained before, high-speed motor tends to be small in size. This motor outer diameter is only 55.8mm and weighs around 139grams. The developed motor was dubbed DDM (Dyson digital motor) 2 and meant to be used in DC31 handheld vacuum cleaner with the capability to run at the speed of 104,000rpm [40-41].

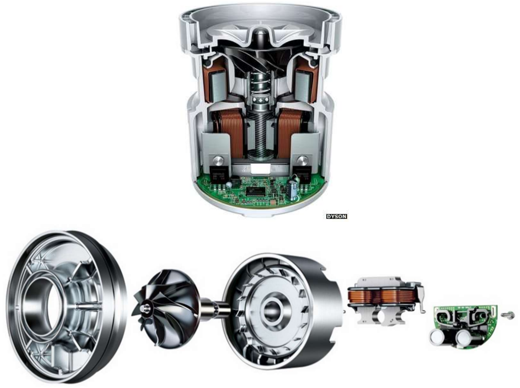


Fig. 16. Structure of Dyson digital motor [www.dyson.com.sg]

B. *Industrial application*

Hilti Corporation specialized in products for construction, building, and mining industry. They reportedly use SRM in their hammer breaker products such Hilti TE 700-AVR, TE 1000, 1500, and 3000-AVR which is claimed to be maintenance-free for life. The structure of the motor is shown in Fig. 17, which details are presented in [42] and [43].

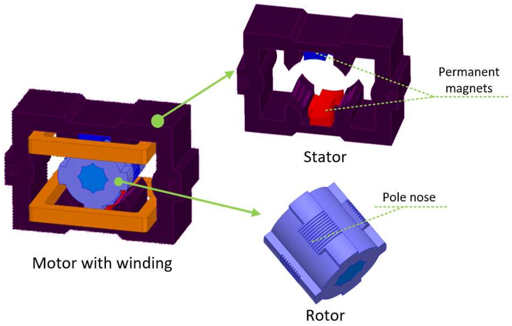


Fig. 17 SRM structure for hammer breaker (Hilti) [43]

C. Electric vehicle

Electric vehicle (EV) has been gaining more interest due to the increasing problems of environmental pollution and energy crisis for the past few years. As described before, NEDO projects in Japan have started the development of rare-earth-free motors that have to be competitive in size, power density, and efficiency to the ones with magnets. Literature in [44] and [45] reported of such development by designing an 18/12 SRM that matches the performance of permanent magnet synchronous machine (PMSM) of the same size. The proposed SRM is targeted for Toyota Prius which is a type of hybrid electric vehicle (HEV) that uses both ICE and electric motor. The prototype of the motor is shown in Fig. 18.

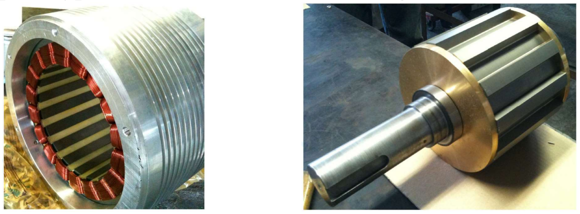

Stator Rotor

Fig. 18 Prototype SRM for traction [45]

Another example of SRM utilization in EV is electric supercharger which function is to provide a boost of air into ICE for sudden acceleration. Valeo reportedly used a 6/4 SRM with the maximum speed of 70,000 rpm and maximum power of 7 kW for a supercharger in Audi SQ7. The response speed is within 350 ms from idle to maximum speed [46]. This is made possible thanks to the low-inertia of the rotor. The cut-off drawing of the system is shown in Fig. 19 as seen in official Audi website.

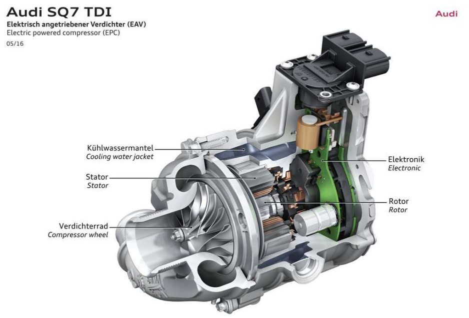


Fig. 19 Electric supercharger system

VI. CONCLUSION

A brief review on SRM research trends is presented in this paper. SRM is simple in structure which is its main attracting point. The rotor is merely a stack of core laminations and the stator winding is that of the distributed type that can just be easily inserted to stator pole. Over the years, there are inventions made to improve SRM performance such as adding rib to the rotor to reduce windage loss, non-uniform air-gap for wider positive torque region, short-flux path to reduce core loss, bearingless structure to increase efficiency by lowering friction, and adding permanent magnets to single-phase SRM to give definite starting position. The reason why SRM research is only growing in the last couple of decades is because of its dependency on power converter. The motor control also become variant and much more improved. For example, direct torque control which was primarily used in AC motors only can now also be implemented in SRM and also sensorless control where rotor position is estimated and mechanical position sensors can be eliminated. Some notable applications are also shortly explained. In conclusion, SRM is a viable alternative to permanent magnet motors and is a good candidate for low-cost and/or high-speed drive. It is the duty of future researchers to investigate solutions to the motor's drawbacks and explore its potential either for research purposes or commercial products.

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