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TECHNOLOGICAL ASPECTS AND APPLICATIONS OF LARGE POWER SWITCHED RELUCTANCE MOTORS IN MINING

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ABSTRACT. The switched reluctance motors (SRM) are known from about the beginning of the 19th century. They are in fact amongst the first rotating electrical machines ever, firstly called electromagnetic engines. Being synchronous salient poles motors they have very simple construction but are difficult to control due to the highly nonlinear magnetic circuit. With the fast development of the power electronics and the computational abilities of the nowadays microcontrollers and field programmable gate arrays SRMs has gained growing popularity especially in fields like the mining industry. This is possible due to their ability to work in heavily polluted and harsh environments and their fault-tolerant operation and control. In the paper the technological aspects of the SRMs are introduced and some typical applications of large power switched reluctance motors in mining are pointed out.

Keywords: switched reluctance motors, electrical drives, nonlinear magnetic circuit, mining, fault tolerant control

ТЕХНОЛОГИЧНИ АСПЕКТИ И ПРИЛОЖЕНИЕ НА МОЩНИТЕ ПРЕВКЛЮЧВАЕМИ РЕАКТИВНИ ЕЛЕКТРОДВИГАТЕЛИ В МИННАТА ПРОМИШЛЕНОСТ

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РЕЗЮМЕ. Превключваемите реактивни двигатели (ПРД) са известни още от началото на 19-ти век. Всъщност те са сред първите въртящи се електрически машини изобщо, наричани първоначално електромагнитни двигатели. Като синхронни двигатели с явнополюсна структура те имат много проста конструкция, но са трудни за управление поради силно нелинейната си магнитна верига. С развитието на силовата електроника и изчислителните възможности на днешните микроконтролери и програмируеми логически схеми, популярността на ПРД силно нараства, особено в области като минната индустрия. Това става възможно благодарение на тяхната способност да работят в силно замърсени и тежки среди и тяхната отказоустойчива работа и управление. В статията са представени технологичните аспекти на ПРД и са показани някои типични приложения на превключваемите реактивни двигатели с голяма мощност в минното дело.

Ключови думи: превключваеми реактивни двигатели, електрозадвижване, нелинейна магнитна верига, минно дело, отказоустойчива работа

Introduction

The Switched Reluctance Motors (SRM) are one of the earliest rotating electric machines ever. Their origins lie in the Sturgeon's electromagnet (Sturgeon, 1825) and they were initially called electromagnetic engines (Miller 1993). They were originally used in locomotive drives but due to their poor performance and the lack of proper electronic control at that time they lost popularity for almost 100 years. With the fast development of the power electronics switches, the computational abilities of the nowadays microcontrollers (MCU) and the field programmable gate arrays (FPGA) SRMs popularity, especially in fields like the mining industry, is continuously growing.

The SRM technology development worldwide, in both practical and theoretical terms, can be seen from the number of patents received and the number of publications over the years. In 1972 Burnice Bedford received 2 patents. According to Fleadh Electronics (Watkins, 2016) 67 patents were published before 1976 and over 1775 patents were published until 1999. The articles on this topic were 11 before 1976 and over 1847 until 1999. According to official data of the United States Patent and Trademark Office (USPTO 2013), patent applications filed for the period 1980-2010 were a total of 5936. The data presented clearly show the increasing interest in SRM technology and its augmented applicability in practice.

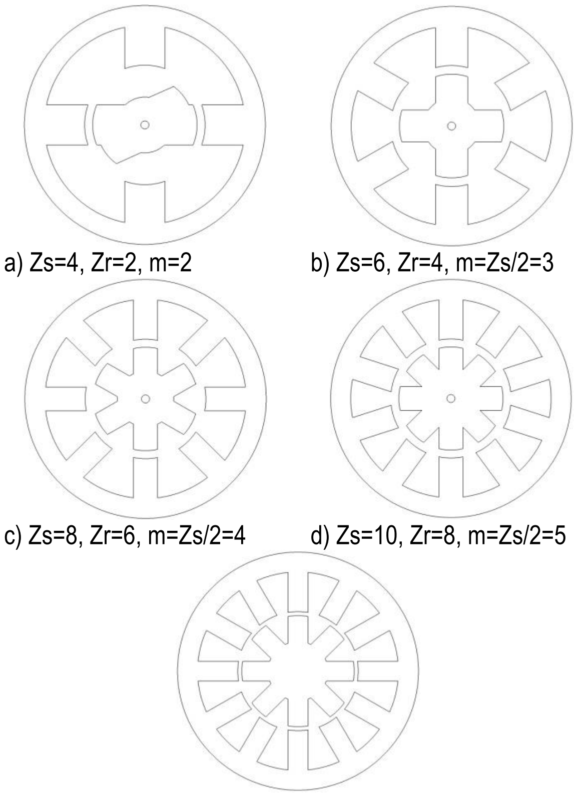
The major distinctive property of the SRM is the strong non-linearity of the magnetic circuit, which predetermines the difficulties in their modelling and control. This problem leads to increased torque ripples and to higher acoustic noise as a consequence. Although their manufacturing is greatly facilitated due to the full absence of rotor windings and mechanical commutator, and also the lack of impregnating resins for the coils, the requirements for mechanical precision are significantly higher than for most other types of electric motors. A higher computational speed is required that often poses a demand for the implementation of parallel algorithms that can be performed in real time. On the other hand, the construction simplicity, the lack of collector sparking, the large power and the extremely increased fault tolerance in terms of both operation and control, makes SRMs more and more popular in heavily polluted and harsh environments such as in mining.

Principle of operation

The switched reluctance motor has a simple salient pole construction with a passive rotor. Both the rotor and the stator armature are made of laminated steel. The windings are located at the poles of the yoke. For each phase, they are located at opposite poles and are coupled in pairs to form the phase sections of the inductor. Furthermore, the windings are connected so that the total magnetic flux is increased. The motor is called "switched" because it commutates the poles with a common magnetic flux of the stator compared to those of the rotor. It is called "reluctance" because of the tendency of the rotor to move to a position with less reluctance, i.e. minimal magnetic resistance. There is no current flowing into the rotor.

In order to produce a starting torque it is necessary the rotor teeth to be displaced with regard to the stator teeth, i.e. to be in an unaligned position. That is why, the rotor poles are generally less in number than those of the stator (DiRenzo, 2000; Wach, 2011). The control signal is not a sine-wave voltage, it consists of current pulses fed in a certain sequence, for which the current direction is irrelevant. The aftereffect of this is the reduced hysteresis loss.

The most common SRM types are shown in Fig. 1.



a) Zs=4, Zr=2, m=2

b) Zs=6, Zr=4, m=Zs/2=3

c) Zs=8, Zr=6, m=Zs/2=4

d) Zs=10, Zr=8, m=Zs/2=5

e) Zs=12, Zr=8, m=Zs/4=3

Fig. 1. Basic stator-rotor configuration of the SRM

The main characteristic is the combination of stator poles - *Zs* and rotor poles - *Zr*. The number of phases *m* is equal to the number of stator teeth *Zs* divided by the pairs of poles *2p*. When the number of pairs of poles 2p = 1, the number of phases is 2 because the diametrically opposed teeth of the stator are simultaneously excited by the same current when the windings are connected in series. For the most common SRM 2p = Zs-Zr. The angular distance between the closest stator and rotor poles (from the unaligned to the aligned position) is given by the expression (1).

$$\varepsilon = \frac{2.\pi}{p} = \left(\frac{1}{Z_r} - \frac{1}{Z_S}\right) = \frac{2.\pi}{p}\,\frac{2.p}{Z_S.Z_r} = \frac{2.\pi}{m.Z_r} \qquad (1)$$

This is the angle by which one phase can be excited. For SRM6-4 this angle is ε=30°, for the SRM8-6 it is ε=15° and it is the same for the SRM12-8, etc.

Although SR motors with 72-48 poles configuration (Elhomdy et al., 2018) exist, the most common large power motor configuration is of type 12-8. The greater the number of poles, the higher the switching frequency, and the more the torque ripples are smoothed but the losses in the steel are greater. At the same time, the mechanical design of the motor and the control electronics become more complicated. Increasing the number of teeth per pole results in an increase in output power (Finch et al., 1984; Qishan et al., 1988) which results in a reduction in the rotational period in which the transformation of energy takes place. For the classical SRM, each stator pole consists of only one tooth. The doubling of the number of teeth can be achieved without substantially reducing the maximum inductance at the aligned position of the rotor and stator teeth. In this way the motoring torque can be almost doubled by using two teeth per one stator pole. Increasing the number of teeth requires a proportional increase in sensor resolution. An increased count of pole teeth is used in the Vernier Reluctance Motors (Harris et al., 1982) where the three-phase coils are mounted on a salient pole stator. For this type of motors the control voltage is sinusoidal and the energising of all of the phases is done simultaneously. At least two phases are required to ensure starting of rotation, whereas at least three phases are required to ensure a desired starting direction. A number of methods exist for reducing the torque ripples which are divided into two groups, namely by control parameters adjustment and by changing the geometry of the poles. The first method is generally preferred as it is the most flexible – for example, phase overlay or phase current profiling can be done. In SRM drives the average torque and the torque ripples are affected by the turn-on and turn-off angles. The SRM torque characteristic can be optimised by applying appropriated pre-calculated turn-on and turn-off angles in function of the motor current and speed.

The mechanical characteristic of the SRM is shown in Fig. 2. It is hyperbolic in nature and is very similar to that of the serially excited DC motor (DiRenzo, 2000; Wach, 2011).

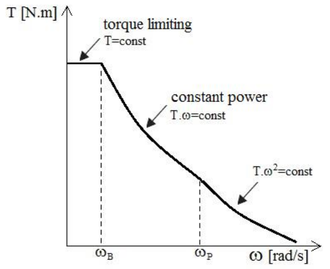


Fig. 2. Mechanical characteristic of the SRM

The torque production in the SRM is dependent on the change of the stored magnetic energy in the phase winding as a function of the rotor position. The maximal torque is related to the maximal current flowing through the winding of the machine. The speed ω is limited by the supply voltage. The speed may be increased over its nominal value but at the expense of the torque reduction.

The instantaneous power equation of the SRM is (2).

$$
\begin{aligned}
U.I &= R.I^2 + I.\frac{d\Psi}{dt} = \\
&= R.I^2 + L(I,\theta).I.\frac{dI}{dt} + I^2.\frac{dL(I,\theta)}{dt}
\end{aligned}
\tag{2}
$$

The left side in the equation represents the instantaneous electric power delivered to the motor. The first term on the right side reflects the active losses. The second term on the right side of the equation includes the sum of the mechanical power and the power that is stored in the magnetic field.

Sometimes it is more appropriate for the torque to be expressed by the magnetic flux, and sometimes by the current through the windings. For this reason in the literature (Balazovic, 2002; Pavlitov, 2005) it is often considered the energy of the magnetic field Wf (3) and the co-energy Wc (4).

$$W_f = \int_0^{\Phi} I(\theta,\Phi).d\Phi \tag{3}$$

$$W_m \equiv W_c = \int_0^{i} \Phi(\theta,I).dI \tag{4}$$

The graphical representation is given in Fig. 3.

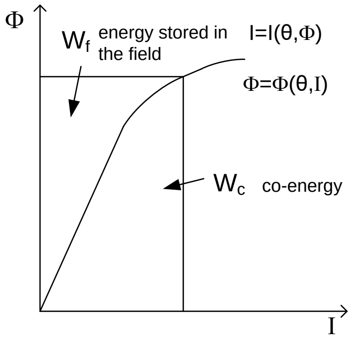


Fig. 3. Graphical interpretation of the energy and co-energy of the magnetic field

In the absence of magnetic saturation the curve will be a straight line and then at any angle the co-energy and the stored magnetic energy will be equal. It can be easily seen that the inductance is highly nonlinear and depends on both the position of the rotor and of the current through the stator. This is due to the salient pole structure of the SRM and the saturation effects. For the same reason the magnetic flux is also dependent on the position of the rotor and the current through the winding.

Several inverter topologies are suitable for driving the SRM (Miller, 1993; Miller, 2001; Ellabban et al., 2014; Murthy et al., 2014). The most appropriate one that is convenient for large power motors like the ones used in mining is shown in Fig. 4. A single phase is shown for clarity but it is being expanded over all phases depending on the exact SRM motor type.

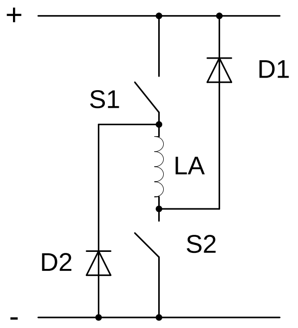
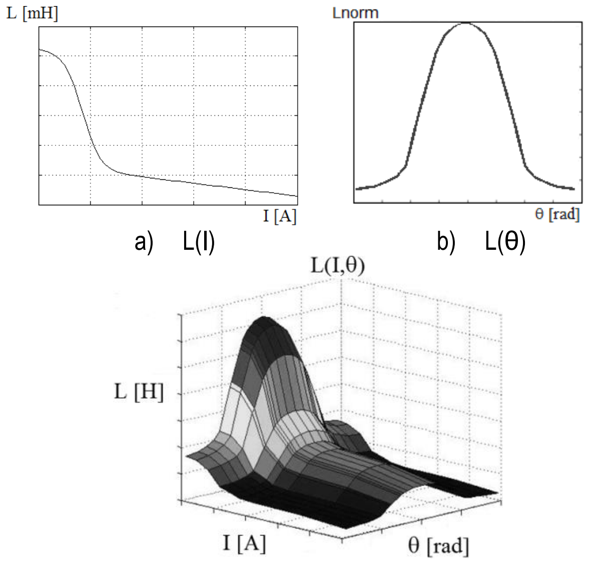


Fig. 4. Single phase part of the asymmetric bridge

As the torque is independent on the current polarity, the inverter needs to contain at least one power switch per phase. This is in contrast with the induction motor that requires at least two power switches. Moreover, the coils of the asynchronous motor are not serially connected to the switches, which can lead to irreparable short circuit faults. In the SRM the winding is always connected in series with the switch. That means that no shoot-though is possible and no dead-time is needed thus making it possible to increase the commutation frequency. In addition, the phases are independent of each other, which is why, even with reduced power, a continuous operation is feasible in a case of one or more disconnected or faulty phases. The mutual inductance between the phases is negligible, which makes phase commutation completely independent but also requires some measures to be taken to dissipate the stored magnetic energy. This is done with the diodes D1 and D2 in the figure. An exhaustive classification and a more detailed analysis of the power inverters for SR motors is given in (Krishnan, 2001).

Modelling and control

Due to the highly nonlinear profile of the stator inductance the mathematical modelling of SR motors is a tough task. A typical inductance profile as a function of the stator current is shown in Fig. 5 a) while the dependence of the normalised inductance as a function of the rotor position is shown in Fig. 5 b). for the sake of simplicity the numerical values are omitted.



a) L(I)

b) L(θ)

c) L(I, θ)

Fig. 5. Stator inductance as a function of two variables

Fig. 5 c) represents the inductance profile as a function of the two variables. In fact the actual inductance depends also on the temperature of the copper coil but in most of the cases this effect is negligible.

The precise mathematical description plays a crucial role for the effectiveness of the control because it permits to determine the right turn-on and turn-off angles for the phase switching and thus to achieve optimal control in terms of speed, torque ripples reduction and efficiency. Many methods exist for solving this task. The mathematical products such as Matlab (Chen, 2001, Ramasamy, 2005, Chen, 2009), Mathcad (Staudt, 2015, Stoyanov, 2016; 2017), Ansys Maxwell (Karim, 2016), Modelica (Bals, 2011) and PC-SRD (Miller 1990) are often used. The mathematical methods can be categorised into two major categories namely numerical methods and analytical methods. The mathematical modelling of non-linearity is most often based on the Finite Element Method (FEM) (Ohyama, 2006; Srinivas, 2005), which is a numerical method for finding approximate solutions for partial differential equations and requires great computational power. This is a very accurate method for static and dynamic modelling, but it is quite complex and time-consuming. Numerical methods are related in general with some difficulties in the implementation of the control algorithms. They also demand knowledge of the physical dimensions and the material of the motor. On the other hand, the analytical methods can be subdivided into:

- linear methods – they usually do not consider the edge and saturation effects and therefore the inductance curve cannot be expressed as a function of the current;
- quasi-linear methods – they represent a piecewise linearization of the magnetic curves in aligned position of the rotor and stator poles;
- nonlinear methods – they include various mathematical approaches for modelling the nonlinearities and are very perspective. At first, there is the Fourier decomposition (Hur 2003) which is made possible because the shape of the inductance is a periodic function and therefore it can be expressed as an endless sum of sinusoids. A fully dynamic model can be build using the Flux lookup table method (Torrey et al., 1995) and the intelligent approach of the Artificial Neural Networks (ANN) (Pavlitov et al., 2009). The last method is an innovative one and is being applied where the formal analysis is very difficult or even impossible.

Applications in mining

SR motors are widely accepted in mining and the trend of their increased usage is sustainable (Arunava, 2012, Chen, 2009, Ptakh, 2015, Szklarski, 2013). This is due mainly to their substantial advantages such as explosion safety because of the lack of a commutating device, as well as a reduced amount of heating; high reliability due to the possibility of working with one or more broken phases; increased starting torque; high overloading capability; inability to short-circuit the inverter; easy maintenance since there are no impregnating resins, and the change of a coil is a matter of removing and reinserting the new winding on the stator tooth. In the mining industry SRMs are mainly used in belt and armoured face conveyors, drilling machines, traction systems and pumps.

A world leader in the research and development of SR motors is the Japan-based Nidec Motor Corporation and its subsidiaries – the U.S. Motors (USA), Emerson Motor (USA) and SR Drives Ltd (UK). In 2012 Nidec acquired Avtron Industrial Automation Inc. (USA) and in 2014 - the China Tex Mechanical and Electrical Engineering Co. Ltd company. Other major players on the market include Ametek, VS Technology, Shandong Kehui Power Automation, Maccon GmbH, Rongjia Motor Co. Ltd, Shandong Desen, Huayang, Heliad, Rocky Mountain Technologies and some others. The global SRM market is assessed at over 440 million USD for 2018 and it is expected to reach 670 million USD by the end of 2025 (Ptakh, 2015).

A 150 kW SR motor manufactured by SR Drives Ltd is shown in Fig. 6. It is installed by the company on a 2300 m belt conveyor (Nidec 2015).

Fig. 6. The 150 kW Diamond drive system of SR Drives Ltd. (image courtesy of SR Drives Ltd. UK)

A major Canadian potash mining company has upgraded its existing load out conveyor with two 200 kW SRM449TN-180 motors on each end of the conveyor pulley after consulting the SR drive made by Synergy Engineering Ltd in cooperation with Nidec (IMJ 2015) – see Fig. 7. The needs of the drive system are for starting the conveyor 35 times/h, 20 hours/day, 350 days a year and 1000 m under the ground for a 30 years lifespan.

Fig. 7. The two-SRM Synergy Engineering drive system

A mining locomotive with a parallel drive system comprised of two three-phase 7.5kW SRM6-4 motors used in a coal mine in China (Chen, 2001) is shown in Fig. 8. The locomotive has a thrust of 7.1kN, a maximum speed of 10km/h and a braking distance of 14m.

Fig. 8. A mining locomotive with a parallel drive system of two 3-phase SRM6-4

The new Cat988KXE is a wheel loader offered by Caterpillar which employs the SR technology. It has a payload of 14.5 t and its efficiency is increased by 25% overall and by up to 49% in face-loading applications. It is shown in Fig. 9.

Fig. 9. The Caterpillar's Cat 988K XE wheel loader

The world's largest wheel loader is the P&H L-2350 manufactured by Le Tourneau (now part of Komatsu Mining Corp.). It is included in the Guinness Book of Records. This wheel loader weighs 266 tons and has an operating capacity of more than 72 tons. Its fuel consumption is about 45% less than comparably sized mechanical drive wheel loaders which is made possible by using an SR Hybrid drive system. Additional advantage is that the SR motor allows for full utilisation of all braking energy during the loading cycle and the service interval is increased to 20000 hours. The P&H L-2350 is shown in Fig. 10 below.

Fig. 10. The Le Torneau P&H L-2350 wheel loader uses a 400 kW SRM

The UK registered Chinese company Kehui International Ltd. is a manufacturer of SR motors of up to 400 kW. A coal shearer by Kehui is shown in Fig. 11. It benefits from the low starting current and a high torque (30% of rated current gives starting torque of up to 150%) provided by the SR motor.

Fig. 11. The Le Torneau P&H L-2350 wheel loader uses a 400 kW SRM

Conclusions

The technology, modelling, control, and applications of large power switched reluctance motors in mining are introduced in the paper. SR motors have indisputable advantages such as simple construction and robustness of the motor, fault tolerant operation and control, high starting torque, high overload capabilities and many more that make them an emerging alternative to the other large power motors used in the mining industry at present. Some keystone examples from the top manufactures worldwide are briefly introduced that prove the intense SRM penetration into the mining industry. It is obvious that despite some peculiarities related to their control the tendency of their increased usage is quite sustainable. The usage of the SR technology on hybrid, geared and direct drive systems is a premise for a more ecological industry.

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