ISSN 2289-6376 DIGES PMU 8 (2021) 10–15

Switched Reluctance Motors: Review on Fundamentals, Controls and Applications

Hamadi Ahmad[1,*], and Norliza Abd Razak[1]
[1]Department of Electrical Engineering, Politeknik Mukah, KM 7.5, Jalan Oya 96400 Mukah, Sarawak, Malaysia
*Corresponding author: hamadi@pmu.edu.my

Abstract

The aim of this article is to review about fundamental, controls and application of Switch Reluctance Motor (SRM). The usage of motor become very important in electric and hybrid electric vehicles. This new type of vehicles requires large power and high efficiency motor. Switched reluctance motor (SRM) has been used to overcome the demand of have large power and high efficiency motor. The features of SRM such as, simple stator and rotor development, smooth stator windings, no permanent magnet, simple cooling system, reliable and good performance over a large speed range.

Keywords: - switched reluctance motor (SRM), application SRM, controls SRM, fundamental SRM

1. Introduction

The usage of motor become very important in electric and hybrid electric vehicles. This new type of vehicles requires large power and high efficiency motor. Most common motor used in this vehicle is permanent magnet synchronous motors. In the same time, to have large power and high efficiency motor, a control method field weakening can be used. However, this design is not sufficient enough for the traction motors, and cut down the efficiency in high rotation speeds (Niguchi et al., 2018).

To meet the demand for a large power and high efficiency motor, the switched reluctance motor (SRM) has been used. Simple stator and rotor development, smooth stator windings, no permanent magnet, simple cooling system, great reliability, and good performance across a wide speed range are all features of SRM (Somsiri et al., 2007). The invention of SRM was made over 150 ago. Many researchers produced different varieties of SRM throughout the year so that they may be employed in a variety of applications. SRM is widely employed in propulsion systems for electric aircraft, hybrid vehicles, and vessels that require extremely high spinning speeds to create efficiency (Zheng et al., 2016). SRM torque is produced by the rotor's inclination to occupy a position that minimizes the reluctance of the magnetic path of the excited stator phase winding. Which is very crucial to understand. (Kannan, 2012).

Furthermore, the popularity and capability of SRM, its universally used in electric vehicles (EVs). By using SRM, cost of construction of EVs motor can be lowered due to material that been used in SRM. It also produced great torque and speed from high speed rotational without having any defect by using simple construction (Ustkoyuncu, 2019).

2. Fundamentals

The SRM is well known to be the best motor in their kind. Many applications used SRM by reason of minimum cost along with the smooth construction. The best part of SRM is having no brushes, commutators, windings, or magnets on its rotor. To generate rotational motor, SRM only focusing on the windings at stator. The converters used for SRMs also easy contrast to the inverter worn in ac motors (Kim and Krishnan, 2009).

Starting in 1838, a locomotive was driven by a device similar to a motor in Scotland, which took several years to develop for the basic operation of reluctance machines. Walker patented a stepper motor in 1920. His motor work is based on the variable reluctance theory. In his work Proceedings of the IEE in 1969, SA Nasar became the first person to publicize the core concept of switching reluctance motors. As rapid switching devices were accessible in the 1970s and 1980s, the applications of SRM grew. This problem arises as a result of SRM, which are suggested for usage in consumer appliances, defiance, and car industries due to its simple and rugged design. SRM will be used in Ford's power assisted steering system in the near future. The need for specialized design and the use of a sensor to control the speed were the key reasons for the tardy commercialization of these motors Torque ripple and acoustic noise are two more SRM flaws. Today, this flaw has been reduced as a result of the development of the concept; no sensor drives have been introduced, and many manufacturers are working on the SRM. This making it easily to find available motor. Switched reluctance motors provide a number of advantages, including great efficiency, the ability to be developed for ratings ranging from a few watts to millions of watts, and the ability to be used in difficult working situations (Ahmad, 2010).

2.1 Construction

SRM's key components are the stator and rotor, both of which have prominent poles in this motor (doubly salient). Concentrated coils are activated consecutively by dc voltage pulses on the stator's salient poles. SRM's rotor is also devoid of any field winding or permanent magnets, and it is in a passive state. The rotor is constructed entirely of laminated magnetic material, with no windings or permanent magnets.

The salient poles = Pr are the number of poles on the rotor. SRM can also have a variety of topologies. It is conceivable to have single-phase, two-phase, three-phase, four-phase, or even more than four-phase systems. The most common configurations are 6/4 three phase and 8/6 four phase machines as shown in Figure 1 (Ahmad, 2010).

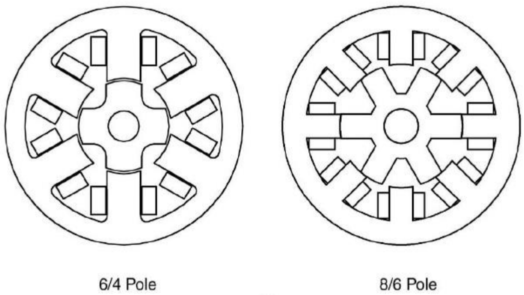

Figure 1: Switched reluctance motor configurations

2.2 Operating Principle

Take consideration that the rotor and stator are aligned and we take rotor poles are $r1$ and $r1\,'$ and meanwhile for stator poles are c and c′. Apply a current to phase a with the current direction as shown in Figure 2a. A flux is entrenched through stator poles a and a' and contribute to pull the rotor poles $r2'$ and $r2$ and toward the stator poles a and a' commonly. When rotor poles $r2'$ and $r2$ are aligned, the stator current of phase a is turned off and the comparable situation is shown in Figure 2b. Next, stator winding b is energized, pulling rotor poles $r1$ and $r1'$toward stator poles b and b′, this energized condition frons tor a to stator b move rotor in a clockwise direction. Furthermore, the last stator poles c is energized for c phase winding resulting in the alignment of $r2$and $r2'$with c and c′, respectively. From this condition, to move the rotor by 90° SRM will need 3 phases empower sequence. Switching currents in each phase are impressed as many times as the number of rotor poles for one rotation of rotor movement. The rotor rotation is reversed when currents are switched in the order a, c, and b. It is seen with the aid of Figures 2a and b.

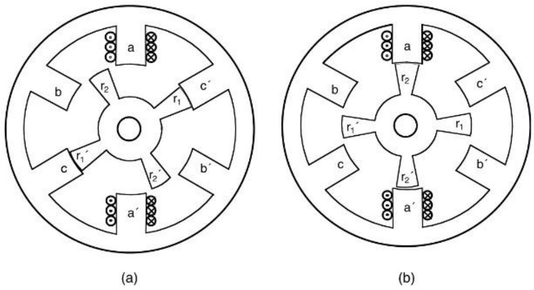

Figure 2: Operation of an SRM for (a) phase c aligned (b) phase a aligned

The direction of a switching reluctance motor is controlled by the principle of "minimum reluctance," which states that as the air gap between the stator and rotator varies, the magnetic flux in the circuit changes, resulting in magnetic torque. The electromechanical energy conversion of a helical tube can be used to express the magnetic torque of a switching reluctance motor., which is shown in 3. Power input can be expressed as:

$$\boldsymbol{W_e = \int eidt = \int eidt\frac{dN\Phi}{dt} = \int Nid\Phi = \int Fd\Phi} \quad (1)$$

Where e stands for EMF, F is the magneto motiveforce, and We for input power. W_f is the input electrical energy stored in the e coil winding, and W_m is the mechanical energy conversion then:

$$\boldsymbol{W_e = W_f + W_m} \quad (2)$$

There is no mechanical movement when the armature (rotator) is at the x1 position; the coil of stored energy is same to the coil input power at this moment, which is expressed in Figure 3 by the area of 6 OBEO and magnetic co energy can be write as $\int \Phi dF$, which is the area the OBAO in Figure 4. Similarly, the armature (rotator) is in $x2$ position, magnetic co energy is the area of OCAO. When energy is changed, it can be shown as (Zheng et al., 2016):

$$\boldsymbol{\delta W_e = \delta W_f + \delta W_m} \quad (3)$$

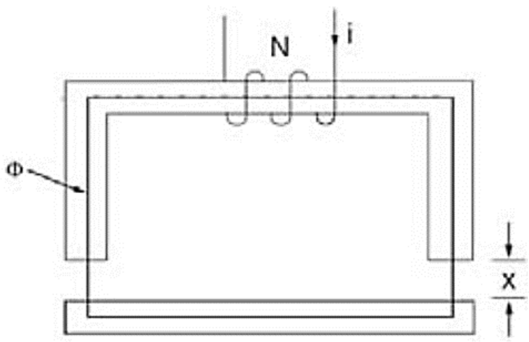

Figure 3: Spiral pipe structure

ISSN 2289-6376 DIGES PMU 8 (2021) 10–15

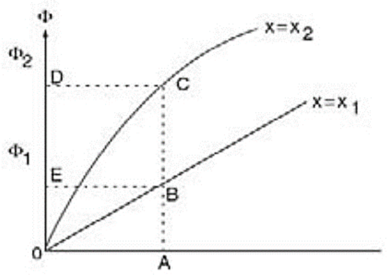

Figure 4: Magnetic flux and magneto motive force characteristics

2.3 Drive

Component like transistor /diode H bridge is the basic component used in power supply and compensation of a single-phase winding of SRM as shown in Figure 5. The torque of the SRM is not proportional to the direction of current flow through the phase winding because it is a reluctance 7 motor. Finally, the commutator bridge does not need to allow current to flow both ways via the winding, the 2 power transistors and 2 diodes are sufficient to provide energy delivery and return to the source (Piotr, 2011).

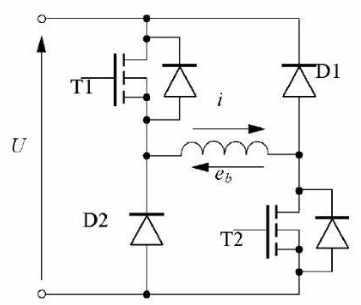

Figure 5: Typical commutation H-bridge circuit for switching current of a single phase of an SRM

2.4 Rotor and Stator

SRM have two main part which is stator and rotor. Because the rotor is merely constructed of stacked silicon steel laminations and just the stator carries the winding, SRM is doubly silent. The construction of typical Switched Reluctance motor is shown in Figure 6 (Kannan, 2012).

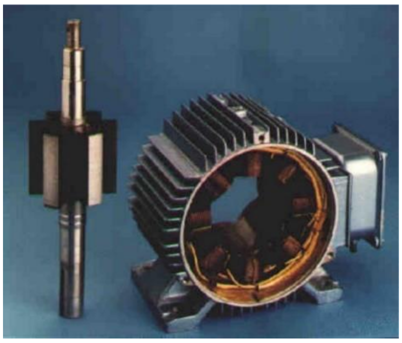

Figure 6: Typical switched reluctance motor

3. Controls

The SRM drive performance can be adjusted using control method. The method used will severs many applications that demand the function of SRM. [10]. In everyday system, SRM can be used in so much perspective. SRM can be used to control current, angle position, controlling torque and noise fluctuations due to friction of stator and rotor. This control SRM drive performance is very critical to our life everyday (Liu and Lin, 2014).

3.1 Current Control

As we know, current and voltage give a great effect to motor rotational. For SRM speed and torque give many advantages. The current controller in SRM is used to control torque of SRM and also controlling the speed. By controlling current only, the torque and speed can be manipulating at the same time. Many industrial companies can use this method for various applications and used to reduce the electrical drive input.

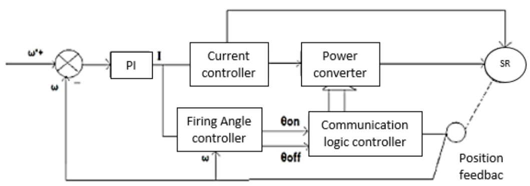

Figure 7: Current-controlled switched reluctance drive block schematic

From block diagram, there is a method call efficiency optimization used to show relation between inductance, phase current and rotor position in current control drive. This method is very important for controlling SRM. The SRM is controlled by a closed-loop current control system which initiate with all the system Rural, 2014).

3.2 Hysteresis Current Control

For advance current control on SRM, hysteresis current control used to obtain the orientation current and hysteresis bond of the motor. There many types of hysteresis current control and one of the types is analogue hysteresis controls. It widely used due to simplicity of the circuits. In the other hand it has one disadvantage, which is the variable switching frequency, where it makes subsonic noise in SRM (Rural, 2014 and Subbamma et al., 2016).

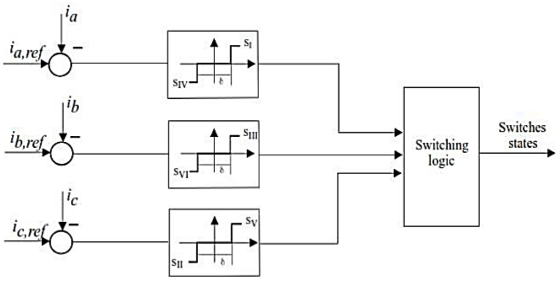

Figure 8: Hysteresis current control

3.3 Intelligent Control Techniques

In technology era, computer intelligent can also be used to control current in SRM. A method called intelligent control system uses different Artificial Bright computing systems. For examples, neural network, Fuzzy logic, Machine Learning, Evolutionary computing, and genetic algorithm. Developing this control method using coding and algorithm specifically to control current. All the system will put the drive will set to the desired value of torque and speed by using different bright controllers (Gao et al., 2015).

3.3.1 Fuzzy Logic Control

Fuzzy logic controllers (FLC) are one of the most popular intelligent controllers. Many of industrial player used FLC in many applications to control motor drives. This method of controller replaces many conventional controllers due to intelligent that it has. Generic proportional, integral, and derivative (PID) controllers are often replaced by FLC. Furthermore, in the new world of automation, this FLC can be used to shift the approach to automatic control challenges. The modification in fuzzy controllers is governed by a special system based on fuzzy rules. The rules are mainly a human operator of logical model (Prasad et al., 2016 and Wadnerkar et al., 2010).

3.3.2 Neuro-Fuzzy Compensator Control

There are many mixed methodologies in soft computing. first is fuzzy logic and secondly is neural networks. These two methods are basically the Neuro-Fuzzy system. The similarity of this system is ANFIS-based torque control. It is recommended in controlling current which is produced torque references to reduce torque ripple (Zhi Jian, 2015). In many years some researcher making observations make rules in this system. Compensation signals are introduced to the PI controller output in the currently managed speed control loop so that the effect of modifying the neuro-fuzzy compensation membership function may be analysed (Gao et al., 2015).

3.4 Self-Tuning Control

In the industrial sector, performance of mass-produced motor drives is very important. The performance produced will also for each motor can be reduced because of that a sophisticated and adaptive control methodology must be used. So in this case the controls in SRM can be effectively used to control scheme by using of closed-loop, to reducing costs with minimum hardware usage. A powerful control can be utilized to compensate for flaws like eccentricity, partial motor failure, and so on etc. Figure 9 shows a flow diagram that optimize the torque and ampere on the SRM drive defines by self-tuning control algorithm. This self-tuning can be used to achieve various goals such as reducing torque pulses, reducing acoustic noise, and so on, etc. With least changes to hardware (Fahimi, 2001).

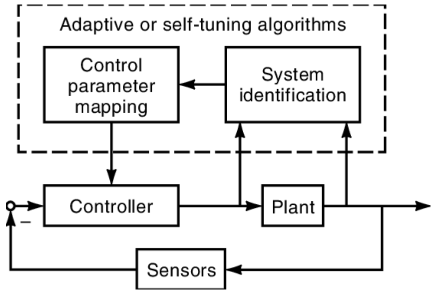

Figure 9: A self-tuning adaptive controller

3.5 Sensorless Control

The rotor position sensor is a key component of SRM control due to the reluctance of torque construction. But also the difficulty of using sensors for system control is that the costs are quite expensive. Figure 10 illustrates the classification scheme. Various suggested methods have their own advantages and disadvantages depending on the principle of operation (Fahimi et al., 2000).

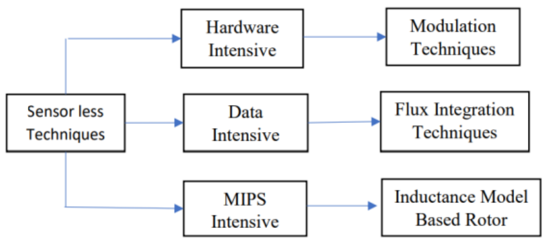

Figure 10: Sensorless control systems for SRM drives are classified

4. Applications

There are plenty of application for SRM, one of main usage is in electric vehicles (EVs) due to the performance of the motor stated past. SRM is used due to the advantages for EVs as an in wheel straight drive motor. By using SRM, EVs can increased efficiency, mechanical structure can be minimized, lightening the car body and minimizing cost. In addition, by using SRM in wheel motor drives giving maximum torque ratios. High value of torque is required to accelerate the vehicle more efficient (Ustkoyuncu, 2019).

SRM can also be used as a supplement to hydraulic or air-filled actuators in more electric aircraft (MEAs). Every component cannot be tolerated in the aircraft industry. It must be of the highest possible quality and free of flaws. Because of its inherent modularity and minimal defect, SRM is an excellent solution for aeroplane applications. In actuality, the SRM structure is made up of a compact winding structure with no permanent magnets (PM). The structure for the SRM can neglect the temperature which can cause damage. It also much safer as regards some vital disappointment conditions. SRM also manipulates some essential parameters for aircraft actuators, such as power-to-weight and power-to-size ratios, as well as efficiency (Tursini et al., 2017).

5. Conclusion

While many are currently using Drive Switched Reluctance Motor (SRM), Companies and industries developing SRM will also upgrade the systems that will be utilized to support SRM operations, such as adding smart controls. The emergence of high-speed microcontrollers and high-frequency semiconductor switches has recently refocused attention on the control systems utilized in SRM applications for example such as; Fuzzy logic controllers (FLC's), Neuro-Fuzzy Compensator Control and many others where the latest control systems will add or help SRM in the operation of super high speed, reliability, and durability, this is done to meet the requirements for heavy applications such as the aviation and automotive industries . However, there is no bias for previous control systems such as senseless, self-tuning and several other methods are also used in several industries because this technology is mature and ready for applications at various speeds and torques.

References

Ahmad, M. (2010). Switched Reluctance Motor Drives (SRM). In *High Performance AC Drives* (pp. 129-160). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13150-9_6.

Fahimi, B. (2001, June). Design of adjustable speed switched reluctance motor drives. In *IECON'01. 27th Annual Conference of the IEEE Industrial Electronics Society (Cat. No. 37243)* (Vol. 3, pp. 1577-1582). IEEE. https://doi.org/10.1109/iecon.2001.975527.

Fahimi, B., Suresh, G., & Ehsani, M. (2000, October). Review of sensorless control methods in switched reluctance motor drives. In *Conference Record of the 2000 IEEE Industry Applications Conference. Thirty-Fifth IAS Annual Meeting and World Conference on Industrial Applications of Electrical Energy (Cat. No. 00CH37129)* (Vol. 3, pp. 1850-1857). IEEE. https://doi.org/10.1109/ias.2000.882131.

Gao, X., Wang, X., Li, Z., & Zhou, Y. (2015). A review of torque ripple control strategies of switched reluctance motor. *International Journal of Control and Automation*, *8*(4), 103-116.

Kannan, S. (2012, December). Novel rotor and stator swapped switched reluctance motor. In *2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)* (pp. 1-4). IEEE. https://doi.org/10.1109/PEDES.2012.6484477.

Kim, J., & Krishnan, R. (2009). Novel two-switch-based switched reluctance motor drive for low-cost high-volume applications. *IEEE Transactions on Industry Applications*, *45*(4), 1241-1248. https://doi.org/10.1109/TIA.2009.2023568.

Liu, Z., & Lin, M. (2014). The control of switched reluctance motor in electric vehicle. *Sensors & Transducers*, *171*(5), 15.

Niguchi, N., Hirata, K., Kohara, A., Takahara, K., & Suzuki, H. (2018, September). Hybrid Drive of a Variable Flux Reluctance Motor and Switched Reluctance Motor. In *2018 XIII International Conference on Electrical Machines (ICEM)* (pp. 238-242). IEEE. https://doi.org/10.1109/ICELMACH.2018.8506959.

Prasad, K. A., Unnikrishnan, A., & Nair, U. (2016). Fuzzy sliding mode control of a switched reluctance motor. *Procedia Technology*, *25*, 735-742. https://doi.org/10.1016/j.protcy.2016.08.167.

Rural, G. (2014). Analysis of energy efficient current control methods in switched reluctance motor. *Middle-East Journal of Scientific Research*, *22*(8), 1138-1144. https://doi.org/10.5829/idosi.mejsr.2014.22.08.21989.

Somsiri, P., Tungpimonrut, K., & Aree, P. (2007, October). Three-phase full-bridge converters applied to switched reluctance motor drives with a modified switching strategy. In *2007 International Conference on Electrical Machines and Systems (ICEMS)* (pp. 1563-1568). IEEE. https://doi.org/10.1109/ICEMS.2007.4412290.

Subbamma, M. R., Madhusudhan, V., & Anjaneyelu, K. S. R. (2016). SRM Speed Control with Various Converter Topologies. *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, *5*(6), 4939–4951. https://doi.org/10.15662/IJAREEIE.2016.0506085.

Tursini, M., Villani, M., Fabri, G., & Di Leonardo, L. (2017). A switched-reluctance motor for aerospace application: Design, analysis and results. *Electric Power Systems Research*, *142*, 74–83. https://doi.org/10.1016/j.epsr.2016.08.044.

Ustkoyuncu, N. (2019). Application of an in-wheel direct drive motor based on switched reluctance motors for low-power electric vehicles. *Sadhana - Academy Proceedings in Engineering Sciences*, *44*(1), 1–6. https://doi.org/10.1007/s12046-018-0992-x.

Piotr, W. (2011). *Dynamics and control of electrical drives*. Springer Science & Business Media, 381–448. https://doi.org/10.1007/978-3-642-20222-3_5.

Wadnerkar, V. S., Bhaskari, M. M., Das, T. R., & RajKumar, A. D. (2010). A new fuzzy logic based modeling and simulation of a switched reluctance motor. *Journal of Electrical Engineering and Technology*, *5*(2), 276–281. https://doi.org/10.5370/JEET.2010.5.2.276.

Zheng, J., Zhu, X., Dong, L., Deng, Y., & Wu, H. (2016). Performance optimization of dual channel fault-Tolerant switched reluctance motor. *AUS 2016 - 2016 IEEE/CSAA International Conference on Aircraft Utility Systems*, *3*, 938–944. https://doi.org/10.1109/AUS.2016.7748189.

Zhi Jian, L. (2015). Switching-off Angle Control for Switched Reluctance Motor Using Adaptive Neural Fuzzy Inference System. *International Journal of Energy and Power Engineering*, *4*(1), 39. https://doi.org/10.11648/j.ijepe.20150401.16.