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An Overview Of Current Control Strategies For Switched Reluctance Machine

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ABSTRACT

Switched reluctance machines (SRMs) appear as an attractive magnet-free invention with a simple rotor structure, low fabrication cost and enhanced robustness. Although SRMs have been an available option for long time, their disadvantages include increased torque ripples, unwanted acoustic noise and vibrations. However, various control strategies for good current tracking capability, smooth torque production, and low noise emissions have evolved for improving the performance of the SRM drives over the past few decades. To clearly present these methods, this paper comprehensively reviews the existing current control strategies and their working mechanism. A simple illustration on classification of the most important methods of current control is introduced, and each one of them is explained including their application areas. Furthermore, comparison of different current control strategies based on their merits and demerits is also included in this work. Finally, a summary of each topic is presented and suggestion of future research topics is discussed.

Keywords: Switched Reluctance Machine; Model Predictive control; Hysteresis Control; Sliding Mode Control; Fuzzy Logic Control.

INTRODUCTION

Switched reluctance machines (SRMs) appear as an attractive magnet-free technology with a simple rotor structure, low production cost and enhanced robustness. Its simple construction allows a safer operation at higher temperature and higher speeds than permanent magnet synchronous motors (PMSM) (Mahalakshmi, 2018). Although SRMs have been an available option for long time, their disadvantages include increased torque ripples, undesirable acoustic noise and vibrations, and the need of special power converter topology for its operation hinder its operation. Nowadays, however, with the advances in power electronics and development of faster and more powerful digital processors, the use of sophisticated design procedures and control strategies can mitigate the main challenges in SRM drives (Dong, 2020).

Several control schemes have been proposed for the control of power converters and SRM drives. Among these, hysteresis control and linear PI control are the most established in the literature (Nagesh, 2020). Traditionally, SRMs are controlled by the combination of a conventional PI controller and hysteresis controller. Although the traditional control scheme may work well in some situations, its design is based on heuristic rules that cannot guarantee a satisfactory performance under al1 conditions. The hysteresis type current controller, in general, has better dynamic performance, but the problem of varying frequency hinders its use in many applications where acoustic noise due to switching is undesirable. This claim is substantiated by the observation made by Kunz, (2010), that the traditional control scheme is sensitive to variations in plant parameters and operating conditions.

Vector control, also known as Field-Oriented Control (FOC), is a technique used to control AC machines. FOC provides good control capability over the full torque and speed ranges. The implementation of this type of control scheme requires transformation of stator currents from the stationary reference frame to the rotor flux reference frame (Khan, 2019). The Direct Torque Control (DTC) technique can minimize the torque ripple by regulating torque within specified hysteresis band. This type of control based on hysteresis regulators presents less performance at low speed and the commutation frequency is not controlled. Compared with vector control, direct torque control has many advantages such as superior dynamic torque and speed response, simpler implementation and without speed sensor (Srihari, 2016). The disadvantage of DTC is the variation of the switching frequency and the dependence by the stator resistance and the hysteresis band comparator (Xu, 2019). Hence, there have been demands for rigorous nonlinear control design methods for SRM to meet the performance criteria.

Some of these new control schemes for power converters include fuzzy logic, sliding mode control, and predictive control. Fuzzy logic is suitable for applications where the controlled system or some of its parameters are unknown (Ardeshiri,.2019). Sliding mode control presents robustness and takes into account the switching nature of the power converters. Other control schemes found in the literature include neural networks, neuro-fuzzy, and other advanced control techniques such as model predictive control (MPC).

Recently, idea of torque control and current control as the fundamental control strategies in SRMs has been a focus of many researchers. This paper reviews the existing current control strategies used for enhancing the performance of SRM drive systems.

DYNAMIC MODEL OF SRM

The structure of SRM consists of copper windings only at its stator and has no permanent magnet associated with its structure. The stator and rotor design are doubly salient which results in its highly nonlinear behavior and discrete nature of its torque production mechanism. Figure 1 shows the geometric layout of 6/4 SRM (6 rotor pole and 4 stator poles).

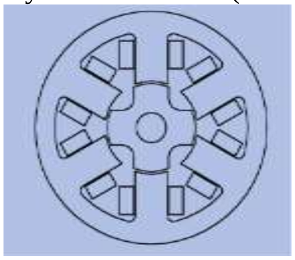

Figure 1: Cross-sectional view of SRM

The SRM model is considered complex due to its magnetic circuit non linearity. Neglecting the coupling between phases as suggested by Li, (2019), the voltage across the phase terminals of the SRM is given by:

$$v = R_i + \frac{d\psi}{dt} = R_i + \omega_m \frac{d\psi}{d\theta} \qquad (1)$$

$$= R_i + \omega_m \frac{d(Li)}{d\theta} = R_i + L\frac{di}{dt} + i\omega_m \frac{dL}{d\theta}$$

where i is the current, ψ is the flux-linkage in volt-seconds, R is the phase resistance, L is the phase inductance, θ is the rotor position, and ω_m is the angular velocity in rad/sec. The last term in equation (2) is the back-EMF (e).

$$e = \omega_m i \frac{dL}{d\theta} \qquad (2)$$

By considering the supply voltage as being dropped across the three terms in (1), the expression for the instantaneous power vi is given by:

$$vi = Ri^2 + Li\frac{di}{dt} + \omega_m i^2\frac{dL}{d\theta} \qquad (3)$$

The rate of change of magnetic stored energy at any instant is given by:

$$\frac{d}{dt}\left(\frac{1}{2}Li^2\right) = \frac{1}{2}i^2\frac{dL}{dt} + Li\frac{di}{dt} = \frac{1}{2}i^2\omega_m\frac{dL}{d\theta} + Li\frac{di}{dt} \qquad (4)$$

According to the law of conservation of energy, the mechanical power developed per phase is given by:

$$P = \omega_m T_e \qquad (5)$$

where T_e is the toque developed per phase. This is what is left after the resistive loss Ri^2 and (4) are subtracted from the power input vi, T_e being the instantaneous electromagnetic torque. Thus from (2) and (3), we write:

$$T_e = \frac{P}{\omega_m} = vi - Ri^2 - \frac{d\left(\frac{1}{2}Li^2\right)}{dt}$$

$$T_e = \frac{1}{2}i^2\frac{dL}{d\theta} \qquad (6)$$

The control objective is to provide each phase with current over an appropriate angle of rotation (the torque productive period of rotation) and to adjust the amplitude of the current such that the desired level of torque is obtained. The desired level of torque will usually be dictated by a feedback loop for controlling the speed of the SRM.

CLASSIFICATION OF CONTROL STRATEGIES FOR SRM DRIVES

Many efforts have been made and papers have been published proposing the different and improved control designs for SRM drive, and still the research is ongoing. The control strategies are mainly divided into two broad categories, namely current control and torque control (Ma et al 2017). Figure 2 shows the classification of control strategies for SRM.

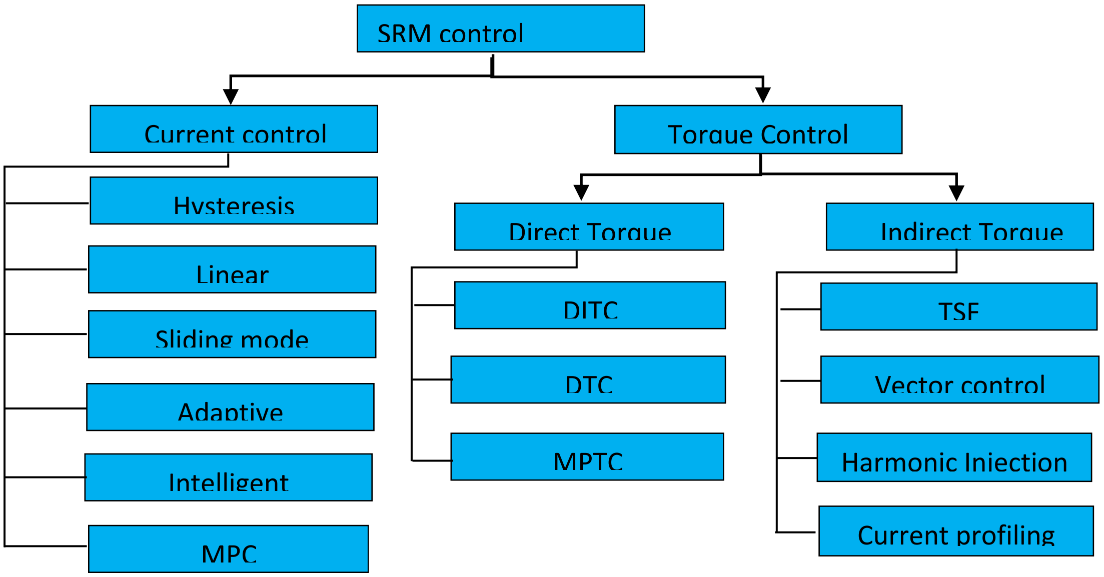

Figure 2: Classification of Control Strategies for SRM

CURRENT CONTROL STRATEGY

One of the most studied topics in SRM drive control is current control, for which there are six basic control strategies that have been extensively studied over the last few decades: namely, hysteresis control (Hard chopping and Soft chopping), linear control using pulse width modulation (PWM), Sliding mode control (SMC), Adaptive control, intelligence control and Model predictive control (MPC).

Hysteresis Current Controller

The basic idea of hysteresis current control is to keep the current inside the hysteresis band ΔH by changing the switching state of the converter each time the current reaches the boundary. Figure 3 shows the hysteresis control scheme for SRM drives. As can be seen, the current error is bounded between two states $\pm \Delta H/2$, and if the current error is higher than the upper limit $+\Delta H/2$, the power switches T1, T4 are turned on and T2, T3 are turned off. The opposite switching states are generated if the error is lower than $-\Delta H/2$ (Krishnan, 2017).

The two main drawbacks of this controller are the increase of the current ripples at steady state and the production of a variable switching frequency, which generate additional acoustic noise in SRM (Zhu et al. 2017). To reduce these ripples, the hysteresis band ΔH must be reduced but it increases the switching frequency of the converter, and therefore increase the power converter losses. Hysteresis current control is divided into two namely, hard chopping and soft chopping (Carlet, 2019). The hard chopping strategy involves driving both power switches with the same pulsed control signal such that the pair of switches are turned on/off in unison. Hence, the voltage across the phase winding switches between +Vs and –Vs (Bilgin, 2019). On the other hand, the soft chopping strategy involves the chopping of a single power switch only.

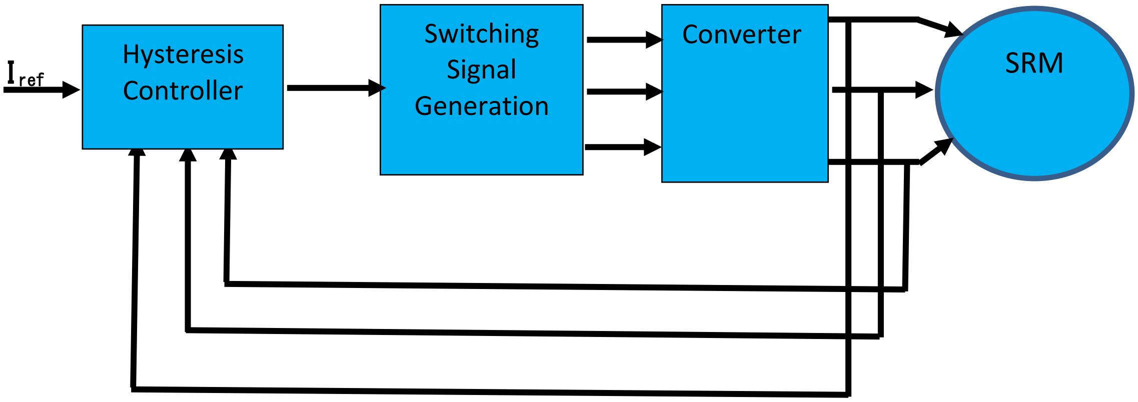

Figure 3: Hysteresis current control

Linear Current Controller

Several papers have investigated the use of PI controllers for the current control of SRMs. These strategies make use of mainly proportional - integral (PI) controllers to calculate a duty cycle for a PWM signal, based on the current tracking error (Ahmad, 2016). State feedback controllers have also been reported by Peng, (2016) for example. Advantages such as a fixed switching frequency and lower current ripple when compared to hysteresis current controllers are observed. Due to the non-linear nature of the SRM, however, the design of linear controllers becomes a challenging task.

Figure 4 shows the block diagram of PI current controller associated with a SRM's phase model, where U is the average reference voltage applied to a phase. Indeed, unlike a conventional machine, the back-emf can be seen as a disturbance for the current control that depends on $\partial L/\partial e$, where θe is the electrical position of the rotor (Song et al. 2016). A compensation of the back-emf improve the current control.

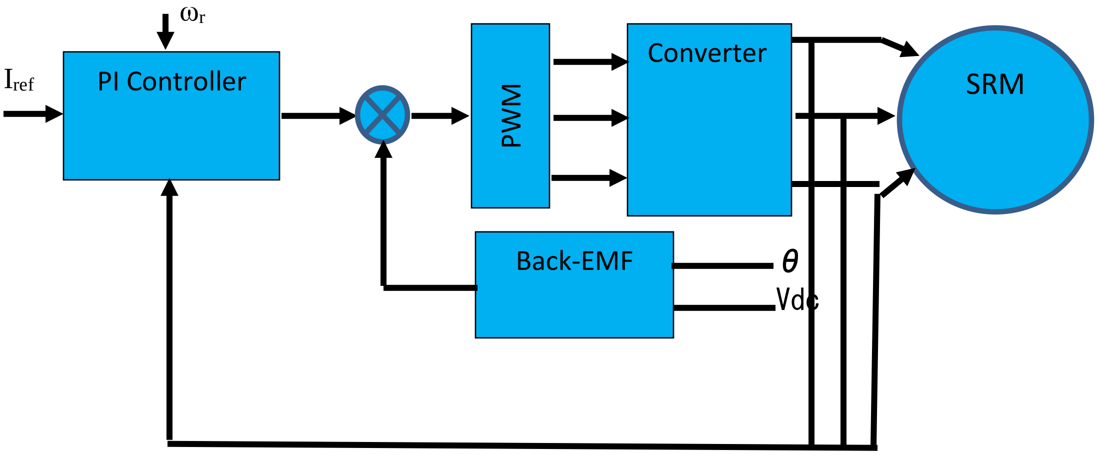

Figure 4: Block diagram of Linear PI Current Controller

Sliding Mode Controller

Another advanced nonlinear control scheme developed in the recent years is nonlinear sliding mode control as proposed by Hu et al. (2018).

SMC is a class of feedback control technique that can guarantee the stability of nonlinear systems. The main idea of SMC is to employ a discontinuous control input to force the state trajectory of a nonlinear system to "slide" along a pre-specified surface in the state space. This surface, called a sliding manifold**,** represents the properties of desired plant dynamics, such as stability to the origin and tracking.

SMC has been applied to electrical machines because its switching control structure is suitable for SRM drive systems. It is generally robust to external disturbances and changes in system parameters because the direction of a state trajectory depends only on the position of the state with respect to the sliding manifold (Huang et al. 2016). Although the SMC control strategies provide better performance compared to the traditional controllers, SMC controllers are complicated and require an accurate dynamic model of the machine (Salem, 2020). One of the major disadvantages of the SMC is the limitation in robustness to load disturbances. In speed tracking control, there exists a steady-state error in the presence of load torque. Figure 5 shows the block diagram of SMC for SRM drive.

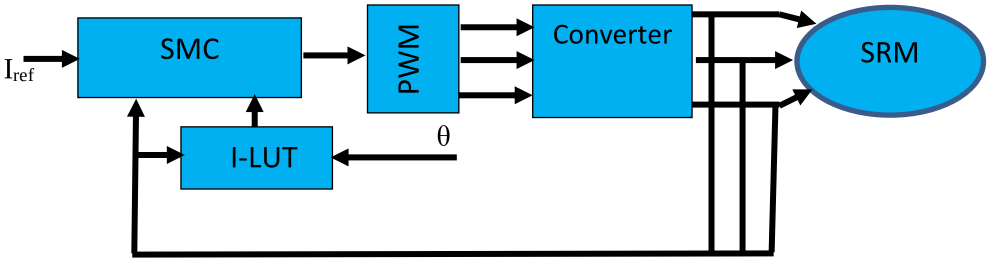

Figure 5: Sliding Mode Current Controller

Adaptive Current Controller

An alternative approach to solving control problems associated with the highly nonlinear behavior of SRMs is to dynamically adjust the controller gains. This allows the controller to be tuned online based on speed or load, for example, improving the dynamic responses and system stability. Such techniques also present as an advantage a fixed switching frequency. However, it should be noted that adaptive controllers present cumbersome calculations, resulting in a more complex controller when compared to linear approaches, for example. Some adaptive current control strategies have been proposed in literature

(Mohammad et al. 2017). The block diagram of an adaptive current controller for SRMs is presented in Figure 6.

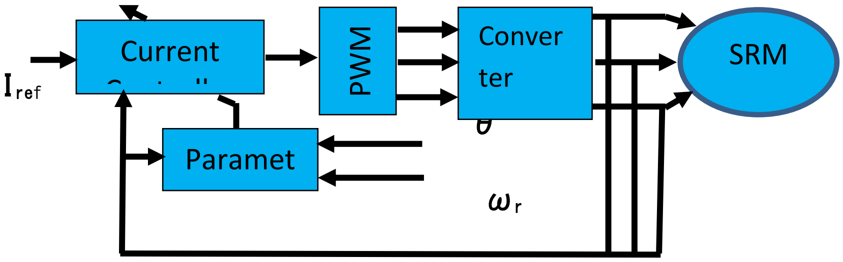

Figure 6: Block diagram of Adaptive Current Controller

Intelligent Current Controllers

Another alternative to deal with the highly nonlinear behavior of SRMs is to employ intelligent controllers such as Artificial Neural Network (ANN) and Fuzzy Logic Controller (FLC) (Alharkan, 2020). This approach involves the addition of a compensating signal to the output of a PI controller in a current-regulated speed control loop. It is known that the torque ripple can be reduced by accurately controlling the shape of the current pulse applied to each phase of the SRM. Thus, the compensating signal is the required modification to the current control signal from the PI controller necessary to produce a reduced-ripple torque profile (Abdel-Fadil, 2018). The compensating signal is necessary because, in steady-state operation with a constant output from the PI controller, the torque profile will have significant ripple. The compensating signal profile is trained via the ANFIS neuro-fuzzy system prior to normal SRM operation.

Once trained, the neuro-fuzzy compensator is incorporated into the SR drive. During subsequent operation of the SR drive, the torque ripple (i.e. the torque signal with the dc component removed), Tipple, and the rotor position, θ, are inputted to the compensator, which produces the required compensating current signal to be added to the PI controller current signal (Ghani, 2016). It should be noted that, to the best of the author’s knowledge, these techniques have not been considered in order to address the current regulation problem in SRMs.

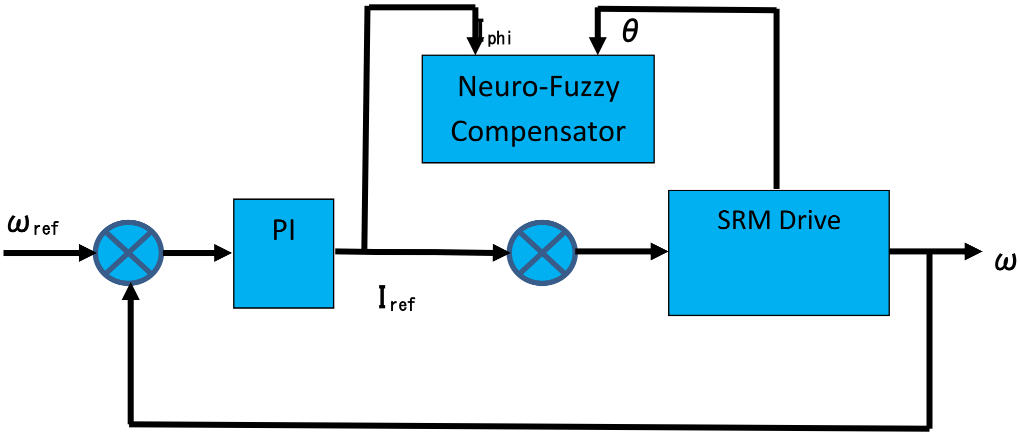

Figure 7: General block diagram of Neuro-Fuzzy Controller

Model Predictive Current Controller

The MPC is a broad class of controllers that have found relatively modern applications in SRM drives. The most interesting feature of predictive control is the use of the system model to predict the future performance of controlled variables. This data is managed by the controller to achieve the optimal actuation and meets predefined optimization criteria (Karamanakos, 2020). It has proven its capability to be a high-performance and reliable multi-objective control technique in several drives and power electronics systems. The main challenge is then the definition of accurate predictive models according to the control needs (Zhang et al. 2022).

One of the major advantages of model predictive control (MPC) is that several control targets, variables, and constraints can be included in a single cost function and simultaneously controlled (Vazquez, 2017). In this way typical variables such as current, voltage, torque, or flux can be controlled while achieving additional control requirements like switching frequency reduction, common-mode voltage reduction, and reactive power control, to name just a few. However, some disadvantages have to be mentioned, like the larger number of calculations, compared to classic controllers. The quality of the model has a direct influence on the quality of the resulting controller, and if the parameters of the system change in time, some adaptation or estimation algorithm has to be considered (Valencia, 2019).

The switching frequency can be fixed using a continuous control set (CCS)-MPC, but recent alternatives have also evaluated the use of modulated MPC, which adds a modulation stage to the output of a more conventional finite control set (FCS)-MPC (Ahmed, 2018). A model predictive current control structure for SRMs is depicted in Fig. 8.

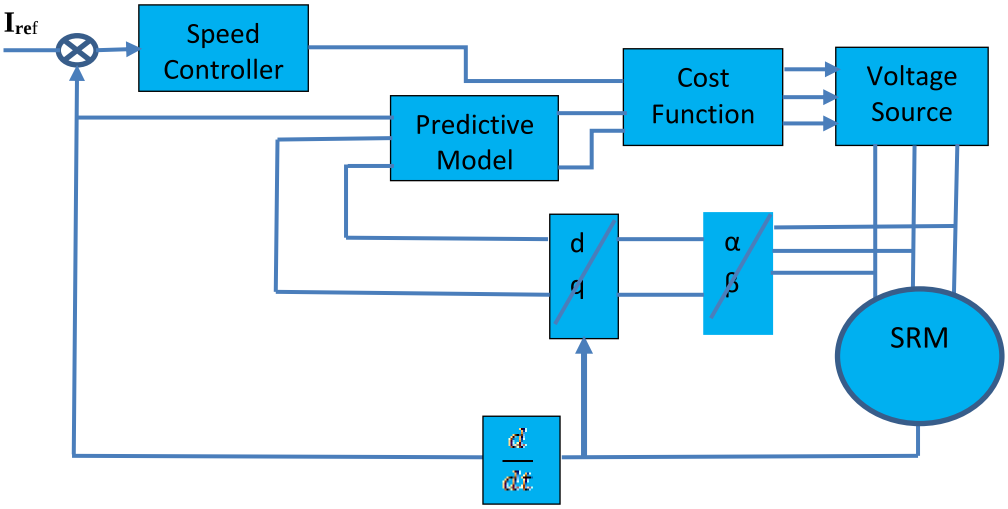

Figure 8: General block diagram of Model Predictive Current Controller

COMPARISON OF THE CURRENT CONTROL STRATEGIES

The comparison of SRM current control strategies reviewed in literature is presented in Table 1. The current control schemes discussed previously are compared in terms of advantages, disadvantages, computational complexity and switching frequency is observed.

The traditional hysteresis controller is a simple model independent approach, however, it presents variable switching frequency and may be susceptible to increased current ripple. Intelligent control is able to deal with the SRM nonlinearities, but requires data and extensive training. Linear control approaches are industry standard, but do not present the required robustness, often requiring gain adaptation or back-EMF compensation. In this sense, MPC presents an optimal control law and takes nonlinearities into consideration, at the cost of requiring complex calculations. Adaptive techniques are robust and capable of online adaptation but often present complex calculations and a complex structure. Lastly, sliding mode approaches are capable of fast dynamic responses with a theoretical certificate of robustness.

One of the disadvantages of the SMC is the limitation to load disturbances. In speed tracking control, there exists a steady-state error in the presence of load torque.

Table 1: Comparison of Current Control Strategies for SRM

Controllers	**Switching Frequency**	**Computational Complexity**	**Advantages**	**Disadvantages**
Hysteresis	Variable	Low	Fast dynamic response, Simple, Robustness	Variable switching frequency, higher - current ripple
Linear	Fixed	Low	Simplicity, industry based	Poor fixed gain - performance, not robust
Sliding Mode	Fixed	Medium	Robustness, fast dynamic response	Chattering problem
Adaptive	Fixed	High	Online adaptation, Robustness	Computational - complexity
Intelligent	Variable/Fixed	Medium	Suitable for nonlinear systems, overtime adaptation	Slow learning process Need for training
MPC	Variable/Fixed	High	Optimal control law Suitable for nonlinear systems	Computational - complexity, model dependent

CONCLUSION

This paper has reviewed the most important types of control strategies used for improving the performance of SRM drive systems. As can be seen, the Current control method is made up of six main classes of controllers namely, hysteresis, linear, adaptive, sliding mode control (SMC), intelligent and model predictive control (MPC). The basic principles and the latest developments of these methods have been comprehensively presented, and their merits and demerits have also been discussed. In conclusion, it should be noted that out of the state-of the-art current control schemes discussed in the foregoing presentation, predictive control strategies will continue to play a strategic role in the development of modern high-performance power electronics and drive systems and will offer a new interesting perspective for future research in this area.

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