IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 24, 2021, accepted April 9, 2021, date of publication May 7, 2021, date of current version May 17, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3078366

Vision, Challenges, and Future Trends of Model Predictive Control in Switched Reluctance Motor Drives

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This work was supported in part by the Natural Sciences and Engineering Research Council of Canada (NSERC). The work of Cristian Garcia was supported by the ANID/Fondo Nacional de Desarrollo Científico y Tecnológico (FONDECYT) through Initiation Research Project under Grant 11180235 and the Anillo Project under Grant ACT192013. The work of Jose Rodriguez was supported by the ANID under Project FB0008, Project ACT192013, and Project 1210208.

ABSTRACT Switched Reluctance Motors (SRMs) have become a popular alternative to replace permanent magnet machines in high-performance emerging applications such as automotive and aerospace. However, its market attractiveness is limited by the difficulty in control given its nonlinear behaviour. Model predictive control (MPC) is a promising solution to deal with this problem as per its notable features to deal with complex systems, nonlinearities and constraints. Still, the applications in SRMs are at an early stage compared to other drives. This paper aims to discuss the recent advancements and challenges in MPC for SRMs and a vision of its future developments and applications. The article describes the main difficulties in SRM control and the different approaches adopted to date by MPC to solve them. It also analyzes the control objectives that should still be considered in SRM drives, their particular challenges and how recent MPC developments in other AC drives can be adapted to the SRM case. The paper then proposes a roadmap of future works to achieve a unified and reliable control strategy that boosts SRM to outperform other drives, relating the control objectives to its potential applications.

INDEX TERMS Acoustic noise, aerospace applications, electrified vehicles, fault-tolerance, high-speed control, model predictive control, sensorless, switched reluctance motors, torque ripple.

I. INTRODUCTION

Electrical drives have been used in several industry applications throughout the years, being in constant evolution in terms of topologies, materials, power electronics and control techniques [1]. Recent developments come from their use in the transportation sector, where applications such as aerospace and automotive traction demand drive systems with higher performance, power density and reliability [2].

These applications have predominantly used permanent magnet (PM) motors due to their comparative advantages in terms of power density, efficiency, and overall performance in the low and medium speed ranges. However, PM machines use neodymium iron boron magnets, which represent not only an economical issue given the expensive and unstable price of rare-earths but also a technical compromise in their robustness due to the demagnetization at high temperature. Initiatives from researchers, governments, and the industrial sector tend to minimize the use of PM materials [3]. The trend is then the migration towards a magnet-less or magnet-free technology, where a proper equilibrium point between power density, costs and robustness is the target [4].

Switched reluctance machines (SRMs) appear as an attractive magnet-free technology with a simple rotor structure, low fabrication cost and enhanced robustness. Its simple construction allows a safer operation at higher temperature and higher

The associate editor coordinating the review of this manuscript and approving it for publication was Rongni Yang.

speeds than PM motors [5]. Although SRMs have been an available option for long time, their disadvantages including high torque ripples, unacceptable acoustic noise and vibrations, and the need of special power converter topology for its operation pushed these drives out of the market. Nowadays, however, with the advances in semiconductor devices and powerful digital processors, the use of sophisticated design procedures and control strategies can mitigate the main challenges in SRM drives [6].

In spite of the contemporary control capabilities, SRM drives are still unable to compete to the performance of PM motors. Moreover, the existing control techniques are difficult to tune and require complex, extensive and computationally heavy methods. Among the existing strategies, there are torque sharing functions (TSF) [7], radial force shaping (RFS) [8], current profiling [9], indirect average torque control and direct instantaneous torque/force control (DITC/DIFC) [10]. Although the proposed techniques are effective in achieving a particular control objective, they still fail to achieve a comparable performance to PM motors in terms of torque density, torque ripple, acoustic noise and vibration. Besides, the diversity of techniques makes difficult to propose an unified technique combining several control objectives for a wide speed range and operating conditions. In addition, some of these techniques might differ in structure and performance for SRMs of different power ratings [11].

Model predictive control (MPC) is a promising approach to control the highly nonlinear behaviour of SRMs due to its straightforward implementation and well-known capability to handle nonlinearities and constraints [12]. Although this alternative has been already adopted in some works for SRM control, there is still considerable potential for its development to handle the diverse issues, exploit their advantages and make them more attractive [13].

This paper is intended to make the case for MPC as an exceptional solution for SRMs control as an unified technique that enhances its operation. The paper highlights the main drawbacks of SRM drives and their comparative advantages with respect to other electric drives, thus proposing a set of control objectives and describing the existing techniques to address them. The current issues and challenges are presented and compared to the solutions proposed by MPC for conventional AC drives, with their potential implementation into the SRM case. This analysis leads to a road-map of future works to achieve the vision of high-performance SRMs, which are competitive with respect to traditional AC drives. This vision is presented along with the potential applications of these high-performance SRMs. The paper is structured as follows: Section II describes the fundamentals of SRM and MPC and the recent developments and applications of MPC for other drives. Section III summarizes the state-of-the-art of MPC for SRM and discusses their challenges and how MPC can be adapted to solve them. Section IV oversees the future trends and applications of this combination throughout the control objectives. Finally, Section V presents the conclusions.

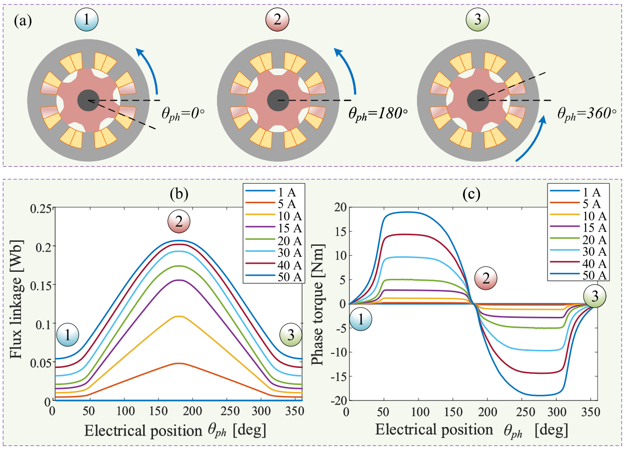

FIGURE 1. **Characteristics of a four-phase 8/6 switched reluctance machine (a) Definition of electrical angle (b) Flux linkage static characteristics (c) Phase torque characteristics.**

II. FUNDAMENTALS AND CURRENT STATUS

A. SWITCHED RELUCTANCE MACHINES

SRM principle relies on the sequential excitation of their phases as the shaft rotates. Fig. 1(a) shows this process, defining also the electrical angle in these machines. In motoring mode, as the phase winding is connected to a DC supply, and the rotor pole is in an unaligned position (1), the stator pole will produce a flux that links with the stator and attracts it towards an aligned position (2). The phase should be turned-off before it reaches an aligned position to prevent the operation in generating mode, and the next phase should be energized. The resulting flux linkage and torque profiles are represented in Figs. 1(b) and 1(c), respectively. It is worth noticing that the torque does not depend on the current direction, and the motor/generator mode is controlled by the rotor position. Also, as the phases are not connected, and neglecting mutual coupling, the machine model is proposed as the phase voltage equation,

$$v_j = i_j R_j + \frac{d\lambda_j}{dt}, \tag{1}$$

where R_j, i_j, λ_j, and v_j are the resistance, current, flux linkage, and voltage of the phase j, respectively. The flux linkage λ_j is represented by the highly nonlinear profile shown in Fig. 1(b), which depends on the current and the electrical angle. The torque is therefore a nonlinear function of these variables, making the overall SRM model more complex. Standard control techniques involve the use of simple hysteresis regulators to track current, while the torque is predefined offline by TSFs [7], or using direct torque control strategies such as DITC [14], most of them based on lookup-tables or approximated analytical models. While there is not a defined trend in terms of noise, vibration and harshness (NVH)-oriented control, the radial force control is an innovative and effective technique that relies on current shaping to reduce this issue [8].

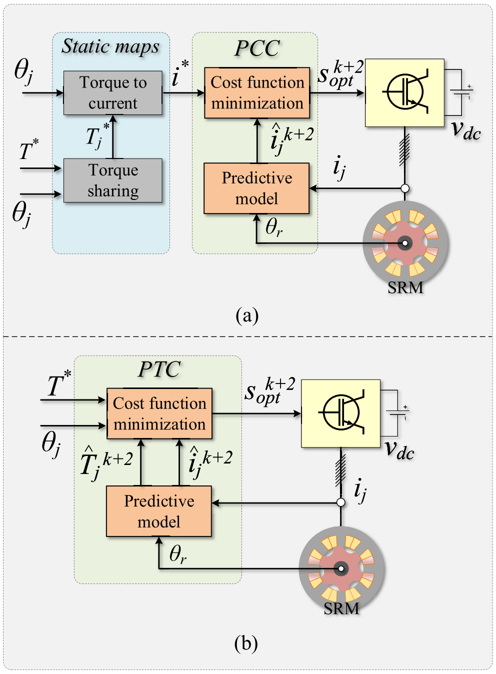

FIGURE 2. **Control block diagrams of predictive control for SRMs (a) predictive current control (PCC) (b) predictive torque control (PTC).**

B. MPC IN SRM DRIVES

The general structure of predictive control for SRMs is similar to the one in conventional AC drives. Fig. 2 shows common alternatives of implementation, which reproduce both the field-oriented control (FOC) that relies on reference currents from pre-calculated lookup tables, and direct torque control (DTC) that deals with the instantaneous estimation of torque. The first approach in Fig. 2(a) uses a predictive current control (PCC) algorithm to track the phase currents. The predictive model employs the measurements of current and position to estimate the future current, and evaluate the optimal switching behaviour through a cost function minimization. The predictive model is based on the discrete machine voltage equation as,

$$\hat{\lambda}_j^{k+1} = \hat{\lambda}_j^k(i_j, \theta_j) + T_s \cdot (v_j^k - R_j i_j^k), \tag{2}$$

where T_s is the sampling period, and the $\hat{}$ index is used to identify estimated or calculated variables. As the flux is not usually measured it should be estimated from static maps.

The algorithm for prediction can use static maps of the flux linkage characteristics [15], or current-based models using inductance profiles [16], [17]. The cost function minimizes the tracking error per sampling period, defining a relation,

$$g_i = \left| i^* - \hat{i}_j^{k+2} \right|^2. \tag{3}$$

The cost function utilizes the prediction at the $(k+2)$th sampling period. This is conventionally implemented as an indirect delay compensation technique, assuming the delay equivalent to T_s and that the next input sequence v_j^{k+2} is applied within the next sampling period [18].

The use of PCC guarantees tracking accuracy on phase currents, but the torque smoothness and other variables depend on the external algorithm to define the current sharing between phases. An alternative consist on including this torque sharing decision within a predictive torque control (PTC) loop, as depicted in Fig. 2(b). The PTC strategy generates the optimal switching from the cost function minimization. In this case, the cost function can be defined as,

$$g_T = \left| T^* - \hat{T}^{k+2} \right|^2 + \sigma_i \sum i_j, \tag{4}$$

where σ_i is a weight factor to penalize the effect of the phase current minimization, T^* is the reference torque and $\hat{T}$ is the predicted torque, defined as,

$$\hat{T}^{k+1} = \sum_{j=1}^{m} \left(\hat{T}_j^{k+1} \left(\hat{i}_j^{k+1}, \hat{\theta}_j^{k+1} \right) \right), \tag{5}$$

where $\hat{T}_j$ is the estimated phase torque and m is the number of phases. It is assumed as an estimated variable since it is common to obtain it from static maps, based on the current and electrical position. The cost function in Eq. (4) includes also a phase current term, which tends to track the reference torque with the minimum phase currents [19]. This last term is considered to minimize conduction losses.

C. RECENT DEVELOPMENTS OF MPC

A well-designed MPC algorithm considers its performance in terms of the predictive model, cost function, prediction horizon and frequency characteristics to guarantee stability with the lowest use of computational resources [12]. The predictive model dictates the accuracy of the control action, which would allow a reduction on the sampling. It must consider both the precision of the model and the discretization procedure, as it is implemented in a digital platform. SRMs electromagnetic modelling is a well-studied field, and options for an accurate estimation are available. A comprehensive review of electromagnetic models is presented in [20]. In terms of discretization, the most common approach is the forward Euler approximation due to its simplicity and good performance. A more complex but accurate option considers Taylor approximation instead [21]. Other techniques involve more accurate results but require extensive or multi-step computations [22]. Recent trends have also considered model-free predictive control [23], considered for current control in SynRMs [24], guaranteeing high-performance without concerns on parameter mismatch or nonlinearities.

The cost function defines the behaviour of the control action. Their main feature is the ability to handle multiple control objectives from different units and magnitude, thus improving the flexibility. However, depending on the impact on the system performance, a weight on these variables is required. The process to calculate these factors is usually based on heuristic techniques [12], thus increasing the development time and effort, plus the additional simulation and testing. Alternatives for tuning have been explored as

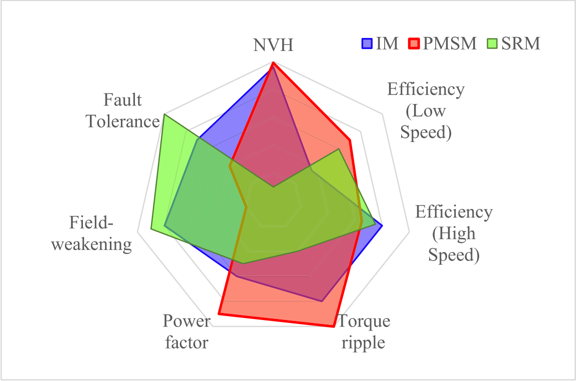

FIGURE 3. Comparison based on reported SRM performance [37], [38].

multi-objective optimization of multiple cost functions with priority coefficients, or cascaded (or sequential) cost functions [25]. The latest presents promising performance with reduced computational burden and simple development time, omitting the use of weight factors or priority coefficients. An alternative is the simplification of the cost function by analytically calculating an equivalent reference voltage vector [26], [27] or a group of virtual voltages [28].

The switching frequency can be fixed using a continuous control set (CCS)-MPC, but recent alternatives have also evaluated the use of modulated model predictive control (MMPC) [29], which adds a modulation stage to the output of a more conventional finite control set (FCS)-MPC. An alternative has been the adaptation of vector control for AC drives within the predictive control [30], also considered for SRMs with a deadbeat approach [31]. The output frequency can be also limited by increasing the prediction horizon, but it usually involves a much higher computational load. This has been recently addressed by techniques such as the sphere decoding algorithm [32], and successfully implemented for AC drives for a horizon up to four steps ahead [33]. Other advanced techniques include the use of higher computational power to increase the prediction horizon with simpler strategies, as the case of using cloud robotics [34].

Finally, as any control technique, MPC must be able to guarantee robustness and stability. Recent works have proposed a Lyapunov-based MPC on both CCS and FCS that proves stability for a given cost function and any prediction horizon applied to power converters and PM drives [35], [36].

III. CHALLENGES AND FUTURE TRENDS

The full potential of SRM drives for different operating conditions and applications have been already discussed and comprehensively analyzed throughout different works [2], [6], [37], [39]. The main takeaway points converge in their advantage to operate with a natural field-weakening mode due to their high-speed back-EMF, as well as their fault tolerant and DC-link voltage utilization capabilities. Fig. 3 summarizes some of the main features of SRMs with respect to conventional induction motor (IM) and permanent magnet (PM) motor drives. The criteria for this figure is based on the numeric results reported in the presented references. The higher the value presented in the figure, the better the machine is on that particular objective. For instance, SRMs get the lowest score in low noise, vibration and harshness (NVH) given their high acoustic noise and vibrations. Unlike the comparison presented in [37], this paper separates the efficiency according to the speed range, as evaluated in [38]. Therefore, although SRMs cannot compete in performance at low speed, their outstanding high-speed efficiency give them benefits in this region, and their capability to go beyond ultrahigh speed limits enhances its field weakening score.

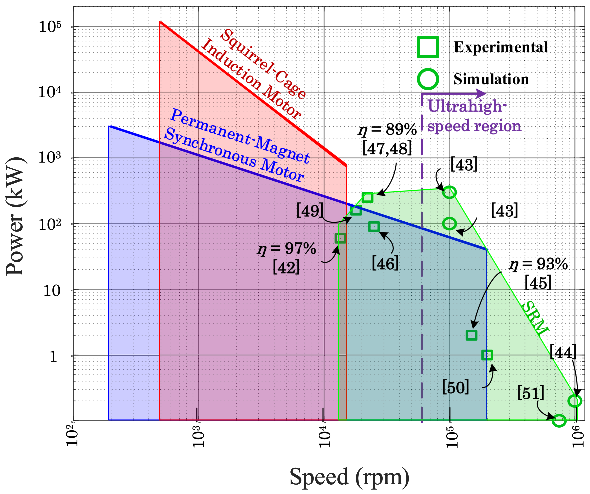

FIGURE 4. Target power levels and designs of SRM drives with respect to conventional AC drives.

Current SRM technology cannot replace IM and PMSM for industrial and automotive applications, respectively. However, if their main drawbacks are regulated up to the minimum requirements of certain applications, it is possible to enhance their comparative advantages and define a potential cluster of interest. In fact, most of the targets for SRM designs and prototypes, as well as existing commercial applications, aim for medium- and high-speeds. Fig. 4 shows a comparison of IMs and PMSMs targets [40], as well as the maximum power and speed capabilities of SRMs in the literature, both in design and tested prototype stages [41]. It is noticeable how SRMs are complementary to other drives and thus should not be targeted to replace them but to complement the operational ranges that those drives cannot traditionally cover [42]–[51].

However, at medium- and high-speed, the control becomes challenging as nonlinear effects such as iron losses gain more relevance. Rotor position sensing becomes a problem on top of the already existing SRM nonlinearities. All the real physical phenomena contain nonlinearities, and assuming linear control objectives for high-performance systems nowadays is outdated. In addition, an unified control strategy is required so SRMs can simultaneously accomplish a minimum requirement while covering certain objectives with exceptional results for particular and specialized applications.

Therefore, MPC is a clear response to these nonlinearities and flexibility requirements. It has been considered

TABLE 1. Control objectives of MPC for SRM and other AC drives.

Control Objective	SRM		Other machines			
	Classic	MPC	IM	PMSM	SynRM	Ref.
Current	[52], [53]	[11], [15]–[17], [54]	☑	☑	☑	[33]
Torque	[7], [9], [14]	[19], [55]–[64]	☑	☑	☑	[65]
NVH	[8]	-	☑	☐	☐	[66]
Sensorless	[67], [68]	-	☑	☑	☐	[69]
Field-weakening	[70]	[64]	☑	☑	☑	[71]
Fault-tolerance	[72]	-	☑	☑	☑	[73]
Overload	-	[74], [75]	☑	☑	☐	[76]

for some applications in SRMs, as summarized in Table 1. However, the related research and developments are at an early stage, as several relevant control objectives have not been targeted while they have been fully addressed in conventional drives. An example of an application of MPC in AC drives is also included in Table 1, which serves as a basis to propose further implementations of MPC in SRMs along with the latest applications mentioned in the previous section. The conventional techniques and the current challenges are presented in this section, as well as a brief explanation on how MPC have handled each objective in other systems.

A. CURRENT AND TORQUE CONTROL

The idea of torque and current control as the fundamental control strategies in SRMs have been addressed in Section II. The implementation of highly innovative MPC strategies can enhance the basic machine operation. The focus should be not only to improve tracking but also to release processor memory and computational burden to allocate additional control objectives.

In current control, the use of virtual-flux brings several advantages in terms of local linearization of the predictive model [15]. This concept has not been fully exploited, as it improves systems robustness by simplifying the general formulation of the control problem [77]. At the same time, the concept of stability of the current loop using predictive technique has not been considered, yet important for positioning the machine. In addition, the use of long prediction horizon can be helpful to reduce parameter sensitivity and improve efficiency [33]. Ultimately, the trend in SRM is to use the current to *shape* certain waveforms that allow minimizing torque ripples and NVH issues [78]. The control algorithm should be extended to shape these currents online.

The online torque sharing has been already considered for torque control, developing high-performance strategies with a finite-set predictive control (FCS-MPC) at low- [19] and high-speed [64]. However, the feasibility of these techniques has not been demonstrated for four-quadrant operation, and there is still room to improve torque ripple at medium speed to meet the standard in automotive applications of 5% [4]. The main challenge is to develop an accurate model that allows calculating optimized conduction angles in real-time with low computational burden.

B. ACOUSTIC NOISE AND VIBRATIONS (RADIAL FORCE CONTROL)

Torque ripple is relatively easy to analyze and compensate through measurements or using static maps. However, smooth torque does not guarantee the elimination of acoustic noise. Stator vibration is usually the primary source of acoustic noise in electric machines. The acoustic noise reduction has been addressed through design techniques, aiming to develop a mechanical structure that can mitigate these vibration levels, some of them summarized and analyzed in [79]–[81]. In contrast, it becomes challenging to include acoustic noise as a control objective as it is a more complex variable.

Apart from the bearings and ventilation system, the vibrations result from the interaction between electromagnetic (EM) forces. The use of a power converter to feed a machine leads to applied voltages rich in harmonic components; these harmonics also appear in the stator currents and produce electromagnetically-excited-vibrations [82]. This is worse in SRMs due to the trapezoidal shape of phase currents in conventional controls. Unlike the torque ripple, originated from the tangential components, the acoustic noise is originated from the radial component of the EM-forces, which causes deformations in the machine structure. In this way, the control solutions have initially aimed the current shaping to reduce the radial force ripple [80], with more specific attention on the current transient during turn-off as the origin of most of the radial force peaks [83] or a closed loop control of the radial force [10]. However, a smooth radial force waveform might not be sufficient to eliminate unpleasant noise for human ears. The phase currents produce an equivalent radial force density waveform per pole, which, decomposed through 2D FFT, produces temporal and spatial harmonic components. The spatial orders resonate with the machine stator's vibration modes at a frequency determined by the temporal orders [84]. The latest frequency depends on the rotor mechanical frequency. Depending on the mechanical characteristics of the frame, these vibrations can be dissipated as sound pressure, which is usually used as the base to measure the acoustic noise through the sound pressure level (SPL) in decibels [82]. Therefore, smoothing the radial force ripple compensates only for the harmonics affecting the spatial order zero, but it neglects the temporal orders affecting higher vibration modes.

The temporal orders of higher circumferential orders have been considered in [8] within an offline optimization, compromising the acoustic noise reduction and the torque ripple

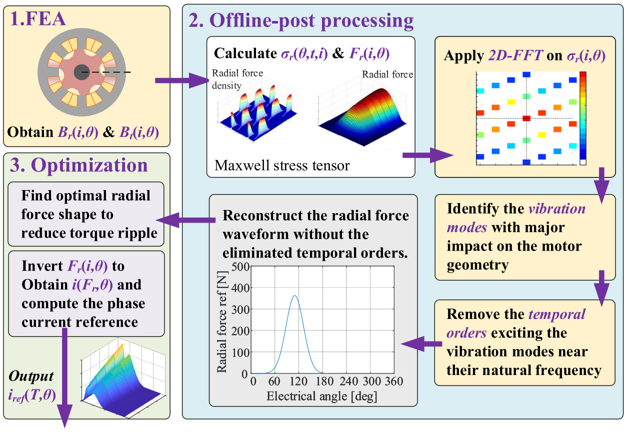

FIGURE 5. Radial force shaping to indirectly reduce the torque ripple and acoustic noise in SRMs (some of the figures were used with the permission of the author) [8].

minimization in radial force shaping (RFS) technique. The iterative process is represented in Fig. 5, where the temporal orders are manually discarded, and inverse FFT allows obtaining a reconstructed radial force static map and a current profile. The control is then reduced to a current tracking problem. Given the high complexity required to solve the iterative process, it is not easy to include operating variables within the RFS algorithm. In this case, the adaptation of such control techniques to a method with an online selection of the optimal switching, such as MPC, would improve real-time performance. MPC has already been used for acoustic noise control in induction motor drives, with a technique that takes advantage of the cost function flexibility and predictive models to directly influence the phase currents as a function of the SPL [66]. It also considers the reduction in the tonality, which can decrease the most disturbing temporal orders from the acoustic noise; however, this is based on an empirical linear model, which might compromise the accuracy and should be adjusted for different motors.

The challenge is then defining a predictive model that can consider the most prominent temporal orders depending on the SRM pole configuration. It would allow MPC to decide the optimal trade-off between efficiency, torque ripple and acoustic noise, depending on the use and operating condition.

C. HIGH- AND ULTRAHIGH-SPEED OPERATION

The main comparative advantage of SRMs is their capability for reliable and efficient operation at high-speed [6]. Currently, electric drives tend to operate at higher speeds, reducing weight and volume, thus offering benefits to systems with a high power density as critical requirements; this is the case of automotive applications [85].

High-speed control in SRM is a challenging condition as the increased back-EMF limits the current regulation capability. It limits the possibility of current shaping for multi-objective control like the one in torque and force ripple reduction [5]. The control in the high-speed region is only possible through a single voltage pulse, and the regulation problem is reduced to calculating the conduction angles. Some approaches have considered using sinusoidal excitation and vector control, but the reported switching frequencies of hundreds of kHz are still impractical for applications with conventional inverters and costs restrictions like in automotive industry [86]. Another alternative is the combination of multiple techniques depending on the operating condition. DITC for current build-up with constant current control and demagnetization, which depends on the angle and speed to find a stable control over a wide speed range [87]; Despite the good results for each operating condition, stability and performance might be compromised due to the transition between different control strategies.

MPC has been already implemented for a similar condition in conventional AC drives, where the field weakening operation presents additional challenges. It solves the issue in IMs, avoiding weight factors with a cascaded MPC strategy and guaranteeing stability, but it increases the computational burden [88]. In [27], this is solved by calculating an equivalent reference voltage vector, thus simplifying the cost function. It also improved the low-speed control by including LUT-based parameters, which are updated online and demonstrate its robustness against parameter variation.

There is another operating condition shown in Fig. 4 as the ultrahigh-speed, which is usually defined for shaft speeds over the 60000 rpm and is useful for specific applications such as vacuum cleaners [89] and turbochargers [90]. Theoretical designs for SRM drives have reached up to one million rpm [44], but experimental evidence of a proper control has been provided for operating speeds up to 150000 rpm [45]. Although this operating region also allows only single-pulse control, the problem arises from the limitation in the position sensing technology, which does not go beyond 60000 rpm. It is usually solved either using multiple Hall-effect sensors or sensorless control [91]. Therefore, an optimal unified control strategy, including ultrahigh-speed, requires the ability to include sensorless and self-sensing techniques, which can also be implemented within predictive control algorithms.

D. SELF-SENSING AND PARAMETER ESTIMATION

The use of parameter estimation and sensorless control techniques has become a target in electric drives to reduce cost, improve performance and guarantee reliability of the system [2]. Self-sensing techniques in SRM have the advantage of using the idling phases to inject perturbations, or to use the measured currents and calculated flux linkages to calculate position through inverse flux linkage maps [6]. The latest is more convenient for position sensorless control, and it has been exploited for online parameter estimation too. These techniques can be generally classified according to the phase state used, the requirement of external hardware [68] and even the speed range [67].

Voltage equations and model-based approaches make the estimation techniques compatible with the principle of MPC. It has already been proposed for online estimation [17], where the CCS-MPC continuously updates the inductance and back-EMF characteristics through an optimization algorithm that guarantees high performance. This has not been implemented using FCS-MPC yet.

The use of FCS with self-sensing techniques is interesting for SRM, given the advantages that skipping the modulation stage has. Although some of the well-known self-sensing techniques for conventional AC drives are not compatible with modulator-free controls such as FCS-MPC, it has been proven the feasibility of new estimation algorithms for such control methods. For instance, position estimation in PM machines could be computed from the current ripple, inherent to FCS-MPC [92]. A similar approach has also been considered for an optimization algorithm with a co-estimation of speed and position [69]. The algorithm has been extended even to multi-parameter estimation avoiding the use of high-frequency current injection [93]. These techniques result not only in a reliable estimation but also on a high-performance predictive control as the model-based algorithm counts with a real-time update of the parameter information while guaranteeing a constrained computational burden [94].

The next generation of SRM controllers must contain such estimation algorithms as a unified MPC technique that guarantees reliable and efficient operation. Although the current ripple in SRM does not directly provide position information, it can be used through the voltage equation and a standard optimization algorithm. Similar approaches consider simplified convex spaces like in [95], which can be adapted either to CCS or FCS-MPC on SRM. The challenge, again, is to overcome the highly nonlinear inductance, which depends on the electrical angle, making it difficult to estimate both. An extra challenge appears at high and ultra-high-speed since there are no more idling phases, and the simultaneous activation of phases in the single pulse operation modifies the model, forcing to consider mutual coupling.

E. FAULT-TOLERANT OPERATION

One of the main advantages of SRMs in terms of fault-tolerant operation is the capability to independently operate their phases. Of course, this would not prevent the occurrence of a fault, but it allows the machine to be functional after a fault. The so-called post-fault operation has been operated by several methods including current profiling [72], Fuzzy logic control, and position signal assistance. In general, the most common faults in electrical drives are open-circuit faults [2], while the short-circuit faults usually lead into an open-circuit. However, in SRMs, this might differ from conventional AC drives as position sensor fault is the main threat at high- and ultrahigh-speed operation. A comprehensive literature review on both fault diagnosis and control algorithms for SRM drives is provided in [96].

To date, predictive fault tolerant control has not been applied to SRM drives. However, predictive control is quite popular to handle post-fault control in highly complex machines. That is the case of multi-phase machines, which provided an increased number of degrees of freedom, usually represented by an additional subspace in the rotating frame, implement predictive control to compensate for faults. An example of implementing FCS-MPC minimizes the total current harmonic content [73]. In addition, a fixed switching frequency fault tolerant control can be achieved by integrating the virtual voltage vectors with predictive method [97].

F. OVERLOAD CONTROL

Overload control takes advantage of the overloading capabilities of the machine to produce a short-term peak torque. The control strategy evaluates the magnitude and time of the overload condition to produce the maximum torque without compromising the motor safety. Overload control also allows preventing oversizing during the motor design process. Although conventional overload limitations were obtained based on static thermal limits [98], recent works have demonstrated the importance of considering the transient thermal response for inverter-driven machines [99]. This feature has been initially explored on induction motors where the time ratings for its operation are defined [100]. However, a controller with good dynamic response to fully consider the real-time thermal behaviour along with the machine transient response is required. MPC has been proposed as the solution given the simple adaptation to the control loop by adopting the appropriate predictive model. The model predicts the instantaneous operating temperature within the next sampling periods and determines the optimal torque/current reference limitation. It has been considered for induction [76], PM, DC motors [101], and even SRMs [74].

The application in SRMs gains more relevance because they can withstand thermal stress better than AC machines. It led to predictive control to handle the highly nonlinear characteristics and predict the winding temperature online, thus limiting the maximum torque to maintain a defined level of copper losses [74]. The iron losses have not been considered given the little impact they have on the low-speed copper losses. However, in high-speed operation, iron losses gain relevance, and improvement of such predictive control technique requires their inclusion into the limitation considerations.

G. TOPOLOGICAL IMPROVEMENTS

1) MACHINE TOPOLOGIES

Beyond the control objectives, certain applications could find benefit on different SRM topologies. Design procedures have come up with variations in the structure or operating principle of the machine. One of them is the mutually-coupled SRM (MCSRM), which uses both the variable inductance components (self and mutual) as a benefit to generate torque [102]. Therefore, MCSRMs are especially designed with a winding distribution that considerably increases the mutual coupling between phases. Their most attractive feature is the claimed improvement in terms of acoustics at the expense of increasing the modeling complexity.

Recent approaches have considered the sinusoidal excitation of MCSRMs, which not only would further reduce its acoustic noise and vibrations but also allows using well-known vector control [102]. Besides, this enables the machine to operate with conventional two-level voltage source inverters. Other excitation methods have been also used such as unipolar, bipolar, and one phase-dc excitation [37].

This is a relatively new research trend and, despite the potential applications, a deep analysis on current shaping for this topology has not been investigated. This has opened a window for predictive control to optimally evaluate the performance of the machine. Deadbeat predictive control has been implemented within unipolar current control for a MCSRM [103]. The potential of the bipolar 2L-VSI-fed machine has also been evaluated within a FCS-MPC approach with promising results for current control [54]. The latest research can be further expanded to torque regulation and all control objectives mentioned in this Section.

Other topologies include double-stator SRM (DSSRM) and the one with a segmental rotor (SSRM). The latest has presented improvements on the machine torque density, while the DSSRM offers a better energy conversion ratio, torque production, and utilization of the machine volume [37]. Both of them show potential to enhance performance objectives with MPC, depending on the target application.

2) POWER ELECTRONICS

One drawback of SRMs is the use of the unconventional asymmetric power converter, which offers flexibility for the individual phase operation thus allowing improved fault tolerant control. The use of sinusoidal-excited MCSRM brings the chance to use conventional two-level voltage source inverters, but it reduces the attractive for post-fault operation. Alternative topologies such as C-dump or $(N+1)$-switch have also been considered through multiple works, and most of these converters are described in detail in [104].

Furthermore, multilevel converters have also been introduced for SRMs, given their potential to enhance high-power and high-voltage machine performance [105], [106]. It is also an alternative to deal with the relative low inductance of the machine at unaligned position during control. This, along with the upcoming wide bandgap (WBG) technology, represents an overall improvement in robustness, controllability, and reduction of cost and volume of these drives [4], [107].

IV. VISION AND POTENTIAL APPLICATIONS

Previous section stated the main challenges regarding SRM control objective and how MPC has the potential to overcome them. Therefore, a high-performance SRM with an unified algorithm for simultaneous optimal control can make these machines suitable for different applications. These are primarily applications with high potential for SRM usage which has seen a limited or nonexistent practical scenarios due to the limitations previously discussed.

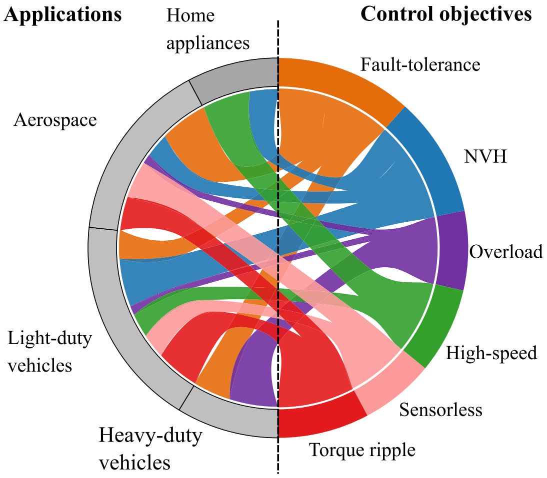

FIGURE 6. Potential usage of SRM control objectives for practical applications.

Beyond current and torque control, which are common for all applications, Fig. 6 illustrates the impact of the described control objectives into some highly appealing applications for SRMs. The first and most important thing to notice is the fact that all require more than one control objective to guarantee high-performance of the electric drive. It also allows noticing how diverse applications might differ in priorities. This allows proposing a vision of how these applications can not only adopt SRMs as main electric machine but also be enhanced by their use among MPC.

Beyond home appliances, where low-power, high-speed and reduced NVH levels are required [39], [79], automotive applications require more diversity of control objectives. However, these applications can also be subdivided. In the case of light duty vehicles, although there exist SRMs able to reproduce the torque-speed envelope of automotive IPMSMs [3], [42], the control technique can still be improved to offer a high-performance outcome. Important trends in automotive applications lead to new challenges such as the integration with other vehicle systems, more traction motors per powertrain, higher power, and higher voltage [4], [108] as well as integrated battery chargers. The latest utilizes the machine's winding as a filter and the inverter as a bidirectional converter to connect the EV battery to the grid [109]. It has been considered in [110], where a FCS-MPC for current tracking is proposed for SRM-based integrated charging.

Alternatively, hybrid heavy-duty harsh vehicles have already implemented SRMs as the noise, torque ripples and vibrations do not represent a significant restriction. Instead, efficiency, robustness and overload capability dictate the best performance for applications like earth-moving vehicles [111]. As these vehicles use an engine to generate electricity for the motors, an unified control might also increase the robustness of the generator-motor SRM drives as a whole, thus improving efficiency and fuel consumption.

Research and industry trends are also pushing aerospace technology towards the more-electric era. Commercial flights tend to use more electric aircraft (MEA) technology, which attempts to replace mechanical, hydraulic and pneumatic systems for electrical ones as much as possible [112]. The replacement is only feasible if the new electrical components bring benefits not only in efficiency and controllability but also weight and robustness. Therefore, SRMs have been seen as a potential solution for the rough conditions the high temperature and pressure levels of commercial and military flights [81], thus offering enhanced robustness and fault-tolerant capability. Alternatively, SRMs have been considered as part of electromechanical actuators replacing hydraulic systems such as fuel pumps, surface actuators for flight control, and flap and rudder actuators [6], as well as for the traction and regenerative applications in taxiing systems, and more recently, for the propulsion of emerging aerospace applications such as electric extremely short take-off and landing (e-ESTOL) aircraft.

V. CONCLUSION

Considering the different control objectives and limitations of SRMs, and the potential to overcome these issues with the latest advances in predictive control, the future market attractive of SRM is promising. The main drawbacks of this machine can be overcome if the machine non-linear behaviour is handled. This behaviour limits the use of predefined control laws, thus stimulating the use of algorithms that can determine the optimal law online. Model predictive control 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. Additional concerns such as parameter sensitivity, stability, multi-objective optimization and so on, have already been addressed in the literature of predictive control.

There is currently an opportunity for the innovation through the implementation of existing high-performance predictive techniques to the most challenging control objectives of SRM. The main takeaway of this paper is then a road-map for future projects, studies, applications, and analysis of MPC on SRMs. Torque ripple, overcurrents, acoustic noise, high speed control and position estimation, fault tolerance are only few among several objectives that would position SRM between the candidate machines for high performance applications. Although these applications might compromise the simplicity of the control technique, upcoming technologies demand higher performance from electrical drives, and the migration to higher computational power is a fact.

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