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TOPICAL REVIEW

A Review on Switched Reluctance Generators in Wind Power Applications: Fundamentals, Control and Future Trends

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ABSTRACT With the ever growing environmental concerns, renewable energy sources emerge as a promise of clean and abundant energy, enabling long-term sustainable development. In this context, wind power gained significant interest due to its relative low cost and availability. Switched reluctance generators (SRGs) are suitable candidates for wind energy conversion systems, as they present a simple structure, robustness, a wide range of speed and are capable of operating in harsh environments. The machine, however, poses challenges such as high torque ripple, acoustic noise production and highly nonlinear behavior. Nonetheless, with the use of adequate control strategies, high dynamic performance SRG-based wind energy conversion systems can be achieved. As a result, this article presents a state of the art review of SRGs in wind power applications. First, the fundamentals of the SRG are presented. Next, two categories of firing angle control are reviewed: optimization and closed-loop control. Then, voltage and power control strategies are discussed, being divided in model-independent and model-based approaches. After that, a review on grid-tied SRG-based wind energy conversion systems is carried out. The most common filter topologies as well as the employed control strategies are detailed. Lastly, an outline of the discussed topics is presented and future trends as well as suggestions for future investigation are listed.

INDEX TERMS Firing angles, switched reluctance generator, power control, voltage control, wind power.

I. INTRODUCTION

The limited supply of fossil fuels as well as the greenhouse gas emissions caused by its combustion have become a major topic of concern for nations worldwide over the past decades. As a result, renewable energy sources have gained significant interest and become the focus of several governmental programs and incentives. Under these circumstances, wind energy has emerged as a viable solution to renewable energy conversion as early as the 1980s, undergoing a significant transformation in the past twenty years due to the latest advances in aerodynamic design, power electronics, microprocessors and control strategies [1]–[9].

Doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG) are often used for wind energy conversion systems (WECS) due to the reduced inverter and filter costs, in the case of DFIGs, and superior power density, in the case of PMSGs [10]–[12]. These systems, however, present some known drawbacks. DFIGs require slip rings and gear boxes for operation, significantly increasing the complexity of the WECS. On the other hand, PMSGs require full size power converters and make use of permanent magnets, increasing the cost of the overall system considerably [13]. Thus, the search for alternative machines with improved characteristics is desired.

In this context, the switched reluctance generator (SRG) has emerged as a promising candidate for WECS. SRGs

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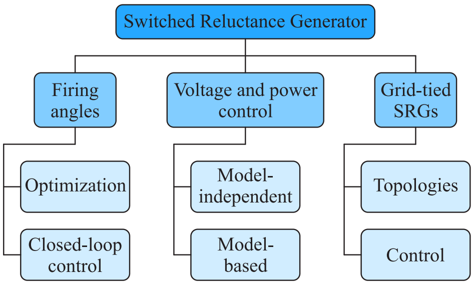

FIGURE 1. Classification of the SRG control strategies.

present several advantages, such as robustness, a simple double salient structure, low manufacturing and maintenance costs, high performance and the absence of windings or permanent magnets in the rotor structure [14]–[16]. The machine is composed of independent concentrated windings, mounted on stator slots, making it inherently fault tolerant [17]. Moreover, SRGs are suitable for harsh environments and capable of operating in a wide range of speed, without the need for gearboxes, ultimately reducing the weight, complexity and cost of the resulting WECS [18], [19].

However, the switched reluctance machine presents some known challenges. A highly nonlinear behavior due to the position-dependent phase inductance, high torque ripple due to the switched nature of the machine and acoustic noise production due to the large radial forces are among the drawbacks of the machine [20]–[22]. In addition, SRGs in wind power applications require adequate parameter selection as well as robust controllers for a wide range of speed [23], [24].

Nevertheless, such challenges should not deter the widespread adoption of SRGs in WECS. Significant work has been conducted in the past couple of decades towards improving the control and dynamic performance of SRGs. As a result, this paper aims to provide a comprehensive state-of-the-art review of SRG-based WECS, encompassing the fundamentals, firing angles, voltage and power control, as well as grid-tied systems. A classification of the reviewed topics, which will be detailed in depth in the following sections, is presented in Fig. 1.

II. SWITCHED RELUCTANCE GENERATOR FUNDAMENTALS

The switched reluctance machine has a simple structure, presenting a double salient-pole construction, with individual concentrated coils wound around the stator poles. Hence, a single source of excitation is present, on the stator of the machine. A cross section of a three-phase 12/8 switched reluctance machine is depicted in Fig. 2. A switched reluctance machine operates as a generator when its phases are excited against the natural tendency of seeking rotor-stator alignment, i.e., when phase inductance is decreasing. For adequate operation, a closed-loop control system and an static converter are required. The following subsections present the mathematical model of the switched reluctance machine, the asymmetric half-bridge (AHB) converter and the fundamentals of an SRG-based WECS.

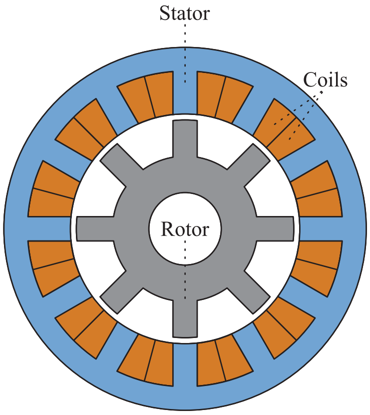

FIGURE 2. Cross section of a 12/8 switched reluctance machine.

A. MODEL

The voltage of an SRG phase, when neglecting mutual coupling between phases [25], is given by

$$v = R_s i + \frac{d\phi}{dt}, \tag{1}$$

where ϕ is the flux linkage, i is the phase current and R_s is the stator winding resistance. When considering magnetic saturation, the flux linkage is a function of both current and rotor position, θ. Flux linkage, hence, can be expressed as:

$$\phi(\theta, i) = L(\theta, i)i(t). \tag{2}$$

By substituting (2) into (1) yields

$$v = R_s i + l(\theta, i)\frac{di}{dt} + \epsilon\ , \tag{3}$$

where $l(\theta, i)$ is the incremental inductance [26]–[28] and ϵ is the back electromotive force (EMF). The latter terms can be expressed as,

$$l(\theta, i) = L(\theta, i) + i\frac{\partial L(\theta, i)}{\partial i} \tag{4}$$

$$\epsilon = i\omega_r \frac{\partial L(\theta, i)}{\partial \theta}\ , \tag{5}$$

where ω_r is the rotor speed.

Due to the double salient structure of the machine and the fact that it often operates in the region of magnetic saturation, switched reluctance machines present a highly nonlinear and complex model. In this context, some effort has been put to the research and development of advanced modeling strategies. These techniques make use of strategies like inductance modeling, magnetic circuit modeling, finite element analysis and lookup tables (LUT) in order to obtain high fidelity models of the machine [15], [29], [30].

In addition, given that it is not possible to efficiently and accurately represent the machine using a linear model, the simulation model of SRMs and SRGs often resorts to the use of characteristics of the machine. Based on the

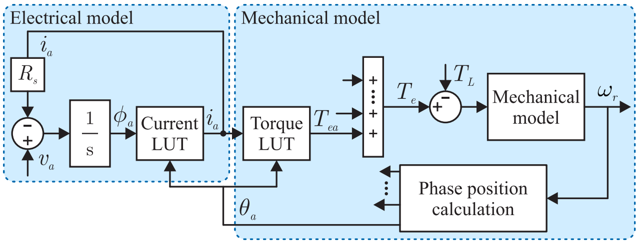

FIGURE 3. Simulation model of a switched reluctance machine.

machine magnetization data, it is possible to build the current lookup table, which returns the current value based on the flux linkage and rotor position, and torque lookup table, which return the torque value based on the current and rotor position [31]. The simulation model is depicted in Fig. 3.

First, based on the state of the converter switches, phase current and voltage measurements are made, enabling the flux linkage value calculation. Then, with the rotor position of the machine and the flux linkage value, the current lookup table is used to determine phase current. With the current value and once again using the rotor position, the electromagnetic torque value can be determined with the use of the torque lookup table. This process is repeated simultaneously for all of the phases of the machine. Next, the total torque can be determined by the sum of the torque produced by each individual phase. In sequence both rotor speed and rotor position can be calculated, where the rotor position is determined by integrating the rotor speed. Lastly, using the absolute rotor position, the phase referred positions can be determined and the simulation procedure restarted [32].

B. ASYMMETRIC HALF-BRIDGE CONVERTER

A static converter is necessary for adequate phase excitation of an SRG. Several converter topologies have been reported in literature over the years, presenting different number of switches and diodes, fault tolerance capability and levels of control complexity. Nonetheless, in general, the most commonly observed is the AHB converter [33], [34], presented in Fig. 4. In this configuration, each phase of the SRG can be controlled individually, ensuring fault tolerance to the drive [35]. In addition, each phase is connected to a single asymmetric half-bridge, composed of two switched and two diodes. Lastly, this topology allows the machine to be controlled either as a generator or a motor, without significant hardware changes. Note that the topology presented in Fig. 4 is known as self-excited, given it presents a battery to provide the necessary initial excitation to the SRG.

The switching states of the AHB converter can be analyzed separately, considering a single phase, as depicted in Figure 5. The first stage is characterized by both of the switches being turned turned on, with DC-link voltage being applied to the phase. This causes phase current to rise as long as the switches remain on. This stage is known as magnetization, and is presented in Fig. 5(a). The second stage is observed once the switches are turned off, causing current to flow through the

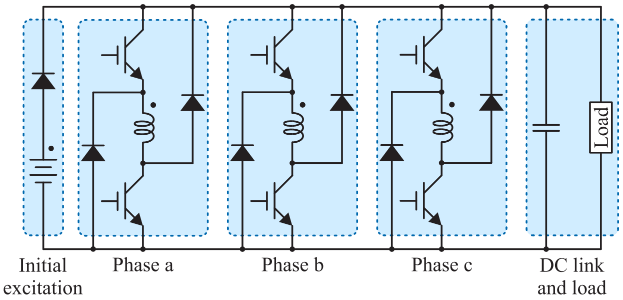

FIGURE 4. Three-phase asymmetric half-bridge converter for self-excited SRG.

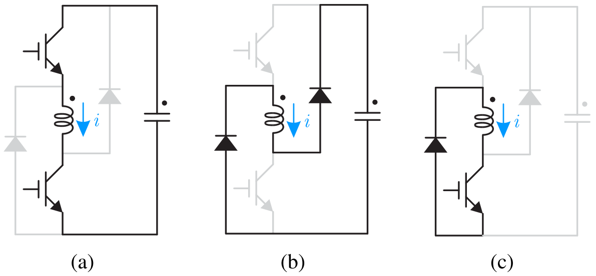

FIGURE 5. Asymmetric half-bridge converter switching states. (a) Magnetization. (b) Generation. (c) Flux boosting.

diodes and to be supplied back to the DC-link capacitor. This is known as the generating stage, and is shown in Fig. 5(b). A third stage is observed when one of the switched is turned on and the other is turned off. In this case, unlike motoring operation, the rate-of-change-of-flux linkage does not oppose the current build up in generating mode. This further boosts the current rate of change, characterizing the flux boosting stage, presented in Fig. 5(c) [31].

C. SRG CONTROL

The control of an SRG is directly dependent on the operating speed of the machine, as will be shown in this subsection.

When disregarding the resistive voltage drop on the phase winding, (3) can be rewritten as

$$v - \epsilon \ = l(\theta, i)\frac{di}{dt}. \tag{6}$$

From (6), it can be seen that after the phase excitation is over, phase current is determined by phase voltage and back-EMF. As a result, phase current can exhibit three different behaviors during the demagnetization period, as depicted in Fig. 6.

For low-speed operation, where the source voltage has a greater magnitude than the back-EMF, phase current will decrease after excitation ends, as depicted in Fig. 6(a). This results in the need for current regulation, often performed by a hysteresis controller, while the rotor moves from the run-on angle, θ_{on}, to the turn-off angle, θ_{off}. For high-speed operation, where the back-EMF has a greater magnitude than the source voltage, the increased back-EMF causes phase current to continue to rise even after θ_{off}, as depicted in Fig. 6(b). As a result, single pulse operation is necessary,

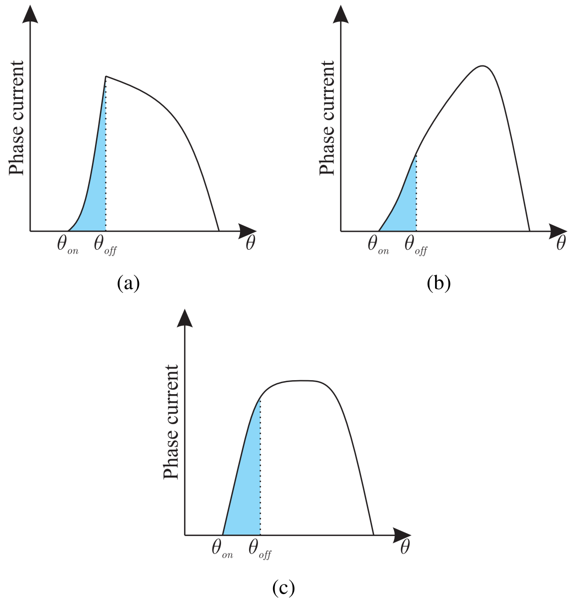

FIGURE 6. Phase current waveforms. (a) $\epsilon < V_{DC}$. (b) $\epsilon > V_{DC}$. (c) $\epsilon = V_{DC}$.

as effective current control cannot be employed at high speed, due to the limited supply voltage [24]. This results in a large uncontrolled current peak, even after the converter switches have been turned off. In the third condition, where the supply voltage has the same magnitude as the back-EMF, the phase current will remain constant after the excitation period, as shown in Fig. 6(c). The speed at which $V_{DC} = \epsilon$ is know as base speed, ω_b, and it should be estimated as a means to determine the control region that the machine is in, as presented below [23], [36].

$$\begin{cases} \omega < \omega_b \rightarrow \text{Current control} \\ \omega > \omega_b \rightarrow \text{Single pulse control} \end{cases} \tag{7}$$

When operating in the current control region, the outer control loop is responsible for generating a reference current value, which the current controller will seek to track. In addition, both the turn-on and turn-off angles are parameters that can also be adjusted in order to improve the performance of the SRG, as will be detailed in a following section. GCC had, when operating in the single pulse region, the outer control loop often provides a reference turn-off angle, which will be tracked by an inner loop controller. Once more, the turn-on can be optimized in order to improve certain performance aspects of the SRG. The general block diagrams for low-speed and high-speed operation are presented in Fig. 7(a) and 7(b), respectively. Moreover, example current waveforms for hysteresis and single pulse control are shown in Fig. 8(c) and 8(d), respectively.

D. SRG-BASED WIND ENERGY CONVERSION SYSTEM

The mechanical power in a wind turbine is given by

$$P_m = \frac{1}{2}\pi\rho C_p(\lambda, \beta) R^2 V^3 \tag{8}$$

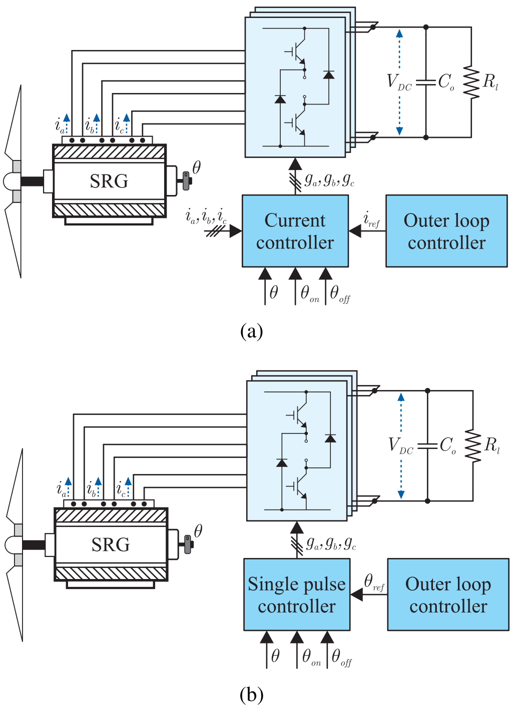

FIGURE 7. General block diagrams for the SRG operating regions. (a) Current control. (b) Single pulse control.

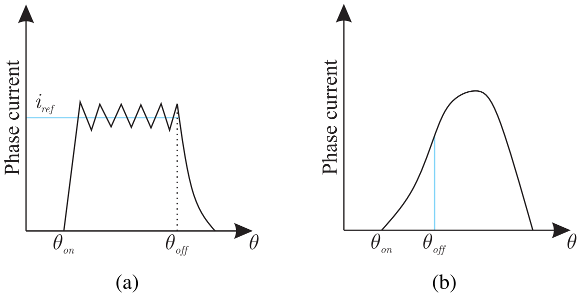

FIGURE 8. Example phase current waveforms for the SRG operating regions. (a) Current control. (b) Single pulse control.

where ρ is the air density, $C_p(\lambda, \beta)$ is the wind turbine power coefficient, λ is the tip speed ratio, β is the blade pitch angle, R is the rotor radius and V is the wind speed [37], [38].

For wind turbines operating below rated speed, improved energy efficiency can be attained by variable speed operation [39]. The optimal output curve of a wind turbine is given by

$$P_{opt} = k_{opt}\omega_r^3 \tag{9}$$

where P_{opt} is the optimal output power, k_{opt} is a constant dependent on the blade aerodynamics and ω_r is the rotor speed. As as example, considering a 12/8, three-phase, 2 kW SRG, similar to those described in [24], [40], an optimal power curve can be obtained. Fig. 9 presents the optimal profile for a wind turbine with a coefficient of $k_{opt} = 5.16 \times 10^{-4}$. Moreover, note that both operating regions are highlighted, below and above base speed.

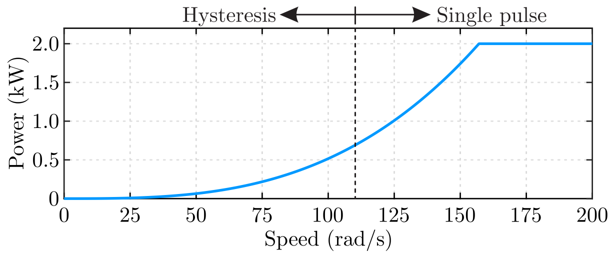

FIGURE 9. Example optimal output power curve.

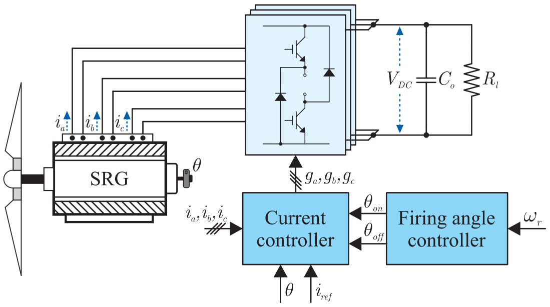

FIGURE 10. Block diagram of a generic firing angle control strategy.

Given the highly nonlinear behavior of SRGs, however, the generated power cannot be expressed by a simple analytical formulation. Nonetheless, by considering some simplifications, the average output power of an SRG can be calculated by [24], [40],

$$P_{out} = \frac{N_s N_r V_{DC}^2}{\omega_r} \left(\int_{\theta_{on}}^{\theta} \frac{(\theta - \theta_{on})}{L(\theta)} d\theta + \int_{\theta_{on}}^{\theta} \frac{(\theta_{off} - \theta - \theta_{on})}{L(\theta)} d\theta \right) \quad (10)$$

where N_s and N_r are the number of stator and rotor poles, respectively, V_{DC} is the DC-link voltage, θ is the rotor position and $L(\theta)$ is the phase inductance as a function of the rotor position.

III. FIRING ANGLE CONTROL

Based on what has been presented in the previous section, and considering equation (10), it can be seen that the output power of an SRG is directly affected by the DC-link voltage, the speed and the firing angles. Different angle combinations also influence other characteristics of the machine, such as torque ripple, root mean square (RMS) current and DC-link voltage ripple [40]. As a result, over the years several papers sought to investigate how to adequately control the firing angles of SRGs. In this section, different techniques for the adjustment of firing angle of SRGs are presented, highlighting their advantages and disadvantages. The strategies are divided in two groups: optimization and closed-loop control. A general block diagram for an SRG operating with a variable firing angle approach can be seen in Fig. 10.

A. OPTIMIZATION

Over time some attempts have been made towards the analytical determination of optimal excitation parameters for SRGs [41]–[45]. However, due to the complex model of the SRG and the difficulty in achieving simple analytical formulations for firing angle selection, several research papers have aimed to determine these parameters with the help of optimization techniques.

An exhaustive search, also referred to as parameter sweeping or brute-force approach, is a simple method to perform parameter optimization. The algorithm consists of enumerating all possible solutions within a defined search space, usually divided in regularly spaced intervals, and evaluating them individually. This allows the response of the entire search space to be observed, enabling the designer to better understand how the system is affected by each parameter. Moreover, such strategies guarantee that an optimal solution will always be found. Given the simplicity of this technique, several contributions have been made towards the optimization of SRG firing angles using exhaustive search algorithms [23], [46]–[52].

An overview of the SRG firing angle optimization problem is presented in [23]. It is shown that performance metrics such as torque ripple and efficiency, can vary drastically for the different excitation parameter combinations, while providing the same output power. In [46], numerous simulations are used to characterize an SRG in terms of torque ripple and energy efficiency. These values are later superimposed as a means to find optimal operating regions. A similar approach is presented in [47], where the effects of the turn-on angle on the SRG behavior are investigated. Once more, suitable parameters that maximize performance are chosen.

The optimal excitation of SRGs operating in high speed conditions has been investigated in [48]–[50]. In [48], angles are optimized according to a minimum phase current metric, while [49] measures the average output power, RMS phase current and losses for every available angle combination. A similar proposal is presented in [50], where two optimization techniques are described: the first attempting to minimize RMS phase current and the second minimizing RMS DC-link current, with both meeting the required power output.

Some research has also been conducted in the context of firing angle optimization of SRGs in wind energy systems. In [51] the analysis and comparison of two different switched reluctance machine topologies, 12/8 and 12/16, is presented. The optimal parameters and the machine that is capable of higher percentage of generated power are determined. An algorithm for optimal parameter selection for SRGs in wind power applications is proposed by [52]. Unlike the previously reported methods, the proposal makes use of a normalized cost function, allowing different variables to be considered in the same metric and ensuring a balance between torque ripples, iron and electric losses. Moreover, the procedure enables the optimal firing angles for the entire speed range to be determined.

Although a very common and simple technique, exhaustive search strategies have some drawbacks. Given that every possible parameter combination must be evaluated, exhaustive searches often present high computational effort. In addition, as the search space increases or the parameter intervals decrease, the problem grows exponentially, significantly increasing computational burden. It should be noted that depending on the size of the search space or the number of parameters to be optimized, the exhaustive search may be impractical.

An alternative for engineering problems with difficult analytical formulation is the use of metaheuristics, such as the genetic algorithm (GA) and the particle swarm optimization (PSO) [53], or learning methods, such as artificial neural networks (ANN). As a result, several paper have made use of intelligent algorithms for the firing angle optimization of SRGs [40], [54]–[65]. In [55], the PSO algorithm is used to optimize the firing angles of an SRG in order to maximize power output and efficiency. The results are stored in a lookup table and implementation is carried out using online interpolation. A similar proposal is presented in [56], where a gravitational search algorithm is compared to the PSO, with the advantages and drawbacks of each technique being highlighted. In [57], a procedure to optimize the firing angles of an SRG in the current-controlled region via the PSO algorithm is proposed. The technique aims to ensure a balance between reduced torque ripple and high energy efficiency, and is compared to a traditional exhaustive search approach, showing the reduced computational effort of the proposal. Similar approaches have been reported in literature making use of GA for angle optimization in [58] and [59]. In [60] a back-propagation NN is used to estimate the adequate turn-on and turn-off angles for a hybrid solar-wind energy system.

A comprehensive analysis of several performance parameters of an SRG operating in the single pulse region is presented in [61], including thermal and acoustic behavior. Then, a multi-objective optimization is proposed considering the turn-off and freewheeling period, making use of a three-term normalized cost function. In [40], the design of computational experiments is used as a means to reduce the computational effort in the optimization of SRG firing angles. Two different space-filling design strategies are used to build a response surface model. Then, firing angle and output voltage optimizations are carried out for the entire speed range using a multi-objective normalized cost function. The proposal is further presented in [62] and [63], where it is used to optimize the angles of SRGs operating in standalone and grid-connected conditions, respectively.

Other optimization algorithms such as differential evolution [64] and parametric regression [65] have also been reported in SRG-related publications. It should be noted that although intelligent algorithms present improved performance and reduced computational effort when compared to exhaustive search approaches, adequate algorithm parameter selection must be ensured in order to guarantee the convergence to global minima. Lastly, note that intelligent algorithms often present a more complex implementation when compared to the brute force strategy.

B. CLOSED-LOOP CONTROL

Although firing angle optimization helps to improve the performance of SRGs, some researchers sought over the years to implement closed-loop control strategies as a means to dynamically adjust the excitation parameters of the machine. The use of online controllers enables the angles to be adjusted for any operating condition, from steady state to unexpected disturbances. In addition, it allows the system to adjust when subject to parametric variations that appear over time, for example, which is often not considered in the previously mentioned optimization-based procedures. On the other hand, the use of closed-loop angle controllers increases the control system complexity, which may imply in increased hardware costs. Moreover, additional controllers must be designed so that the WECS can operate, which can be a more complex task when compared to the use of optimization approaches. [42]–[44], [66]–[69].

An optimal performance investigation regarding SRGs operating in the current-controlled is conducted in [42]. In order to verify the impact of the excitation interval on metrics such as efficiency and torque ripple, a large number of computer simulations are performed. As a solution to this problem, a simple controller is proposed, allowing the firing angles to be controlled online. The authors extend the proposal in [43], in order to account for the single pulse region. A unified approach is presented in [44], considering four-quadrant operation and ensuring smooth transition between the different control regions. In [66], a closed-loop excitation parameter controller for high speed SRGs is proposed. The controller ensures optimal efficiency, while not making use of lookup tables or extensive simulations. Firing angle control is used in [67] in order to improve the current tracking problem in SRGs. In [68], a firing angle controller based on a fuzzy logic algorithm is proposed. The proposal is intended for an SRG used in a WECS, allowing the system to operate at high energy efficiency over a wide speed range. A three-part controller for SRGs in wind energy applications is presented in [69]. A firing angle control strategy is described along a self-tuning fuzzy logic speed controller and a current control algorithm, enabling the system to operate with improved efficiency.

C. COMPARISON OF THE FIRING ANGLE CONTROL STRATEGIES

A comparison of SRG firing angle control strategies presented in literature is given in Table 1, highlighting the advantages and disadvantages of each approach.

Analytical approaches are systematic and can be derived generically, being able to be used with different machines. However, due to the nonlinear nature of the SRG, achieving analytical formulations is very complex. Exhaustive search techniques are fairly simple and straightforward, but present significant computational burden, sometimes

TABLE 1. Summary and comparison of the SRG firing angle control strategies.

Technique	Advantages	Disadvantages	References
Analytical	Systematic and generic approach	Very complex analytical formulation in the case of SRGs	[41]–[45]
Exhaustive search	Easy implementation, allows the entire search space to be observed and ensures optimal solution	Significant computational burden, sometimes not viable depending on the search space and intervals	[23], [46]–[52]
Intelligent algorithms	Suitable for problems with complex formulations, reduced computational effort	Intricate implementation, requires adequate parameter selection	[40], [54]–[65]
Closed-loop control	Continuous online control, able to adjust to disturbances and parametric variations	Increases the complexity of the control system, requires the design of additional controllers	[42]–[44], [66]–[69]

even being impractical. Intelligent algorithms are suitable for problems with complex formulations, and successfully reduce computational burden, however, they present intricate implementation and require adequate parameter selection to guarantee convergence. Lastly, closed-loop control strategies allow continuous regulation of the firing angles, being capable of adjusting even in the face of disturbances and parametric variations. On the other hand, this strategy increases the complexity of the control system and requires the design of additional controllers.

IV. VOLTAGE AND POWER CONTROL

In the context of wind power generation, output voltage and power control are essential in order to guarantee adequate power delivery. The output control of SRGs, however, is quite challenging for a few reasons. First, switched reluctance generators present a significant load dependence. This is due to the current source characteristic of the generator, where the SRG injects current into the DC-link. For example, a decrease in load may cause the output voltage to rise temporarily, while sudden transients may lead to sharp oscillations [70]. Moreover, the nonlinear behavior of the machine poses additional challenges in the control of SRGs. Lastly, the SRG output presents an unstable behavior in open-loop conditions [23]. As a result, over the years, researches have investigated several high performance control strategies. This section presents the different algorithms investigated for the voltage and power control of SRGs, with the methods being categorized as model-independent and model-based strategies. A general block diagram for a voltage or power control strategy can be seen in Fig. 11.

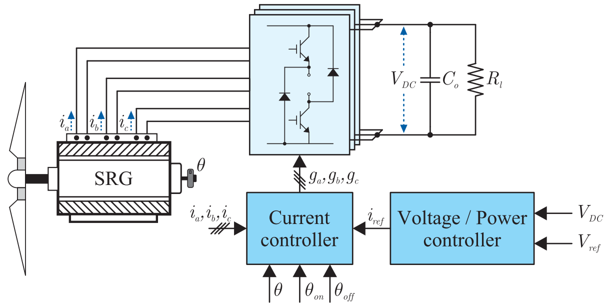

FIGURE 11. Block diagram of a generic voltage or power control strategy.

A. MODEL-INDEPENDENT STRATEGIES

In the realm of model independent control strategies applied to SRGs, the use of some intelligent control techniques applied to SRGs has been reported in literature [70]–[72]. Intelligent strategies make use of learning mechanisms in order to adequately tune a controller. Training may be performed online, making use of experimental measurements, or offline, making use of simulation data. As a result, these techniques benefit from not requiring knowledge of the machine parameters, being robust to parametric variations, given that they are able to adapt over time, and being suitable for highly nonlinear systems, such as the SRG. On the other hand, such strategies often present slow learning processes, have increased computational burden and rely on large amounts of training data.

In [70] an ANN is designed in order to replace a PI controller in an SRG-based WECS. Variables such as torque and wind speed are used as inputs in order to generate the reference current values. A terminal voltage control strategy based on a fuzzy logic approach is proposed in [71]. The controller uses as inputs the tracking error and its derivative as a means to generate a PWM signal and vary the excitation voltage, allowing effective DC-link voltage control. In [72], a fuzzy voltage controller for a 6/4 SRG is presented. The developed controller presents four processes, them being: fuzzification, knowledge base, inference machine, and defuzzification. The controller is compared to a traditional PI controller in order to verify its effectiveness.

Other techniques based on intelligent algorithms, such as iterative learning control, have been evaluated for switched reluctance motor (SRM) drives, as detailed in [20]. For SRG-related applications, however, authors were unable to find attempts of using this technique to address voltage or power control problems. Moreover, to the best of the authors knowledge, no other major model-independent voltage or power control strategies have been reported in literature.

B. MODEL-BASED STRATEGIES

Among the most common model-based control approaches for SRGs are the linear strategies, such as the Proportional-

Integral (PI) and state feedback controllers. These methods are industry standard and present simple implementation. Moreover, design methodologies for linear controllers are widespread and consolidated in literature, making them an attractive, low-cost and reliable solution. Consequently, several applications of traditional PI controllers for the control of output voltage and power of SRGs can be found in literature [63], [73]–[82].

Note that designing linear controllers for highly nonlinear systems, such as the SRG, is a very complex task. Thus, to circumvent this issue, some papers have made use of linearized models in order to design closed-loop linear controllers [39], [83]–[86]. A behavioral modeling of SRGs is presented in [83]. The proposal delivers a simple model, which reproduces the average behavior of the input–output variables. In [39], a small-signal model is used in order to design the PI controller of an SRG in a wind energy system. It is noteworthy that similar modeling strategies applied to SRMs are also present in literature, such as [84]–[86], for example.

Although modeling techniques are reported in literature, the design of PI controllers may still be a challenge for SRG applications. As a consequence, alternative design techniques have been proposed [47], [87]–[89]. A unified approach to the voltage feedback control of SRGs is presented in [87]. First, the dynamic model is estimated and then, considering the three points of a desired voltage response, the controller design is carried out. A similar approach is used in the design of a PI voltage controller in [88]. This time, however, a robust error cancellation control scheme is employed, where a compensation command is obtained from the tracking error, ensuring superior output voltage regulation. In [89], two fractional-order PI direct power controllers are depicted. The tuning process is performed using an optimization technique, namely harmony search algorithm, and the tracking error is used as the cost function. Similarly, an optimization based design for a PID voltage controller is shown in [47]. A three-term cost function optimizes the performance of the controller in terms of dynamic tracking capability, overshoot and steady state error.

Another topic of interest regards the use of more sophisticated controllers. Different control strategies may provide robustness, predictive capabilities, improved tracking or ease of implementation, for example. In this context, several control algorithms have been investigated as alternative solutions [24], [90]–[94]. In [90] a proportional resonant (PR) control approach is used for the direct power control of an SRG. The resonant controller is added as a means to reduce power ripple when compared to a traditional PI controller. Note, however, that appropriate controller tuning is required to achieve superior performance. Sliding mode (SM) control strategies have been reported in [24], [91]–[93]. In [91], a variable structure SM controller is proposed. A genetic algorithm is implemented along the SM strategy, allowing the output voltage to be successfully controlled even in critical no-load scenarios. A SM technique is employed in the output voltage control of an SRG in [92]. The same controller has been used in a grid-tied system in [93], attesting to its robustness. Design is carried out based on the system state-space model and stability analysis is performed considering a Lyapunov candidate function approach. In [24], the SM algorithm is applied to the direct power control of SRGs. Two different controllers are presented, for low to medium and high-speed operation, along with a commutation strategy. It should be noted that SM controllers present chattering as a drawback. Chattering is often referred to as an oscillation of finite amplitude and frequency, resultant from sliding mode control [20]. A PI controller is used for comparison purposes, showing the superior performance of the SM approach. Finally, other strategies such as passivity based control (PBC) have also been employed for the output voltage regulation of SRGs [94]. Stability and voltage ripple improvements are observed. Moreover, a back-EMF estimation strategy is employed, enabling an adaptive PBC structure.

C. COMPARISON OF THE VOLTAGE AND POWER CONTROL STRATEGIES

A comparison of voltage and power control strategies presented in literature is given in Table 2. The key advantages and disadvantages of each approach are summarized.

Intelligent control techniques don't require knowledge of the machine parameters and are robust to parametric variations, being suitable alternatives for highly nonlinear systems. However, they demand large amounts of training data and often present slow learning processes and increased computational burden. Linear controllers, such as the PID and state feedback, are industry standard, presenting simple implementation and well-known design methodologies. Nonetheless, these strategies are not suitable for nonlinear systems, present poor fixed-gain performance and may lead to a complex design stage for SRG applications. More sophisticated controllers have advantages such as robustness, predictive capabilities, adaptive behavior, improved tracking or ease of implementation, for example. Some drawbacks may be present, however, such as cumbersome calculations, complex structure or undesirable effects such as chattering.

V. GRID-TIED SRG WECS

Grid integration is an important aspect in renewable energy conversion. Inverters are a key component in this system, as they are responsible for guaranteeing high power quality injection into the grid, ensuring that the grid-injected currents are in compliance with the strict limits for harmonic distortion, such as the ones present in the IEEE 1547 Standard [95], [96]. In addition, a low-pass filter is required to attenuate the harmonics resultant from the pulse-width modulation. Some filter topologies are more effective at harmonic attenuation, while others present increased control simplicity, for example. Besides, each passive filter present different frequency responses, with some presenting a large resonance peak, for example [97]. Moreover, from a control

TABLE 2. Summary and comparison of the SRG voltage and power control strategies.

Technique	Advantages	Disadvantages	Model independent	References
Model-free (Neural networks, fuzzy)	Doesn't require knowledge of the machine parameters, robust to parametric variations, suitable for highly nonlinear systems	Slow learning processes, increased computational burden, need for large amounts of training data	Yes	[70]–[72]
Linear (PID, state feedback)	Industry standard, simple implementation, well-known design methodologies, low-cost	Not suitable for nonlinear systems, poor fixed-gain performance, complex design for SRG applications	No	[39], [47], [63], [73]–[89]
Proportional Resonant	Improved tracking, simple implementation	Requires accurate tuning	No	[90]
Sliding mode	Robustness, fast dynamic performance	Chattering	No	[24], [91]–[93]
Passivity-based	Robustness to parametric variations and nonlinearities	Presents a more complex controller structure	No	[94]

standpoint, it is important to ensure proper performance and stability, even when operating against distorted grid voltages and parametric uncertainties, such as uncertain grid impedance [98]. Considering the aforementioned issues, researchers have proposed several solutions for the grid connection of SRGs. In this section, the different converter and filter topologies as well as the control techniques used in grid-connected converters (GCC) in SRG-related applications are detailed, showing the merits and shortcoming of each topology and technique. A general block diagram for a grid-tied SRG-based WECS can be seen in Fig. 12.

A. TOPOLOGIES

The more common approach to connecting SRGs to the grid is though the use of a voltage source inverter (VSI) and an inductive filter, also referred to as L or first order filter, presented in Fig. 13(a). This approach present several advantages, such as high energy efficiency, a simple control structure and usually requires a reduced number of sensors when compared to more complex filters [99], [100]. As such, several uses of this topology can be found in literature [24], [39], [93], [101]–[113].

In some instances, slight modifications to the usual topology are observed. As an example, the use of power transformers in place of the inductors is verified in [114]–[117]. Similarly, a multilevel inverter has been used in [71], as opposed to the traditional two-level VSI. Some strategies make use of an additional DC-DC converter in order to adjust the DC-link voltage levels for improved grid integration [36], [63], [88], [118]–[123]. This also enables greater flexibility as it allows the SRG to operate at an optimal output voltage level, while the DC-DC converter is responsible for adjusting the DC-link voltage for the VSI. As an example, in [88], an interleaved DC-DC converter is used as a means to boost the SRG output voltage. Similar applications are observed in the context of SRG-based DC microgrids [63], [119], [120], [123], however, with converters that often present bidirectional capabilities.

Although first order filters are widely used, a large inductance is generally required to suppress the high-frequency switching ripple. This can lead to a very bulky and expensive solution depending on the system requirements. As a result, higher-order passive filters are often used in grid-tied systems as a means to reduce cost and size, while still ensuring adequate high-frequency harmonic cancellation [99]. In this context, the application of LCL filters, presented in Fig. 13(b), for the grid connection of SRG WECS is proposed in [124], [125]. Even though the higher order filter presents several advantages, they also present some disadvantages. LCL filters are known for their resonance peaks, which frequently require the use of a passive or active damping approach. Moreover, cost-optimized filters present increased control complexity due to the low-inductance and high-capacitance characteristics [99]. Lastly, it should be noted that the use of LCL filters is more financially attractive for higher power levels [126]. Given that most SRG WECS are for lower power applications, the cost of this solution may be prohibitive.

B. CONTROL

The most frequently used strategy for the control of grid-tied SRG WECS is the PI controller [88], [104], [109]. This is due to its simplicity, straightforward design stage and widespread industry adoption. However, note that for sinusoidal reference tracking the use of a PI controller is not adequate and will result in a constant steady state tracking error. In [36], [118] a master and slave control strategy is used for the control of the GCC. A PI controller is implemented along with a robust error cancellation control mechanism, ensuring superior tracking performance. Nonetheless, for grid connected applications that make use of the synchronous reference frame, the use of such approach will commonly result in satisfactory performance. Several reports of such approach applied to SRG systems are present in literature [24], [39], [63], [101], [102], [105], [111]–[117], [119], [124]. The proposals are mainly focused on three-phase GCCs, and

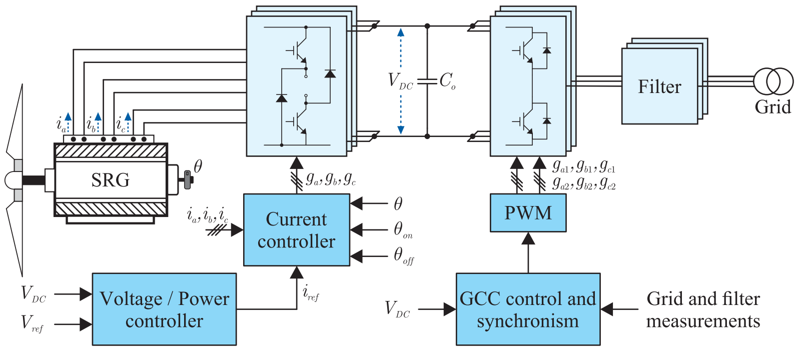

FIGURE 12. Block diagram of a generic grid-tied SRG-based WECS.

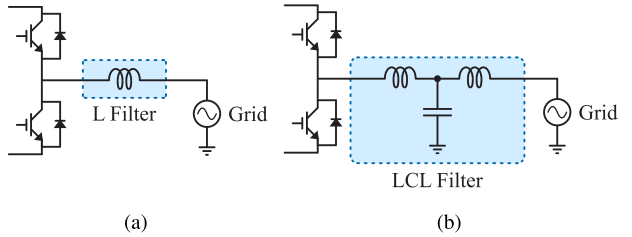

FIGURE 13. Example of common GCC filter topologies. (a) L filter. (b) LCL filter.

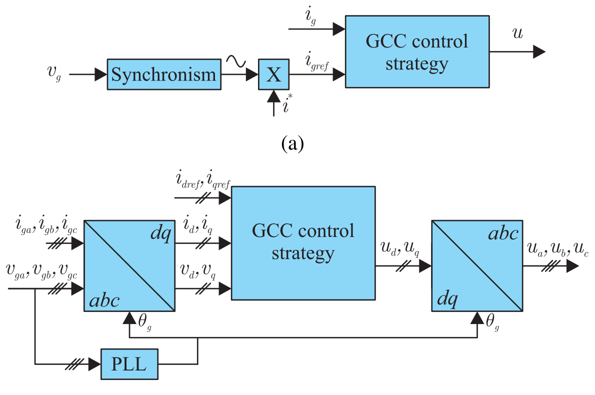

FIGURE 14. Block diagram of generic GCC control structures. (a) Stationary reference frame. (b) Synchronous reference frame.

no major novelty from a control standpoint is presented. A general block diagram for a GCC controlled in a stationary reference frame can be seen in Fig. 14(a), while the block diagram for the control in a synchronous reference frame can be seen in Fig. 14(b).

As an alternative, some researchers have used PR controllers in single phase GCC applications [106], [108]. This type of controller is suitable for ensuring sinusoidal reference tracking while also presenting relatively simple design and implementation. It should be noted, however, that proper tuning is necessary to ensure adequate performance. Moreover, depending on the application, several PR controllers tuned to different harmonics may be required in order to comply with the strict limits of IEEE 1547 [96].

One of the key challenges in the control of GCCs is ensuring adequate active filter damping, in the case of LCL filters, and proper performance and stability, even in the face of parametric uncertainties, such as uncertain grid impedance, and distorted grid voltages. Moreover, GCCs should also be able to operate under voltage sag and swell conditions, often considered a disturbance in the design of controllers [127]–[129]. Nevertheless, well design controllers should be able to cope with these short duration voltage variations, not affecting operation. In this context, some investigation has been carried out in the field of the robust control of GCCs in SRG WECS. In [93], a robust state-feedback controller is designed based on linear matrix inequalities (LMI). The proposal aims ensure to adequate performance and stability for the entire range of uncertain grid inductance, while synthesizing the desired grid-injected current. The proposal is extended in [125], where a three-phase GCC with LCL filter is used. Although robust controllers may present superior stability and performance, it should be noted that they may present a more complex design stage and intricate control structure.

C. COMPARISON OF THE GRID-TIED SRG TOPOLOGIES AND CONTROL STRATEGIES

A comparison of voltage and power control strategies presented in literature is given in Table 3. The key advantages and disadvantages of each approach are summarized.

Regarding the grid-tied topologies, the L filter presents a simple control structure and may require a smaller number of sensors. However, it often presents a larger and more expensive inductor. Topologies with an additional DC-DC converter present greater flexibility given they enable the SRG to operate at an optimal output voltage level. On the other hand, this approach presents a greater number of components, ultimately resulting in increased cost and complexity. Lastly, the LCL filter exhibits a superior filtering performance, while delivering lower size and cost. Nonetheless, it presents some challenges such as the pronounced resonance peak, increased control complexity and restrictive cost for low power applications.

TABLE 3. Summary and comparison of the grid-tied SRG topologies.

Topologies	Advantages	Disadvantages	References
L filter	High energy efficiency, simple control structure and usually requires a reduced number of sensors when compared to higher order filters	Inductor with increased size and cost, not suitable for high power applications	[24], [39], [71], [93], [101]–[117]
DC-DC converter + L filter	Greater flexibility, allowing the SRG to operate in an optimal region	Increased number of components, cost and complexity	[36], [63], [88], [118]–[123]
LCL filter	Reduce cost and size, improved filtering capabilities	Resonance peak, increased control complexity, too expensive for low power applications	[124], [125]

TABLE 4. Summary and comparison of the grid-tied SRG control strategies.

Strategies	Advantages	Disadvantages	References
PI	Simplicity, widespread industry adoption and straightforward design stage	Poor sinusoidal reference tracking (stationary frame)	[24], [39], [63], [88], [101], [102], [104], [105], [109], [111]–[117], [119], [124]
PR	Suitable for ensuring sinusoidal reference tracking, simplicity	Proper tuning is necessary, several PR controllers tuned to different harmonics may be required	[106], [108]
Robust (LMI)	Robustness to parametric variations, such as uncertain grid inductance	May present a more complex design stage and intricate control structure	[93], [125]

Regarding the control strategies applied to grid-tied SRGs, PI controllers are the more commonly observed approach due to its simplicity, widespread industry adoption and straightforward design stage. The strategy, on the other hand, presents poor sinusoidal tracking reference and may not be adequate in single-phase applications, for example. The PR controllers are a good alternative for adequate sinusoidal reference tracking, however, proper design is necessary and several PR controllers tuned to different harmonics may be required. Lastly, robust LMI-based strategies have shown robustness to parametric variations, such as uncertain grid inductance, while also ensuring adequate system stability. Nonetheless, such controllers may present a more complex design stage and exhibit a more intricate control structure.

VI. FUTURE TRENDS

Although the control of SRG WECS has been extensively studied, as presented in this article, relevant issues still remain to be addressed. Moreover, existing control algorithms can still be improved. As such, in this section, some of the future trends on the application and control of SRGs are explored.

A. INDUSTRY APPLICATION

Considering the work referenced in this article, it can be seen that significant academic research has been carried out in the field of SRGs in wind power applications. However, it should be noted that, to the best of the authors knowledge, no industry application of an SRGs in wind turbines can be observed up to this moment in time. Some references are found in literature to the Ecowhisper wind turbine, a project of the Australian company Renewable Energy Solutions Australia Holdings [130], [131]. The project, however, appears to have been discontinued, due to the fact that no recent updates or information can be found. Enedym Inc, a technology start-up company from McMaster University focused in switched reluctance machines, has a product called Ventium. The system is composed of an SRM and inverter, intended for the control of the blade pitch angle of a wind turbine. The solution presents advantages over the traditionally used brushed DC pitch motors, which suffer from high maintenance costs and low reliability, often increasing turbine downtime [132].

Nonetheless, given the promising advantages of the SRG, such as rare-earth-free characteristics, inherent fault tolerance and wide speed range operation, without need for a gearbox, it is expected that commercial wind turbines making use of the machine are produced in the future.

B. HARDWARE-IN-THE-LOOP SIMULATION

From what has been presented in Section III, it can be seen that firing angle optimization using exhaustive search approaches is a very popular solution. As previously discussed, however, these strategies have some known drawbacks, with the more relevant one being related to the high computational burden. This may lead to significant simulation time, as well as the use of expensive computers. Moreover, as the search space increases or the parameter intervals decrease, the problem grows exponentially, up to the point of making the approach impractical. A viable solution to this problems is the use of hardware-in-the-loop (HIL) simulations. HIL allows real-time simulations, significantly accelerating optimization and test driven design processes, while also allowing the generation of automatic reports, for example [133]. Some research has been done regarding the use of HIL for the simulation

SRMs [134]–[136], however, note that no effort has been put towards SRGs or the parameter optimization of the machine.

C. IMPROVED VOLTAGE AND POWER CONTROL

A significant number of voltage and power control strategies applied to SRGs were reviewed in Section IV. Although several techniques present suitable behavior, many control approaches can still be investigated for this purpose. Control algorithms such as model predictive, adaptive, deadbeat, iterative learning, among others, have successfully been investigated for switched motor applications and are examples of strategies that can be applied to the SRG. Furthermore, these strategies present significant advantages over standard linear controllers, such as robustness, predictive capabilities and model independence, for example.

D. ROBUST GRID-TIED INVERTER CONTROL

Similar to what has been said for the voltage and power control, a large number of grid-tied SRG systems have been reported in literature, as depicted in Section V. Most of those systems, however, made use of first order filters and relatively simple control strategies. Significant work can be carried out regarding the search for robust controllers, taking into account parametric uncertainties, for example. Moreover, different nonlinear control approaches may also be investigated, such as sliding mode, model predictive, deadbeat, etc. It is worth noting that the use of an LCL filter is reported in very few instances. Authors should seek to provide new control strategies along with the use of higher order filters, specially the well known LCL alternative.

E. ADVANCED CONTROL STRATEGIES

Although the SRG control has been extensively studied, the advanced control of SRMs is significantly more developed [20]. First, torque sharing and current profiling techniques are often used for SRMs. These techniques can be employed to SRGs as a means to improve torque, losses and output voltage performance, for example. Even though a technique has been reported in literature, little effort has been dedicated to this topic applied to SRGs [137]. Second, improved current control strategies can be developed and tested for SRG applications, allowing superior reference tracking and improved performance for systems subject to current profiling strategies, for instance. Moreover, the machine operating as a generator could also benefit from the fixed switching frequency. Lastly, acoustic noise and vibration are frequent issues in switched reluctance machines. Several techniques have been proposed for the acoustic noise reduction and vibration suppression in SRMs, however, no implementations of such strategies for SRGs have been found. Moreover, to the best of the authors knowledge, no attempt at addressing the problem specifically for generator operation has been verified.

VII. CONCLUSION

Renewable energy sources have been the focus of research and governmental incentives due to the increasing environmental concerns. In this context, wind power has gained increased interest due to its low cost and abundant availability. Switched reluctance generator have emerged as a viable alternative to other electrical machines in wind energy conversion systems. However, the machine present significant challenges from a control standpoint. As such, this article has presented a state-of-the-art review of the control of SRGs in WECS. Initially, the fundamentals and basic control aspects of the machine operating as a generator were detailed. Then, a review of the firing angle control strategies is presented, highlighting the optimization and closed-loop control approaches. After that, a survey on the voltage and power control strategies applied to SRGs is carried out. The strategies were divided in model-independent and model-based approaches, highlight the advantages and disadvantages of each algorithm. Then, an overview on the grid-tied SRG WECS is provided. An analysis of the utilized passive filters as well as the control techniques is performed. Lastly, some future trends are listed, showing relevant topics that still have not been addressed for SRGs.

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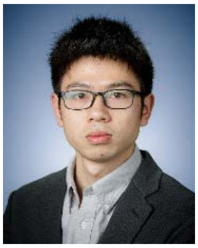

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