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A Review "The Research Status of Switched Reluctance Generator"

Lalarukh Haseeb*, Yueping Mo and Muhammad Mudasser

College of Electrical Energy and Power Engineering, Yangzhou University, Yangzhou 225127, P.R. China.

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ABSTRACT

Switched Reluctance Generators (SRGs) have become quite popular lately because they offer some big advantages compared to regular generator technologies. This comprehensive review paper is dedicated to illuminating the latest developments in the realm of SRGs, offering a deep dive into their operational intricacies, diverse types, design principles, control strategies, versatile applications, and the formidable challenges that lay ahead. The paper begins by explaining in simple terms how Switched Reluctance Generators (SRGs) work and uncovering the main ideas that make them special and different from other generators. It then proceeds to categorize SRGs into various types, providing an insight into the diverse design features that distinguish them. This foundational understanding sets the stage for a more profound exploration of SRGs. The review focuses significantly on studying the complex control methods that manage SRGs, exploring the advanced techniques used to make them work better and more efficiently. As SRGs continue to evolve, their applicability spans a broad spectrum, ranging from clean energy generation to enhancing transportation systems and powering industrial machinery. This review carefully explains how SRGs can help change many different industries for the better. It shows how they have a lot of potential to make big improvements. Nevertheless, SRGs do not come without their share of challenges, encompassing issues related to efficiency, reliability, and the complexities inherent in control strategies. This review serves as an informative exploration of SRGs, highlighting their potential across various industries. It acknowledges their development and urges them to keep exploring their promising abilities. As switched reluctance generators become more popular, this discussion provides a detailed guide for those interested in understanding how they work and navigating their complex features.

1. Introduction

Switched reluctance generators (SRGs) have gained increasing attention from both academics and industry in recent years as they offer several advantages over traditional generators. The objective of this research is to study SRGs and the current research on this topic. SRGs might exhibit higher torque ripples and need a more complex rectifier with larger power switches compared to permanent magnet synchronous generators (PMSMs), they offer distinct benefits such as robustness in harsh conditions and suitability for variable speeds, making them preferred in applications where resilience, and flexibility in speed control are

* Corresponding author.
E-mail address: ypmo@yzu.edu.cn
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prioritized over some performance trade-offs. The switched reluctance generator has a double salient structure. The maintenance and manufacturing cost of this generator is low. In the structure of the rotor, permanent magnets are used, and there is no use of winding in the rotor. The winding is present on the slots of the station and for this reason, it has a high tolerance for faults [1].

The working principle of a switched reluctance generator is very simple. Magnetic flux always follows the path of low reluctance. In the generator, the rotor follows the low reluctance path, which is how the SRG works. SRGs are particularly attractive for applications in which high power densities, high efficiencies, and robustness are required, such as in wind and marine power generation, electric vehicles, and renewable energy systems. The main advantages of SRGs compared to traditional generators are their lower cost, higher power density, higher efficiency, and higher robustness. Switched reluctance generators have significant importance due to several benefits such as the absence of magnets, a robust system, a high factor of effectiveness. An in-depth analysis of SRGs, their different characteristics, and their applications is carried out. For variable speed applications, switched reluctance generators are mostly utilized [2].

2. Materials and methods

The purpose of this review is to explore the state of the art of switched reluctance generators (SRGs) and discuss their potential applications, control techniques, and challenges. The review draws on a variety of sources, including journal documents, conference proceedings, and books, to provide an up-to-date overview of SRGs. The review begins with an overview of the operating principles of SRGs. This is followed by a discussion of the different types of SRGs and their basic design features. Next, the review presents an overview of the control techniques for SRGs and the potential applications of SRGs, including in wind and marine power generation, electric vehicles, and renewable energy systems. Switched reluctance generators are also used in wind turbines. The design of an SRG is very simple when compared to PMSMs. In the structure of an SRG, there is simply a rotor, a stator, and no concept of a magnet. SRGs have the least number of components, so the costs of SRGs are also lower. Compared to PMSMs, SRG can be used in variable-speed applications. However, there are some disadvantages in the case of wind turbines. For wind turbines, the efficiency is lower, especially at low speeds. When compared to PMSMs, SRGs are less effective [2].

When compared to a heteropolar generator, the effectiveness of an SRG is higher, especially at lower speeds. There is less production of torque ripple in SRGs, and this is due to their simple design. The thermal and dynamic behaviors of SRGs are improved due to the absence of magnets. SRGs can be widely utilized in different applications where other generators are not used. Finally, the review presents the challenges associated with SRGs and provides an outlook for future research and development. Overall, the review provides a comprehensive overview of the state of the art of SRGs, including their operating principles, types, control techniques, and potential applications. The value of the output power is found by the formula below [2]:

$$P_e = E_{dc} i_{dc} \tag{1}$$

In Equation (1), P_e, E_{dc}, and i_d denote the electrical power, dc link voltages, and dc link current, respectively. The review also discusses the challenges associated with SRGs and provides an outlook for future research and development. In several applications, the grid connection has issues such as current oscillations. These issues can result in power quality issues for grid connection applications. The majority of these applications are wind energy conversion systems [3]. The ripple torque is also found via the following formula:

$$T_{ripple} = \frac{T_{max} - T_{min}}{T_{avg}} \tag{2}$$

where T_{ripple} is the ripple torque, which can significantly impact the switched reluctance generator. T_{max} is the maximum torque value, T_{min} is the minimum torque value, and T_{avg}

represents the average torque value. To solve the issue of power quality, one researcher attempted to close the voltage control loop via the pre-processing of the voltage ripple [4]. In different practical applications, the measurement of voltage is a key component. According to the author, voltages are measured using two significant approaches. In the first approach, a low pass filter is utilized which has a cut-off frequency under the operating speed of the switched reluctance generator. In the second approach, the control sampling is carried out according to the position of the rotor [5]. The mass production of SRGs has been achieved, and they are used in different applications. SRGs have been used in small-scale wind turbines for decentralized power generation. Their simplicity, robustness, and ability to operate under variable wind conditions make them suitable for off-grid or remote locations. SRGs in exhaust gas energy recovery systems capture waste heat from exhaust gases and convert it into electrical energy, improving the overall energy efficiency. They can withstand high temperatures, are lightweight, and contribute to reducing environmental impact. Thermal management and integration with heat exchangers and control systems are important for optimal operation [5]. The factor of phase voltage can be found for switched reluctance generators and is provided in the section below [5]:

$$v = R_s i_i + L(\theta_r, i_i)\frac{di}{dt} + e(i, \omega_r), e(i, \omega_r) = \frac{\partial L(\theta_r, i_i)}{\partial \theta_r}\omega_r i_i \quad (3)$$

In Equation (3), the symbols v, ω_r, T_{ei}, i_i, $L(\theta_r, i_i)$, and θ_r represent the phase voltage, rotor speed, phase-developed torque, phase winding current, winding inductance, and rotor position, respectively. Switched reluctance generators (SRGs) typically use electrolytic capacitors for power conditioning and control purposes rather than as a direct component of the generator itself. They help regulate voltage, smooth out power fluctuations, and assist in controlling the electrical currents within the generator system. A boost converter is also utilized by researchers and is used for the active filtration of the switched reluctance generator's current. This approach is an alternative to using highly rated capacitors and with this method, there will be no more need for capacitors. The prior goal of using this approach was to reduce the oscillations of the circuit, and the overall rating of the capacitor was also reduced significantly [6].

The configuration of an SRG is provided with in-depth observations. A voltage source is utilized for the generation of current in the three-phase ring-connected winding. On the windings of the stator, a rectifier is utilized for obtaining DC voltage. For the stator winding, two topologies are observed, and both have different polarities. These configurations are known as asymmetric and symmetric configurations. The line voltages of both configurations are observed in the state of an open circuit. The symmetric topology has a higher power when compared to the asymmetric topology. In this configuration, the value of the iron loss is also higher [7].

For high-speed applications, SRGs are utilized. This assessment is carried out by performing a simulation [8]. In this particular structure, a buck converter is also used, and this converter is utilized as a connection between the switched reluctance generator and the grid. Deflection dual stator switched reluctance generator with its dual-stator setup and switched reluctance technology, revolutionizes power generation. Its unique design minimizes torque fluctuations, promising high efficiency and increased power density. A game-changer in renewable energy, this generator holds immense potential for sustainable systems, offering improved performance and lower maintenance. A DDSRG (deflection dual stator switched reluctance generator) has several advantages over a simple generator. To better understand the structure of a DDSRG, the electromagnetic model of this generator is studied. This model has the characteristics of space and time distribution. Further, the analysis of this model is performed through the use of finite element software. With the use of this software, all the characteristics of the system are analyzed properly. The vibration characteristics of the stator are also observed via vibration analysis. This concept can be observed with the help of Figure 1.

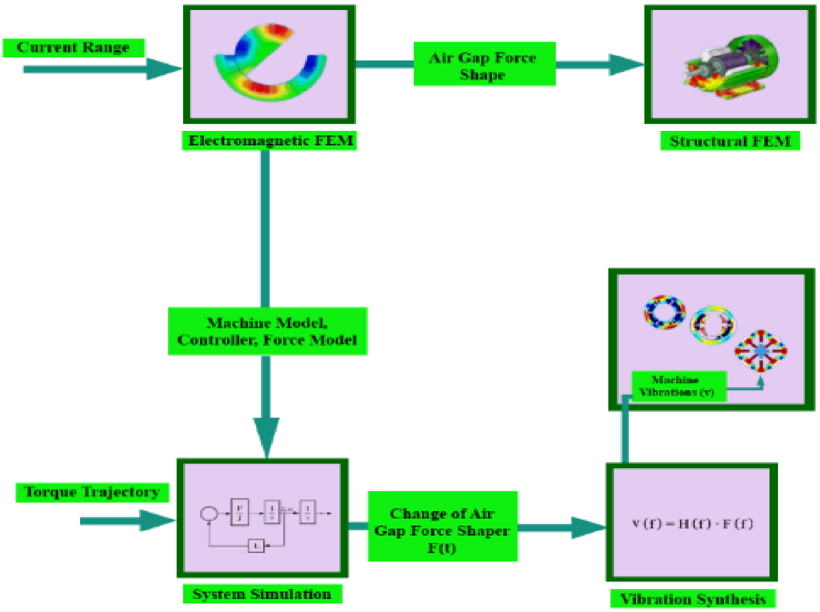


Figure 1. Frame diagram of electromagnetic vibration [8]

The analysis carried out for a DDSRG is a combination of a transfer function structure, a finite element analysis, and an analysis of vibration coupling. By using this analysis approach, improved results are achievable through enhanced analysis. [9]. The actual structure of an SRG is shown in Figure 2.

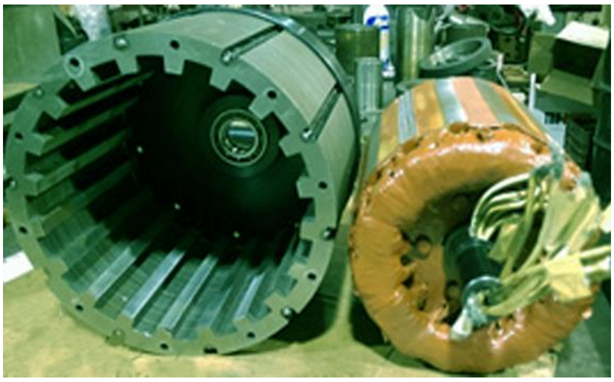


Figure 2. Actual structure of a switched reluctance generator [9]

The electromagnetic torque is provided below [9]:

$$T = \frac{d}{d\theta}\int L(\theta).idt = \frac{1}{2}\frac{i^2 dL(\theta)}{d\theta} \qquad (4)$$

In Equation (4), T, i, and L show the electromagnetic torque, value of phase current, and inductance, respectively.

The phase voltage relationship is provided in Equation (5):

$$V_{dc} = R_s i + L(\theta, i)\frac{di}{dt} + i\omega\frac{d(dL(\theta,i)i)}{d\theta} \qquad (5)$$

where V_{dc}, R_s, $(L(\theta, i))$, and ω denote the values of the phase voltage, resistor, inductance, and the speed of the motor, respectively. The Equation (6) aids in determining the rotor pole height. [9]:

$$h_r = \frac{1}{2}\left(D_{or} - D_{ir} - 2b_{yr}\right) \qquad (6)$$

In Equation (6), h, D_{or}, D_{ir}, and b_{yr} represent the height of the pole, the outer diameter of the rotor, the inner diameter of the rotor, and the rotor back iron, respectively.

Switched reluctance generators are also utilized in wind turbines. Double stator generator has a fast response and compact size. This approach enhances the effectiveness of power and power density. A DDSRG has the freedom to operate at the rated speed of the generator. Operating at the rated speed ensures full utilization of wind energy. The energy could be generated effectively, and the cost of generating power could also be reduced. The significant benefit of a DDSRG is that it has a double stator structure internally and externally. Wind energy generation systems and electric vehicles utilize switch reluctance generators as key components [10]. The output power for the setup is found below:

$$P_{opt} = k_{opt} W_r^3 \tag{7}$$

In Equation (7) above, k_{opt} is a constant that depends upon the aerodynamics of the blade, whereas W_r, and P_{opt} represent the rotational speed and the value of the output power, respectively [10].

$$T_{ei} \Delta \frac{1}{2} \sum_{i=1}^{N} i_i^2 \frac{\partial L_i(i_i, \theta_r)}{\partial \theta_r} \tag{8}$$

In Equation (8), θ_r is the angle of the rotor. A new switched reluctance generator model is presented, and it is known as a deflection dual stator switched reluctance generator (DDSRG). The advantages of this newly developed DDSRG are observed in-depth. The characteristics of the DDSRG are extracted and verified. These characteristics are also calculated and analyzed. With the help of a simulation, the vibration characteristics are observed, and they are then verified via an experimental approach [11]. The structure of the DDSRG is shown in Figure 3.

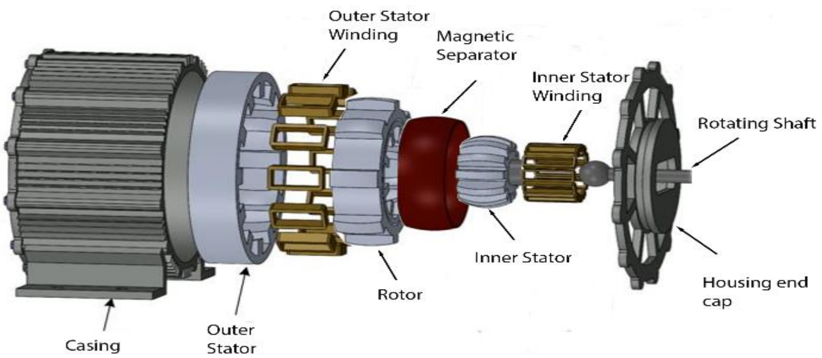


Figure 3. Structure of DDSRG [11]

A dual stator switched reluctance generator (DSSRG) represents a type of switched reluctance generator suitable for underwater power generation. The propeller is directly linked with the DSSRG. When the propeller moves, it rotates the DSSRG, generating power underwater. In this way, the efficiency of the generator could also be boosted. The torque and pressure characteristics of the propeller are significant. These characteristics were observed at different angles of deflection, and this study was carried out using the software CFX [12]. A DSSRG was also modeled and analyzed. At the different angles of deflection and speeds, current and voltage characteristics are observed. The prototype of the DSSRG is introduced to observe the stability and feasibility of the underwater generation system [12].

Switched reluctance generators have some issues with power quality. Due to these undesirable oscillations, the expected performance cannot be achieved. For this particular reason, a methodology based on in-loop filtration was proposed, and this approach enhances power quality. The main concept behind this approach is to decrease the voltage oscillations. To practically decrease these ripples, two approaches are utilized. These two approaches include the use of moving average filters and notch cascading filters. There is a certain type of switched reluctance generator known as a deflection dual stator switched reluctance generator. This particular generator has a high value of efficiency [13].

Switched reluctance generators have the capacity to work at low input voltage values, so a buck converter is used with this type of generator. In a wind energy conversion system, the key component is a switched reluctance generator [14].

A novel model is introduced for SRGs. This model comprises a rotor, stator, current chopper, PID controller, and power converter. In the modeling process, Modelica is utilized as the language. Modelica is actually both a language and a software environment. It's an open-source, object-oriented language used for modeling complex physical systems, especially in the domain of engineering and systems design. In the model, the complex section comprises the non-linear characteristics of an SRG. The machine flux linkage depends upon the position of the rotor and the stator current. The electromagnetic torque also depends upon the rotor position and the stator current. For the representation of non-linear characteristics, the function approximation method and finite element method are utilized. Both of these approaches are used, and the simulations are compared for both of them. The introduced model of a three-phase, self-excited switched reluctance generator. This model has three pairs of stators and two pairs of rotors [15].

A simple simulation model is introduced for SRGs. A control method is introduced for the SRG system, and this system had been used for wind power generation. The SRG can be utilized in a wide variety of applications. To obtain a high level of power efficiency, an excitation angle condition is introduced for the SRG. A high level of power generation efficiency had been obtained by reducing copper losses. To minimize copper losses, we employ specific electrical patterns and controlled angles within the generator's operation. Excited current waveforms dictate the pattern of electrical flow, while angle excitation control adjusts the timing of these currents to optimize magnetic fields in a switched reluctance generator, enhancing its efficiency and power output. These current waveforms are divided into three categories. The link between several terms is found, and in the list of these terms, the power generation efficiency, the excited current waveforms, the energy conversion loop, and copper loss are included [16].

A current distribution control method is introduced. By using this approach, the generating capacity had been increased, and the reliability of parallel generation had been improved. This approach is based on the algorithm of differential evolution. SRGs are utilized in a parallel configuration. This approach is simulated, and the required results are obtained. This approach is also compared with the traditional current sharing approach [17]. For the regulation of power and its efficiency optimization, a new approach is introduced. This approach is known as the optimal control theory. SRGs are also utilized in aircraft power systems. The gradient descent approach is utilized for finding different angles. In the list of angles, the turning-off angles, turning-on angles, and the angle of zero voltage are included. All these angles regulate the provided power. To obtain maximum efficiency, the angles of control are determined. These control angles are determined via particle swarm optimization. The maximum efficiency had been obtained through these control angles. Simulations are also performed for the verification of these results [18].

A wind energy conversion system is a suitable application of an SRG. The converter is also a significant segment of the whole system. A modified converter design is introduced for the wind energy conversion system. This converter has a lower number of active switches and a low production cost. Simulations are also performed to clarify the abilities of this converter [19].

The electromagnetic characteristics of the SRG are observed. A new SRG is also introduced which is known as a mutually coupled SRG (MCSRG). Two-dimensional finite models of ANSYS are utilized to create the structures of a typical SRG and an MCSRG.

The working parameters of both SRGs are also observed. Different forms of windings are utilized in the structures of these SRGs. For both types, torque, current characteristics, and core losses are determined for the complete excitation cycle. By comparison, it is observed that the MCSRG has a higher average current value. According to the results, the average current value current for the MCSRG is 13% more than the typical SRG. The ripple value is 1% smaller for the MCSRG when compared to the typical SRG. The core loss factor for the MCSRG is 1% smaller than the core losses of typical SRGs. The input torque requirement is 10% smaller for the MCSRG than the typical SRG. Taking those results into consideration, it can be said that MCSRGs were utilized as priority bases for different applications [20].

For the production of clean energy, a wave energy conversion system is a vital approach. In this way, a huge amount of energy could be produced at sea. The practical implementation of this approach is difficult due to the harsh conditions of the environment and the need for a low frequency for the process of energy conversion. A new linear electric generator is introduced in the research. This generator entirely relies on a novel switched reluctance generator that was developed for the project and is called Sea Titan. The calculation and the process of design are also expressed for a better understanding. Sea Titan plays a vital role in manufacturing and testing. A feasibility study of this generator is also included [21].

The hysteresis current control approach is introduced. This method is used for a three-phase SRG, and this method is based on the non-linear inductance model. Finite element analyses are conducted for the electromagnetic field in the application of wind energy. The non-linear characteristics of an SRG are observed. The characteristics of the power converter are also observed. An asymmetric half-bridge topology is utilized to create the structure of the converter circuit. For control purposes, two strategies are introduced. In these approaches, control of the angle position and current chopper are included. The behavior of the SRG, its modeling, and its simulation are presented. These results yield various output characteristics with the SRG. The designed SRG system achieves a higher level of efficiency as well [22].

Switched Reluctance Generator converters are very crucial for this system and its structure, and different topologies are observed. The sole purpose of this study is to improve the efficiency of the system. The characteristics of the different converter topologies are observed. This research introduces advanced approaches to control SRGs.In this way, wind generation systems based on SRGs can be better introduced as effective systems [23]. SRGs are also used in the automotive and aerospace industries [23]. The evolution of wind power is presented in Figure 4.

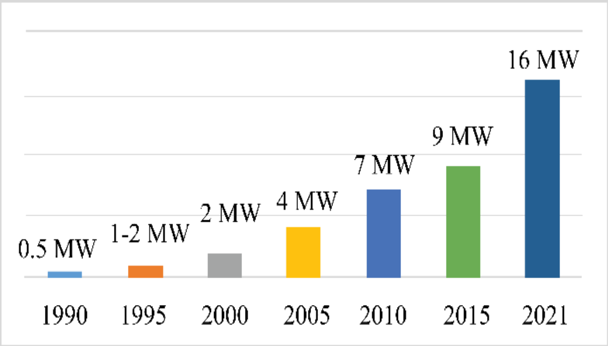


Figure 4. Evolution of wind power [23]

SRGs act as generators in regenerative braking, converting braking energy into electrical energy for battery charging. This feature enhances the overall efficiency of the charging process. SRGs are key components used in the braking systems of electric vehicles. By using an SRG, the factor of performance can be boosted. The strategy of the braking system is developed with the parameters of safety, braking energy, and high- and low-speed conditions. The aim of introducing this braking system is to improve the smoothness of torque and current and improve the power generated. As a result, the battery life can be improved, and the driving range of the vehicle can also be improved. As a result, it is observed that this system increases the comfort of vehicle braking and is effective at increasing the battery life [24].

SRGs are utilized in constructing low-voltage DC grids, ensuring higher efficiency levels. To obtain better results, simulations are carried out and experiments are also performed. An SRG is linked with a resistive load, and the generator is operated at different rotational speeds. From the results, it is observed that the efficiency of the drive is almost 70% at 1500 rpm. In the case of a normal load, the efficiency is improved and is almost 80% [25].

For an SRG, a new strategy is introduced that is based on a fuzzy algorithm. By employing this logic, solutions are sought and ranked based on their viability. This algorithm is completely designed according to the perspective of the decision-maker. In the algorithm, the preferences of the designer are considered significant. With these preferences, decision-making efficiency could be improved significantly. Through the simulation, the proposed strategy is observed, and positive results are found [26]. A microgrid is observed that is entirely based on a wind SRG. A section on SRG design and control is provided. Using an SRG enables obtaining a wide range of power and boosts efficiency. The voltage regulation characteristics are also found to be impressive. In the microgrid system, the flow of power is continuous between all stages. The SRG is utilized in a range of power from 0.5 kW to 5 MW [27]. The structure of the induction motor switched reluctance generator setup is shown in Figure 5.

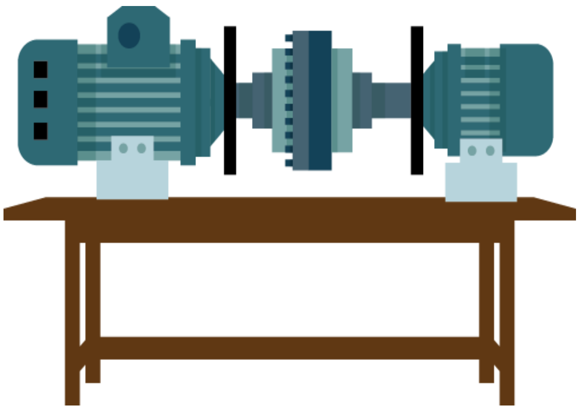


Figure 5. Induction motor switched reluctance generator setup [27]

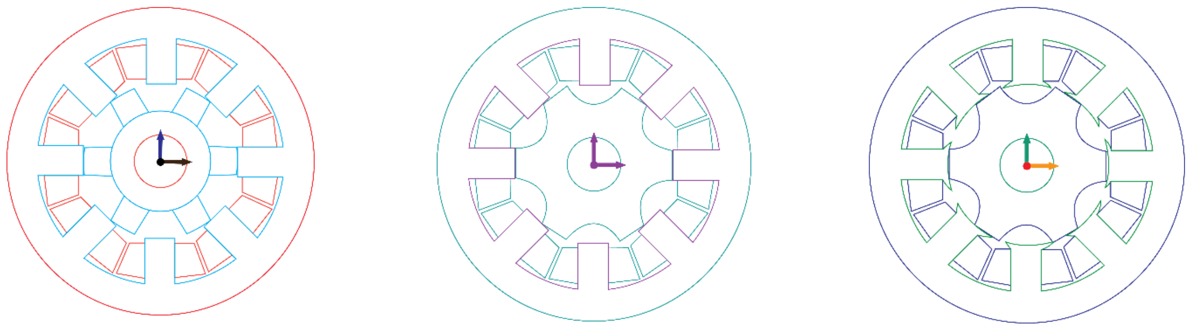
The electromagnetic torque for a switched reluctance generator is calculated via Equation (8) [27]:

$$T_e = \sum_{i=1}^{N} T_{ei} = T_i - B\omega_r - J\frac{d\omega_r}{dt}, P_{ag} = T_e\omega_r \quad (9)$$

where T_e, T_i, ω_r, N, T_{ei}, B, and J denote the electromagnetic torque, input torque, the speed of the rotor, phase number, phase-developed torque, total frictional coefficient, and the total amount of inertia.

The appealing physical traits of an SRG allowed direct linkage with any mechanical unit, while the SRG's control mechanism relied entirely on the associated application. To derive an SRG with good efficiency, a new controlling model is introduced. This model is also known as a novel active power control scheme. This scheme enables the derivation of SRGs across a wide range. With the help of a simulation, the mathematical analysis is verified, and an experimental approach is also taken to obtain better results [28].

SRGs are used in wind energy conversion systems, and the switching angles for the rotor and stator are extracted. For the effective operation of an SRG, the converter plays a vital role. Through an analysis of the SRG inductance profile, the switching angle is extracted. By using Infolytica MagNet software, an SRG was analyzed in depth. For the observation, the SRG was run at a constant speed, and the length of the air gap was 0.5 mm. In the analysis, a specific material, cold-rolled steel, was used. The dimensioning of the generator was carried out according to the B-H curve of the material. The voltage source was used for the excitation of the SRG. Once the SRG is turned on, the generated power will be transferred to the load accordingly [29]. The rotor structure is shown in Figure 6.



(a) (b) (c)

Figure 6. (**a**) General rotor structure. (**b**) Curved rotor structure. (**c**) Curved rotor structure with pole shoe [29]

The torque of a switched reluctance generator could be found in Equation (10):

$$T = \frac{P}{\omega} \tag{10}$$

where the symbols P, ω, and T denote the values of the power, angular speed, and torque for the switched reluctance generator, respectively. The efficiency of the switched reluctance generator is also found with the help of the formula below [29]:

$$Efficiency = \frac{P_o}{P_e + P_m} \tag{11}$$

In Equation (11), P_o, P_e, and P_m represent the output electrical power, existing electrical power, and mechanical power, respectively. The performance of an SRG is a significant factor, and a process is introduced that increase the performance of an SRG. By increasing the performance of an SRG improves efficiency and enhances power regulation. To practically enhance the performance, the turning angles of SRG are controlled. An adaptive gradient algorithm is utilized to achieve better control of the SRG turning angles. In this way, accurate power regulation can be achieved.

The combination of the control angles and the maximum efficiency is extracted via the sine cosine algorithm. To check the validity of the proposed method, a simulation is performed. In the process, there is no need for any complex process of formula derivation [30]. In the operation of an SRG, various conditions may arise. For the estimation of these conditions, a simplified current rise model is presented for SRGs. This model requires the characteristics of machine magnetization, and these characteristics are obtained via experimentation. To ensure accuracy, dividing the interval of the current rise into several small segments is advisable. To obtain better results, different segments are introduced, and the respective error is observed. For one segment, the factor of error is 20%, and when further increasing the segments, the error will decrease eventually. For five segments, the error will be reduced to 7%, and for ten segments, the error will be 6%. The proposed model is used with 5 and 10 segments to achieve good accuracy [31].

In power plants, different fuels are utilized. In these fuels, fossil fuel included, which is becoming a significant threat to human beings and for the environment. Several modern energy sources have attracted researchers. In these energies, wind power is included. The maximum use of wind power is studied, and the efficiency of an SRG is also observed [32]. The efficiency of an SRG could be controlled by controlling the firing angles. The particle swarm optimization approach was used to control the turn-off and turn-on angles. In the proposed approach, the concept of linear interpolation is also used. The firing angles are investigated, requiring a small amount of time for execution.

To better understand the practical results of this approach, the losses are considered. In the list of these losses, conduction, switching, and copper losses are included. All these losses are utilized in the process of simulation. MATLAB is used for the simulation of the proposed approach. In the simulation, a three-phase switched reluctance generator is utilized, demonstrating its potential applicability across various applications [32].

In the current SRG (switched reluctance generator), there are several issues. These issues include a low level of efficiency, the high vibration of the rotation of a single rotor, and high levels of noise. Due to these issues, a new generator is proposed, which is a deflectable double stator switched reluctance wind generator. This generator has a double stator structure. On both sides of the rotor, the hydraulic console is connected, and by using this console, deflection can be freely achieved. By using this generator, the direction of the wind could be changed as well as it could be used on different occasions for wind power generation [33]. The vibration displacement, stress, and increase in temperature could be ascertained via simulation. For the analysis of loss, a mathematical model is introduced. In the list of losses, a copper loss is significant, and it is reduced by decreasing the phase current. To improve the efficiency of this generator, a combination of turn-off and turn-on angles and a low-value phase current is used. In this way, the copper losses could be reduced significantly. This optimization approach is evaluated by comparing the before-optimization and after-optimization results. This approach demonstrates potential for achieving higher efficiency [33].

The occurrence of a fault is a common factor in switched reluctance generators. A new power converter is introduced that has the ability to tolerate the fault. The overall structure of this converter is simple, and in every working mode, a single transistor is used. Due to the low number of transistors, diagnosing a fault is very easy. An improvement approach is introduced to measure current. In this way, more information regarding the fault is obtained. The equations of current are obtained via the positions of the rotor and the current sensors. By solving these obtained equations, the phase current is obtained. Comparing the gate signal and current slope consistently allows for the determination of short circuit and open circuit faults [34]. To know the location of the fault, the relationships among the bus current magnitude, threshold, and phase current are compared. By using this fault-tolerant strategy facilitates the replacement of open circuit transistors. A simulation is performed to obtain the results for this approach. An experiment is also carried out to observe the results. The results indicate the identification of short circuit and open circuit faults of transistors through this approach. [34].

SRGs (switched reluctance generators) are used in different high-voltage applications. This type of generator is also used in different DC distribution systems that have voltages ranging from 270 V to 540 V. In these distribution systems, electric aircraft are also included. The control schemes are proposed for their use in electric air crafts [35]. SRGs (switched reluctance generators) are utilized in different applications. SRGs are also used in small-capacity wind power generating systems. These generators are installable on the rooftop. Since the wind power generating system is installed on a small portion of land, it has the capacity to generate electricity for a wide range of speeds.

This emf is generated at the lower speed of the generator. A specific approach is introduced that is used for the selection of a capacitor. For the selection of the capacitor's value, there are several factors. In these factors, the voltage magnitude of the SRG, the plot of flux linkage variation with the position of the rotor and current, the reactive power requirement, and the voltage ripple at the output of the SRG are included. At the very initial step, the equations for the SRG are obtained. The value of the capacitor is then determined with the reactive power requirement and voltage ripple. These factors are verified with the help of simulation and experimental results. These simulations and experiments are performed for different of wind velocity conditions. A closed-loop control system is introduced that increases the power-harnessing process of the SRG [36]. In the proposed process, the phase current reference value is adjusted and, in this way, the generator produces power with full potential.

In this process, any wind velocity is used to obtain the maximum power from the SRG. A simulation is performed to ascertain the exact facts regarding the proposed approach. An experiment is also performed to obtain the experimental results for the same approach. The results suggest that the proposed approach effectively attains full power from the SRG. [36].

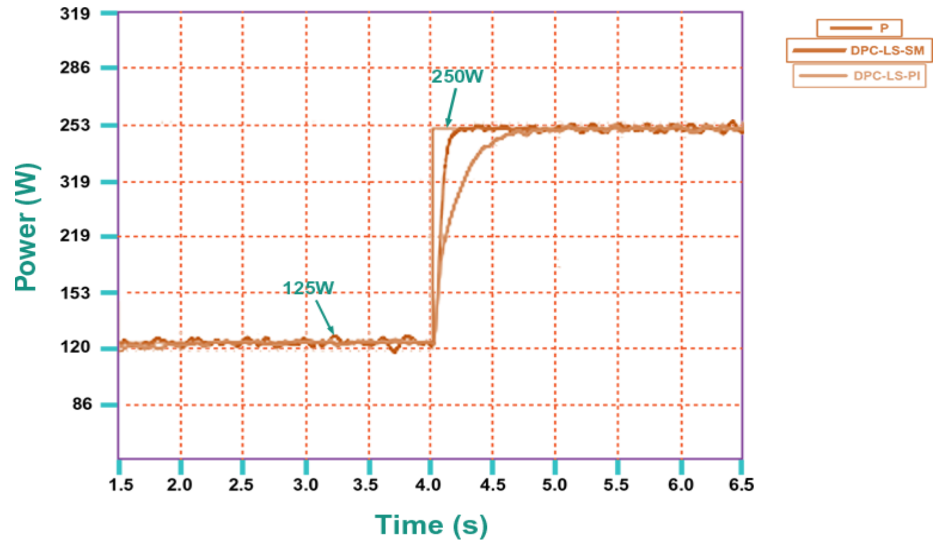
3. Results

The results of this review paper are expressed in the form of a table which is shown in the section below. In the Results section, a significant part is the transient voltage load response, as shown in Table 1.

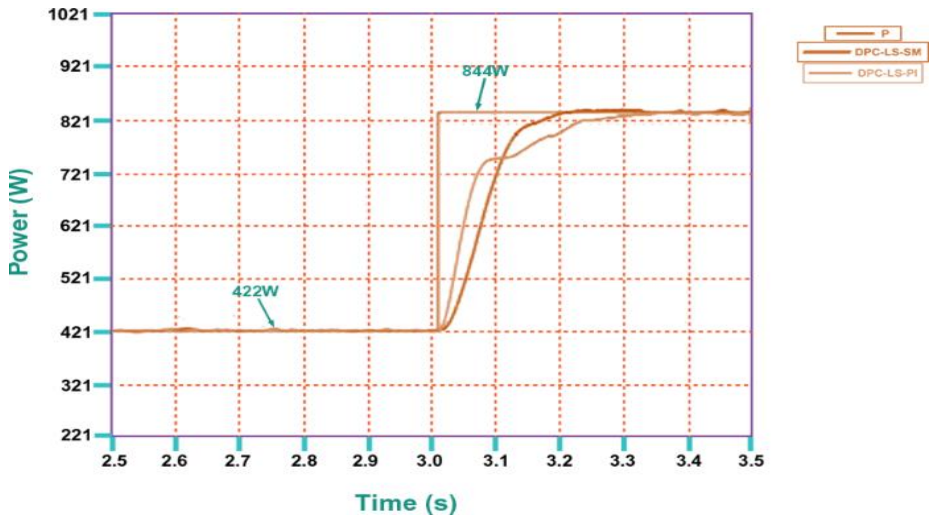
Table 1. Comparison table for SRGs.

Offset angle	Variation of speed	Decrease in loss	Efficiency	Reduction in voltage transient	Output Voltage	Torque Ripple	Reduction in capacitor size	Output rating	Reference
-	-	-	75%	-	400V (DC	-9N.m	-	2000W	[3]
-	36,000r/m	Ignored.	-	23%	270V (DC)	-	-	29KW	[4]
-	6000r/m	Ignored.	-	-	400V (DC)	-	-	-	[5]
-	7500r/m	-	88.5%	-	350V	6.3N.m	60%	20kW	[6]
-	400r/m	-	85.76%	-	60V	10N.m	-	2.57kW	[9]
-	900r/m	-	-	-	400V (DC)	-	-	400W	[10]
-	1500r/m	-	-	-	400V (DC)	-	-	3.7kW	[11]
5 degrees	200r/m	20%	5-8% increase	-	380V	70N.m	-	2.5kW	[12]
	954r/m	-	-	-	270V	-	-	-	[13]
8 degrees	6000r/m	-	-	-	100V	-	-	-	[14]
-	800r/m	-	-	-	-	-	-	-	[15]
45 degrees	2000r/m	-	-	-	250V	-	-	-	[20]

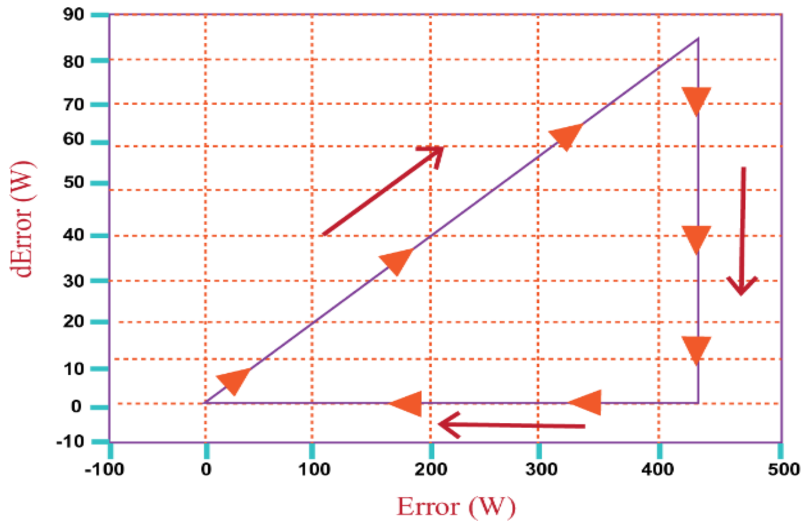
In this section, different resources are utilized and all of these resources are about the different characteristic parameters of SRG. In these resources, the different applications of SRG are also observed. The main points of these resources are presented and compared also in the form of a table. The simulations and experimental results are shown in Figure 7 and Figure 8, respectively.



(a)

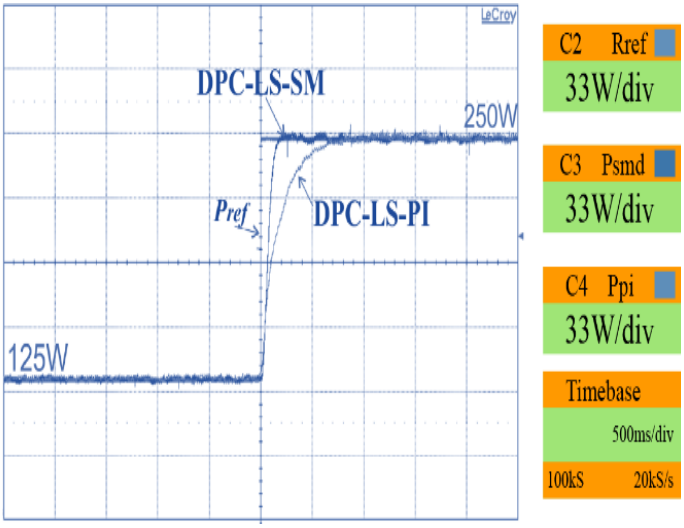


(b)

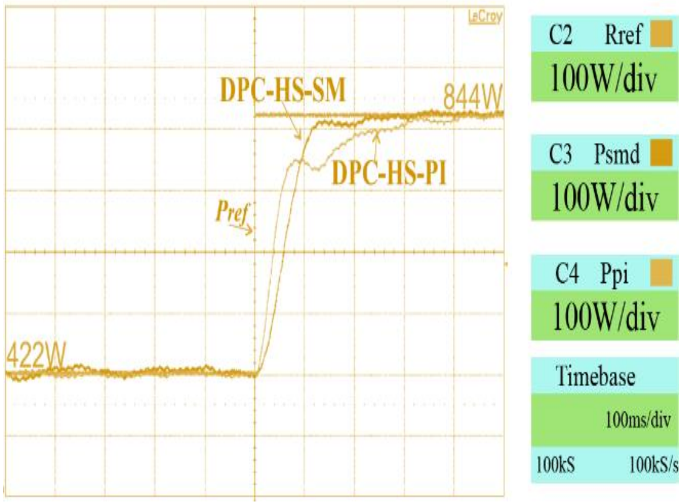


(c)

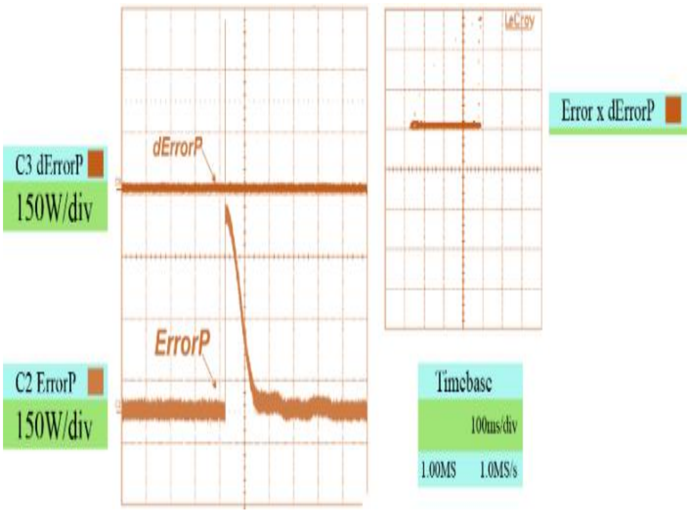
Figure 7. (a, b, c). Simulation results [10].



(a)



(b)



(c)

Figure 8. Experimental results [10].

4. Discussion

All of the past works are observed in-depth and all of these works are also compared. In the comparison, the findings of all the past works are used. A deep discussion is made on these findings and that discussion are also shown in the form of a comparison table. In all the resources, the different parameters are extracted and all of these parameters are shown in the comparison table. So, that a better review can be made regarding the topic. In [1], an in-depth study is made on SRG, and the internal structure of SRG is observed. It is found that the manufacturing cost of SRG is low because in SRG, the rotor did not have windings. Instead, it was typically made of a magnetic material and designed with teeth or poles that interacted with the stator's windings. The stator contained multiple windings that created electromagnetic fields. SRG is having oscillations and due to these oscillations, there is an issue with power quality. In [3], the different applications of SRG are discussed with examples. In the list of these applications, the wind energy conversion system is an important one. The overall efficiency of the proposed system is found to be 75%. The bus voltages are 400V, the respective power rating is 2000W and the torque ripple is 9Nm.

In [4], a solution is presented for the lower quality of power. The approach that is used in [4], is the pre-processing of voltage ripple. By using the proposed approach, a reasonable decrease in the voltage ripple is found and that is almost 23%. The power rating is 29kW, the speed is 36,000r/m and the losses are ignored. In [5], a voltage measurement is considered to be a vital ingredient in all the processes. The output voltages of the proposed circuit are 400V DC and the speed is 6000r/m. In SRG, there are current oscillations that causes a power quality issue. Normally, a capacitor with a higher rating is used to deal with the current oscillations. In [6], an approach is introduced that reduces the high size of the capacitor. Using the approach reduces the overall size of a capacitor by 60%. The efficiency is 88.5%, the respective speed is 7500r/m and the torque ripple is 6.3N.m.

In [7], upon examining the internal structure of the SRG, it is evident that the rotor does not contain windings; rather, it holds a rectifier for DC conversion. However, there exist two distinct configurations within the rotor. The symmetric configuration yields greater generated power compared to the asymmetric setup. Both these attributes can be regulated through the manipulation of switching angles. These angles are established through simulation, ensuring the desired speed and power output. This method effectively achieves the targeted speed and power levels as required.

In [9], a new approach is introduced to improve the efficiency of DDSRG. By the proposed approach, 85.7% efficiency is obtained. The value of output power in the system is 2.5kW. The torque ripple is 10Nm and the speed is 400r/m. Permanent magnet synchronous motors are traditionally used. A permanent magnet synchronous motor has higher efficiency and lower ripple torque. On the other hand, a switch reluctance generator is having a simple structure and lower cost. So, it is preferred on permanent magnet synchronous motors. The requirement for maintenance is low for SRG. SRG is also having high reliability as compared to permanent magnet synchronous motor. Due to these factors, SRG is preferred over permanent magnet switching motors.

In [10], the benefits of DDSRG are discussed and due to these benefits, it is utilized in different applications. It is also used in wind turbines due to its benefits. It is having a double salient structure and the operational cost of DDSRG is also low. This generator is also resistant to faults. Due to all of these benefits, it is preferred in different applications. This system has a speed of 900 r/m and the output power of this system is 400W.

In [11], a new model of SRG is introduced, which is known as DDSRG. The advantages of this switched reluctance generator are observed. The vibration characteristics of DDSRG are also analysed in-depth. For this analysis, the simulation approach is selected and the experiment is also performed for the verification purpose. The results of the simulation and experiment are the same as well as, they are positive.

In [12], DSSRG (Dual stator reluctance generator) is observed due to its usage in an underwater generation. Utilizing DSSRG significantly boosts the generator's efficiency. For simulation purposes, CFX software is used. In [12], modeling and analysis of DSSRG are also done.

In [13], the types of SRG are discussed and in these types, DDSRG is also included. This type is more efficient than the normal ones. The increase that is found in the efficiency is from 5 to 8% and the speed of the system is 200 r/m. Torque ripple is 70Nm for DDSRG. For this study, the angle of offset is 5 degrees for DDSRG. In this case, the losses are reduced to 20% and as a result, the efficiency is increased.

In [14], the advantages of SRG are discussed in-depth and due to these advantages, SRG is utilized in the different applications. For the operation of SRG, a small value of input voltage is required. That's why, the buck converter is also utilized with the generator. Due to these specified benefits, SRG is preferred in different applications. The value of the output voltage for this system is 400V DC. The output power is 3.7kW and the speed is 1500r/m

In [15], a new model is introduced for SRG, that is having the combination of several segments. The introduced model is three phases of self-excited SRG. In the structure, there are three pairs of stators and two pairs of rotors.

The value of output voltage in [15], is 270V and the speed is 954r/m. A separate language is also introduced for the working of this generator. In [16], the approach to get high efficiency is introduced and that is practically done by the excitation angle. By the excitation angle, the value of copper losses is reduced and as a result, the efficiency could be improved. The simulation is also done for the proposed approach and the speed of the system is 6000r/m. In [17], the approach for increasing the generation capacity is introduced. The speed of a switched reluctance generator (SRG) that is connected in parallel can vary but is often within the lower range of RPMs. In SRGs configured in parallel, the minimum speed might be around 400 to 800 RPM or even lower, depending on the specific design, starting torque, and operational requirements. In the approach, several SRGs are connected in the parallel configuration. In this way, the generation capacity of the system could be improved as well and the reliability of the system could also be enhanced. The speed of the proposed system is 800r/m and that is due to the parallel configuration of SRGs. The angles of control are significant in defining the maximum efficiency of the SRG.

In [18], these angles are obtained using the approach of particle swarm optimization. Simulation is also performed for the system. By the results, maximum efficiency is obtained from the system. In [19], the advantages of SRG are expressed. In these advantages, low cost, robust system, and simple structure are included. Due to these advantages, it is utilized in wind energy conversion systems. In [20], a new type of SRG is introduced that is known as MCSRG. This new type of generator has a higher value of average current. According to the results, this new generator is having 13% more current than simple SRG. The losses are also lesser MCSRG as compared to the simple SRG. In [21], a wave energy conversion system is introduced and this system could generate clean energy at the sea. In [22], the hysteresis current control approach is introduced and this approach is used in three-phase SRG. By using the proposed approach, the improvement in efficiency is seen. The speed of the proposed system is 2000 r/m and the offset angle is 45 degrees.

According to [23], SRG is utilized for making wind energy conversion systems. By using SRG, the effectiveness of the system is increased. In [24], a new braking system is introduced to increase the performance of vehicle driving as well and it is effective for increasing the life cycle of the battery. In [25], SRG is introduced as a vital component for feeding the DC load with almost 80% efficiency. In [26], a new algorithm is introduced for SRG and this algorithm has the capability to rank the different solutions. By this algorithm, the concept of decision-making is improved significantly. In [27], a wind SRG-based microgrid system is introduced, that has a wide range of power. The power flow in the system is continuous at all stages of the system.

In [28], the physical characteristics of SRG are observed and in these characteristics, the controlling operation of SRG is also observed. In [29], the characteristics of SRG are observed by using the software. This method allows for a more thorough analysis of SRG characteristics. The performance factor of SRG is significant. Efficiency and power regulation are the key ingredients of SRG. Improving these factors enhances the overall performance of SRGs. With the help of simulation, the performance of SRG is verified and that is reasonable [29]. There are different working conditions for SRG and the factor of accuracy in SRG functioning is crucial. To estimate these practical conditions, the current rise model is introduced.

To get accuracy, the interval of the current rise is divided into segments. By the concept of segments, the accuracy is enhanced and the respective error is almost ignorable at 10 segments [31]. Wind power is a significant source of power and it is discussed in [32]. In [32], the efficiency of SRG is also discussed in complete detail. The efficiency of SRG is directly linked with the firing angles. For the simulation, MATLAB is used.

In [33], a new generator is proposed due to the current issues of SRG and this generator is a deflectable double stator switched reluctance generator. This generator has a simple structure. In [33], an approach is proposed that can improve the efficiency of the generator as well as it can reduce the copper losses of the generator. In SRG, the faults are very common and in [34], a new power converter is proposed. This power converter has a significant resistance to faults. The current sensors and rotor positions determine current equations, enabling the identification of short circuit and open circuit faults.

In [35], the high voltage applications of SRG (switched reluctance generator) are discussed. SRG is also used in high DC distribution systems like electric aircraft systems. In [36], the closed loop system is introduced that completely harness the power of SRG. For observing the results, simulations, and experiments are done.

5. Conclusions

Switch reluctance generator is becoming famous in theoretical as well as practical applications. It is used for wind power generation and also for variable speed applications. It's utilized in wind turbines and electric vehicles as well. There are several benefits of using SRG (switched reluctance generator) and that is why, it is preferred in different applications. In the review paper, the current research on SRG is discussed in complete detail. The structure of SRG is very simple and it is just having a single winding at the stator. SRG is also used in the wind energy conversion system for the generation of power. By using the low pass filter, the quality issues of SRG are solved. A boost converter is used in SRG for decreasing the oscillations. In SRG, the controlling of voltages and speed is done by using the switching angle. The efficiency of DDSRG (Deflection dual stator reluctance generator) is enhanced by up to 85%.

There are different types of switched reluctance generators and in these types, three-phase self-excited SRG is also included. In DDSRG, the efficiency of the generator is also increased from 5 to 8% with the wind direction and turbine offset angles reduced by 5 degrees. Reducing wind direction and adjusting turbine offset angles decrease aerodynamic losses in wind turbines. By aligning the turbine more accurately with the wind and optimizing the angle at which the blades intercept airflow, there is a reduction in aerodynamic drag, improving the overall efficiency of the generator. This alignment and adjustment enable the turbine to capture more wind energy, minimizing energy losses that might occur due to inefficient blade orientation. In this scenario, the losses are reduced to 20% and as a result, the efficiency is improved. By the excitation angle, the efficiency of SRG is increased significantly. By the parallel configuration of several SRGs, the generation capacity increases. The particle swarm approach determines the control angles. By these control angles, the maximum efficiency of SRG is obtained. MCSRG (Mutually coupled SRG) is a new type of SRG, that has a higher average current and it is also having lower losses. Wave energy conversion system is introduced as a clean form of energy. SRG is a key ingredient of the wind energy conversion system. By using the different approaches, the efficiency of SRG is increased.

A microgrid system is also introduced, that is having SRG as a vital element. The characteristics and controlling operations of SRG are observed. To increase the output power, new approaches are introduced. For the simulation of SRG, Simulink is used as a significant resource. In the types of SRG, DSSRG is also included and it is used for the generation of power underwater. Due to all of these benefits, SRG is used in different applications. In this effort, the research was on the structure of SRG, its types, and its efficiency. SRG is used in hybrid power generation approaches as well. In the future, conducting this study can enhance the significance of SRG, highlighting the ongoing need for its development.

Table of acronyms

Abbreviations	Full form
SRG	Switched Reluctance Generator
PMSM	Permanent Magnet Synchronous Motor
DDSRG	Deflection Dual Stator Switched Reluctance Generator
MCSRG	Mutually Coupled Switched Reluctance Generator

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