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Optimization of Disk-Type External Rotor SRGs for Wind Power Generation

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Abstract— In small-scale wind power generation, the disk-type external rotor switched reluctance generator (SRG) emerges as a promising innovation, offering distinct advantages. This comprehensive study, through rigorous steady-state and dynamic simulations, meticulously examines the performance of a carefully designed disk-type external rotor SRG using advanced finite element analysis tools such as Maxwell and Simplorer. The simulation results validate the excellence of this novel design, demonstrating its capability to achieve commendable power generation in both steady-state and dynamic scenarios. The simulations provide strong evidence of the generator's ability to maintain stability under varying operational conditions while consistently delivering promising power generation. This research contributes to the validation and recognition of the disk-type external rotor SRG as a reliable and efficient solution in direct-drive wind power systems. By highlighting the generator's robustness and efficiency, this study paves the way for the adoption of this innovative SRG design in practical applications, advancing wind power generation technology.

Keywords: Current signal, PSCAD simulation, Solar Photovoltaic.

INTRODUCTION

Switched reluctance generators (SRGs) have gained popularity due to their numerous advantages over traditional generators. They are preferred over permanent magnet synchronous motors because they can manage higher torque ripples. SRGs have a double salient structure, a complex rectifier circuit, and low maintenance costs. They use permanent magnets in the rotor, reducing winding needs and increasing fault tolerance. The absence of permanent magnets and windings on the rotor, along with the machine's robustness and ability to operate over a wide speed range, make the SRG a good candidate for variable speed applications. However, the generating operation of the SRG is still under study, and further research is required to improve its performance and acceptance [1]. Switched reluctance generators (SRGs) operate based on magnetic flux principles, following paths of least reluctance. These innovative machines offer advantages such as high-power density, efficiency, and robustness, making them suitable for wind and marine power, electric vehicles, and renewable energy applications. Compared to traditional generators, SRGs have lower costs, superior efficiency, and effectiveness due to their lack of magnets and robust design.

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Research is ongoing further to improve SRG performance and acceptance, particularly in variable-speed applications [2].

The Switched Reluctance Generator (SRG) boasts a streamlined design with stator-only windings, reducing copper losses for heightened power efficiency. The Disc Outer-rotator SRG (DOSRG) directly connects to wind turbines, optimizing transmission efficiency in direct-drive wind power systems. This fusion of simplicity and effectiveness in energy generation offers several advantages, including high power density, efficiency, and robustness. The DOSRG's stator-only windings and absence of permanent magnets on the rotator reduce costs and increase fault tolerance, making it a promising candidate for variable-speed applications in wind and marine power, electric vehicles, and renewable energy [3]. Switched Reluctance Generators (SRGs) feature a streamlined design with stator-only windings, reducing copper losses for enhanced power efficiency. The Disc Outer-rotator SRG (DOSRG) directly connects to wind turbines, optimizing transmission efficiency in direct-drive wind power systems. SRGs share windings for excitation and power generation, controlled via a power converter, ensuring efficient time-sharing regulation. This cooperative system ensures robust fault tolerance, harmoniously balancing excitation and generation efforts. SRGs output DC directly through the power converter, enabling remote control without an inverter. DC transmission over long distances reduces energy loss [4].

Switched Reluctance Generators (SRGs) have been mass-produced and used in various applications, such as small-scale wind turbines for decentralized power generation. Their simplicity, robustness, and ability to operate in variable wind conditions make them suitable for off-grid or remote locations. Exhaust gas energy recovery systems use SRGs to capture waste heat from exhaust gases and convert it into electrical energy. They are lightweight, can withstand high temperatures, and contribute to reducing environmental impact. Thermal management and integration with heat exchangers and control systems are important for optimal operation [5]. Researchers have introduced a boost converter to enhance Switched Reluctance Generators' (SRGs) performance. This approach eliminates the need for high-rated capacitors, reducing oscillations and the overall capacitor rating. A boost converter actively filters the SRG's current, improving efficiency and reducing energy loss [6]. The stator windings use a rectifier to obtain DC voltage. There are two observed topologies for the stator winding, known as asymmetric and symmetric configurations, which have different polarities. Observing the line voltages of both configurations in an open circuit reveals that the symmetric topology has higher power compared to the asymmetric topology. Additionally, in the symmetric configuration, the value of the iron loss is also higher [7]. For high-speed applications, engineers utilize the SRG. This assessment is performed by performing the simulation [8].

Switched Reluctance Generators (SRGs) operate efficiently with low input voltages, making them ideal for wind energy systems. However, SRGs have issues with power quality due to undesirable oscillations that affect their performance. To address this, researchers have proposed a methodology based on in-loop filtration to improve power quality. This approach aims to decrease voltage oscillations by using moving average filters and notch-cascading filters. Reducing these ripples improves power quality and optimizes the SRG's performance. The proposed approach eliminates the need for high-rated capacitors, reducing overall costs and improving efficiency [9]. A highly efficient type of Switched Reluctance Generator (SRG)

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is the Deflection Dual Stator SRG. This innovative generator design offers superior performance and potential for improved energy conversion applications [10].

A new Switched Reluctance Generator (SRG) model includes a rotor, stator, current chopper, PID controller, and power converter. Modelica captures the SRG's complex non-linear characteristics as the modeling language. The rotator's position and stator current determine the machine's flux linkage, while the rotator's position and stator current affect the electromagnetic torque. To represent non-linear characteristics, we use function approximation and finite element methods. We conduct simulations for both methods and compare the results. The model is a three-phase self-excited SRG, consisting of three pairs of stators and two pairs of rotators [11]. A simple simulation model for Switched Reluctance Generators (SRGs) helps in wind power and other applications. To achieve high power efficiency, a control method is introduced that includes an excitation angle condition for the SRG. This condition reduces copper losses and improves generation efficiency. The excited current waveforms fall into three categories, linking to power generation efficiency, energy conversion, and copper loss. By optimizing the excited current waveforms and excitation angle, high-efficiency power generation can be achieved [12].

The simulations use parallel configurations of Switched Reluctance Generators (SRGs) to produce the desired results. This setup compares with traditional current-sharing methods. [13]. A new method, optimal control theory, regulates power and improves efficiency in Switched Reluctance Generators (SRGs). This approach is applied to SRGs used in aircraft power systems. The gradient descent approach finds various angles, including turning-off angles, turning-on angles, and zero voltage angles, to regulate power. Particle swarm optimization is used to determine the control angles that maximize efficiency. Simulations verify the results. The proposed approach improves power generation efficiency by reducing copper losses and optimizing excited current waveforms and excitation angles [14]. Switched Reluctance Generators (SRGs) are gaining popularity due to their simple structure, cost-effectiveness, and robust operation. Unlike traditional generators, SRGs lack rotor windings, making them ideal for wind energy systems. The converter is a vital component of the system, and a modified design with fewer active switches and lower production costs has been introduced. Simulations validate the performance of this modified converter. Advanced control methods like optimal control theory and particle swarm optimization improve SRG efficiency and stability in different conditions. SRGs power aircraft systems and demonstrate their versatility. Simulations verify the findings and confirm the proposed designs' accuracy. [15].

The electromagnetic characteristics of a Switched Reluctance Generator (SRG) have been studied, and a new type of SRG, known as a Mutually Coupled SRG (MCSRG), has been introduced. 2D models using ANSYS are employed to create the structures of both the typical SRG and the MCSRG, and their working parameters are observed. Different forms of windings are utilized in the structures of these SRGs. The torque, current characteristics, and core losses for the complete excitation cycle are determined for both types. A comparison reveals that the MCSRG exhibits a higher average current, with an average value 13% greater than that of the typical SRG. Additionally, the ripple is 1% lower for the MCSRG compared to the typical SRG, and the core loss factor for the MCSRG is 1% less than that of the typical SRG. Furthermore, the input torque requirement is 10% less for the MCSRG than for the typical SRG. Based on these results, it can be concluded that the MCSRG is preferred for various applications.

The study provides valuable insights into the performance differences between the typical SRG and the newly introduced MCSRG, highlighting the potential advantages of the latter in terms of current characteristics, core losses, and input torque requirements. These findings contribute to a better understanding of the capabilities and suitability of the MCSRG for specific application scenarios [16]. The hysteresis current control approach is introduced for three-

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phase Switched Reluctance Generators (SRGs), utilizing a non-linear inductance model. Finite Element Analysis (FEA) is employed to analyze the electromagnetic field during the development of wind energy conversion systems. The non-linear characteristics of SRGs are investigated, along with the examination of power converters' properties. An asymmetric half-bridge topology is adopted for constructing the converter circuit. Two control strategies are introduced: one focuses on angle control, while another employs current choppers. Through these approaches, the behavior of SRGs, their modeling, and simulation are demonstrated, leading to various output characteristics and potentially higher efficiencies [17].

Switched Reluctance Generators (SRGs) have various applications, including wind energy conversion systems, where SRG converters play a crucial role. The structure and different topologies of these converters are being studied to enhance system efficiency. The research aims to introduce advanced control approaches for SRGs, to establish wind generation systems based on SRGs as effective and reliable systems [18]. Additionally, SRGs are also utilized in the automotive industry and aerospace. The evolution of wind power is also presented in Figure 1.

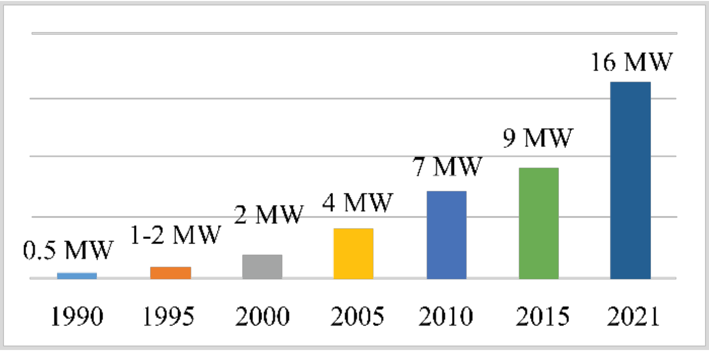

Figure 1. Evolution of Wind power

Switched Reluctance Generators (SRGs) serve as critical components within the regenerative braking systems of electric vehicles. During braking, SRGs generate electricity from the kinetic energy, which is stored in batteries for later use. This feature enhances overall efficiency and extends the driving range of electric vehicles. The SRG-based braking system is engineered with considerations for safety, braking energy, and high and low-speed conditions. Its implementation leads to smoother torque and current profiles, thereby improving battery life and providing a comfortable braking experience. In summary, SRGs are integral to the regenerative braking systems of electric vehicles, offering numerous benefits such as improved efficiency, extended driving ranges, and safer, more comfortable braking experiences. The technology leverages the unique characteristics of SRGs to recover energy during braking, thus contributing to a greener transportation future [19]. Switched Reluctance Generators (SRGs) are utilized to create low-voltage DC grids with enhanced efficiency. Through simulations and experiments, the SRG's performance is evaluated while connected to a resistive load and operated at various rotational speeds. The results indicate that the drive achieves an efficiency of approximately 70% at 1500 RPM. Under normal loads, the efficiency improves to almost 80%. These findings demonstrate the potential of SRGs to significantly improve the efficiency of low-voltage DC grids, making them a promising technology for various applications [20]. A microgrid exclusively powered by wind-based Switched Reluctance

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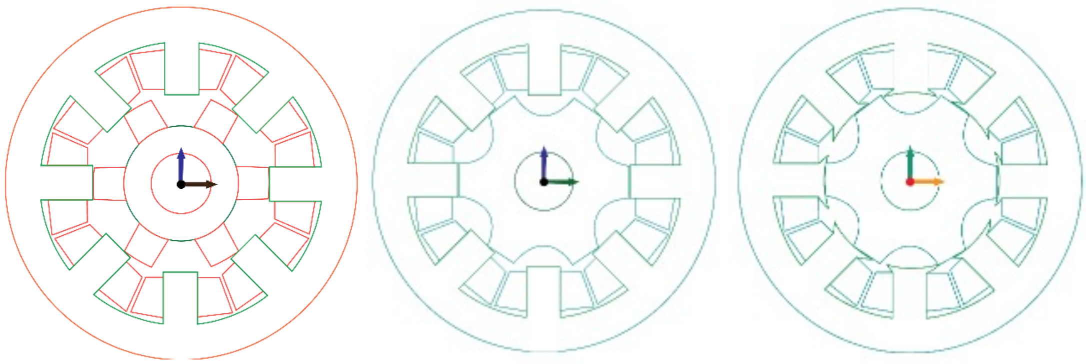
Generators (SRGs) is observed. The sections covering SRG design and control reveal the capability to produce a broad spectrum of power while simultaneously enhancing efficiency. Impressive voltage regulation characteristics are noted throughout the microgrid system. Power flows continuously among all stages, with SRGs ranging from 0.5 kilowatts (kW) up to 5 megawatts (MW).

These findings suggest that SRGs offer a viable solution for developing clean, flexible, and scalable microgrid architectures. The technology's inherent simplicity, combined with advanced control strategies, makes it possible to integrate SRGs effectively into diverse microgrid settings, ultimately promoting renewable energy adoption and sustainability goals [21]. Switched Reluctance Generators (SRGs) are essential components in renewable energy applications, particularly in wind energy conversion systems. The switching angles for the rotor and stator are extracted to ensure effective SRG operation. The converter plays a vital role in the system's efficiency, and the SRG inductance profile is analyzed to extract the switching angle. Infolytica MagNet software is used to conduct an in-depth analysis of the SRG, with the generator run at a constant speed and a 0.5mm air gap length. Cold-rolled steel is used as the specific material, and the generator is dimensioned according to the material's B-H curve. The SRG is excited by a voltage source, and the generated power is transferred to the load accordingly. These findings demonstrate the potential of SRGs to improve the efficiency of renewable energy systems, making them a promising technology for various applications. The technology's inherent simplicity, combined with advanced control strategies, makes it possible to integrate SRGs effectively into diverse renewable energy settings, ultimately promoting sustainability goals [22].



(a) (b) (c)

Figure 2 (a) General rotor structure **(b)** Curved rotor structure **(c)** Curved Rotor Structure with Pole Shoe

An Adaptive Gradient Algorithm is employed to gain better control over Switched Reluctance Generator (SRG) turning angles, thereby achieving accurate power regulation. The Sine Cosine algorithm is used to extract the combination of control angles and maximum efficiency. No complex formulas require derivation in this process. The validity of the proposed method is checked through simulations. This approach highlights the potential of SRGs to improve the efficiency of renewable energy systems, making them a promising technology for various applications. The technology's inherent simplicity, combined with advanced control strategies, makes it possible to integrate SRGs effectively into diverse renewable energy settings, ultimately promoting sustainability goals [23]. A simplified current rise model is proposed for Switched Reluctance Generators (SRGs) to estimate different operational conditions. This model relies on machine magnetization characteristics obtained through experimentation. To enhance accuracy, the current rise interval is divided into small segments. The introduction of multiple segments reduces the associated error, with a 20% error for 1 segment, 7% for 5

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segments, and 6% for 10 segments. The proposed model utilizes 5 and 10 segments to achieve greater accuracy [24]. Simulations can be used to obtain data on vibration displacement, stress, and temperature rise in Switched Reluctance Generators (SRGs). A mathematical model is introduced to analyze losses, with copper loss being a significant factor that can be reduced by decreasing phase current. To improve SRG efficiency, a combination of turn-off and turn-on angles, along with low phase current, is used to significantly reduce copper losses. This optimization approach is evaluated by comparing results before and after optimization, demonstrating its potential to increase efficiency [25]. SRG (Switched reluctance generator) is used in various applications, including wind energy conversion systems. SRG can be installed on rooftops and can generate electricity for a wide range of wind speeds. A specific approach is introduced for the selection of a capacitor, which requires the characteristics of machine magnetization obtained through experimentation. Equations for SRG are obtained, and the value of the capacitor is determined with the requirement of reactive power and voltage ripple. A closed-loop control system is introduced to increase the power-harnessing process of SRG. Simulations and experiments are performed at different conditions of wind velocity to verify the factors of voltage magnitude, flux linkage variation, current requirement, and voltage ripple. The potential of SRG in wind energy conversion systems is still being researched, and further research is required before it can be established as an effective system [26].

METHOD

Finite Element Analysis (FEA) for switched reluctance generators represents a groundbreaking foray into understanding the intricate magnetic dynamics governing these innovative machines. By employing FEA, a virtual realm opens, allowing an in-depth exploration of magnetic fields, flux distribution, and performance characteristics within the generator's architecture. This method unveils a mesmerizing tapestry of forces and energies, unveiling the secrets behind optimal power generation and efficiency. It's akin to unraveling the veils of the unseen, offering a visual symphony of magnetic interactions and behaviors, empowering engineers to fine-tune designs for maximum efficacy and minimal losses. The precision and detail offered by FEA propel the understanding of these generators, forging paths toward heightened performance, reliability, and sustainability in the realm of electrical power generation [27].

A. Model Creation and Analysis

Utilizing AutoCAD, a 2D model of the motor is meticulously crafted to match specified criteria and then imported for analysis. The static magnetic field analysis in Maxwell explores distinct positions within the motor, revealing magnetic field line distributions at key locations; Rotor pole leading edge coinciding with the fixed position, Sub-pole leading edge alignment with the fixed position, alignment of stator and rotor pole center lines, minimum inductance position where the rotor and stator pole centerlines align, rotor pole leading edge alignment with the stator pole center line [28].

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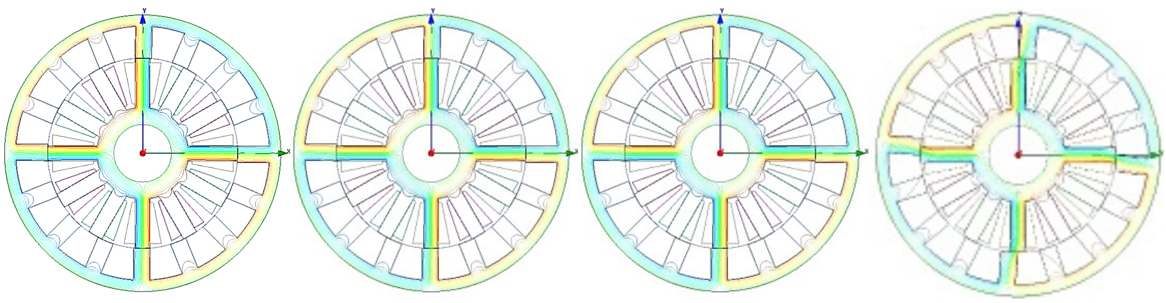
Figure 3. 12/16-pole DOSRG finite element 2D model diagram

B. Modeling and Structure Overview:

The study employs Maxwell finite element analysis to examine a structured three-phase 16/12-pole switched reluctance generator. This model integrates the motor and power conversion device, detailed in Figure 4. Essential motor parameters are outlined in Table 1.



(a) (b) (c) (d)

Figure 4. Magnetic field line distribution diagram

(a) Alignment position of stator and rotor poles (**b)** Alignment position of stator and rotor pole center lines (**c)** Stator and rotor tooth slot centerline alignment position (**d)** Rotor pole leading edge and stator pole center line coincidence position

C. Magnetic Field Behavior

At maximum inductance position (when rotor and stator poles are aligned), the magnetic flux distribution demonstrates minimal leakage, portraying a relatively coherent magnetic field. However, as rotor and stator poles gradually separate, magnetic flux leakage escalate noticeably, peaking when poles align again. The analysis highlights critical points in the magnetic field behavior of the switched reluctance generator, emphasizing the significance of aligned positions for optimal magnetic flux distribution and minimal leakage.

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Table 1. Motor Basic Parameters

Number	Appearance		
	Parameters	**Optimized**	**Unit**
1	Electrical load A	30000	A/m
2	Magnetic load	0.45	T
3	Number of stator poles	12	
4	Number of rotor poles	16	
5	Phase number	3	
6	Stator outer diameter	336	mm
7	Rotor outer diameter	482	mm
8	Stator pole arc βs	9.1	degree
9	Rotor polar arc βr	9.8	degree
10	Core length	27.1	mm
11	Stator yoke height	27.9	mm
12	Rotor yoke height	25.1	mm
13	Single phase series turns	556	
14	Number of turns per pole	139	
15	First air gap g1	0.52	
16	Second air gap g2	55.7	
17	Shaft diameter	100	mm
18	Conduction angle	7.49	Degree (mechanical angle)
19	Slot full rate	About 43%	

RESULT AND DISCUSSION

This section delves into the intricacies of dynamic modeling and simulation specifically tailored for the Disc Outer-Rotor Switched Reluctance Generator (DOSRG). It explores the virtual construction of a dynamic model mimicking real-world behavior and simulates its operations. By leveraging advanced simulation techniques, this segment aims to unveil the system's dynamic responses, providing valuable insights into its operational dynamics and performance characteristics. The integration of Maxwell and Simplorer is pivotal for a comprehensive understanding of the DOSRG system. Maxwell's finesse in modeling the motor body and Simplorer's simulation capabilities create a cohesive platform to analyze the dynamic interplay between the generator and its power conversion components [29]. Motor Model Construction: Leveraging Maxwell, a detailed model of the motor body is constructed, capturing its intricate structure and magnetic behaviors. Power Converter Setup: The power conversion setup includes IGBTs for switch tubes, diode modules for freewheeling, and a 19.36Ω resistor load. Figure 5 visualizes this setup, outlining its critical elements.

Motor Control Strategy: The control strategy revolves around precise manipulation of IGBTs, ensuring synchronized activation and deactivation of motor phases for effective control. Operational Sequence: Operating within a 3-phase 12/16 structure, the system follows a single-phase conduction sequence to maintain motor functionality. Current Regulation: To prevent motor damage due to excessive current, a current chopper is implemented, controlling current within safe thresholds. Limits Setting: Setting upper and lower chopping limits at 30A and 29A respectively provides an additional layer of protection for the system. Dynamic

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Operation: Through the integrated simulation, the synchronized phase control and current regulation dynamics become clearer, offering insights into the system's operational behavior. Operational Integrity: The simulation unravels the intricate interplay between components, offering critical insights for ensuring robust performance and operational integrity of the DOSRG system. The joint simulation platform of Maxwell and Simplorer provides a comprehensive analysis of the DOSRG system, capturing motor phase current, load voltage, copper loss, and iron loss. Figures 6 to 9 depict the simulation results, showcasing a detailed view of the system's behavior.

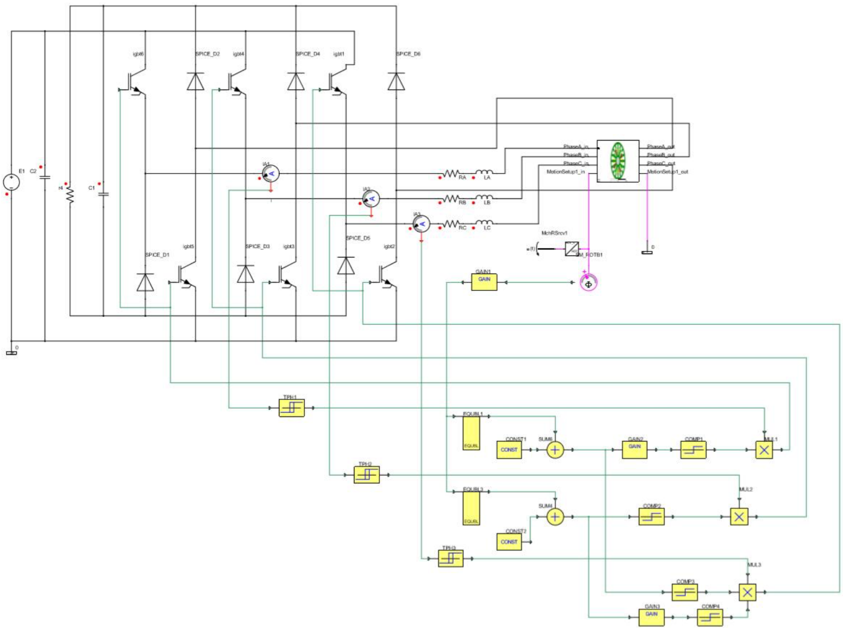

Figure 5. SRG Power Converter and Commutation Circuit

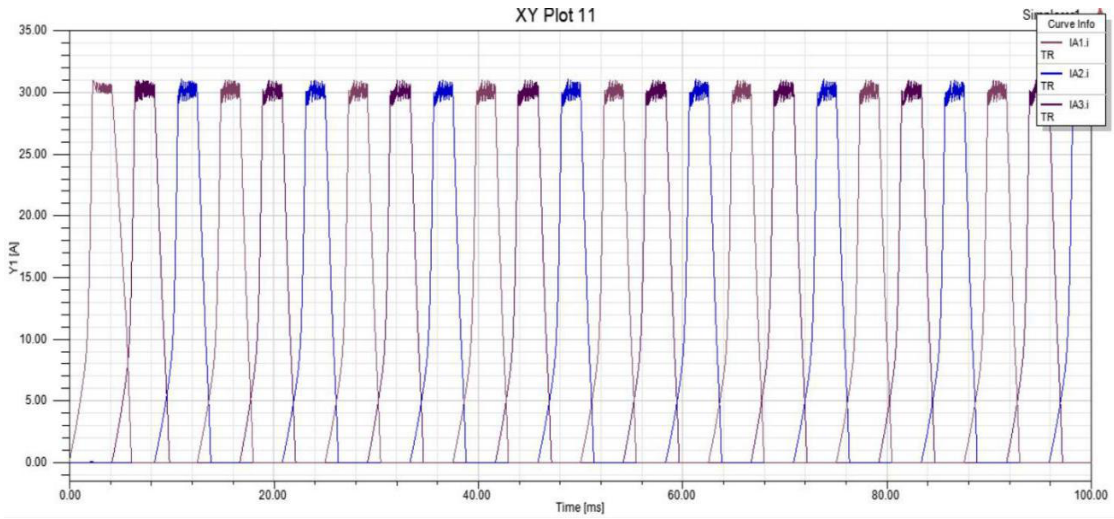

Figure 6. Co-simulation phase current waveform

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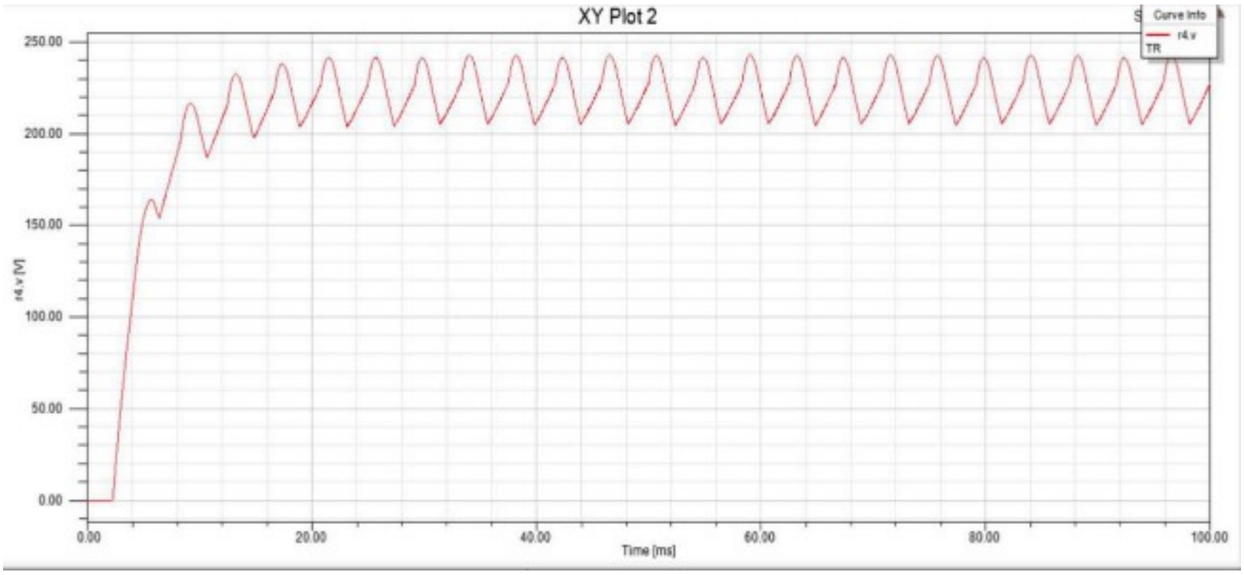

Figure 7. Co-simulation load voltage waveform

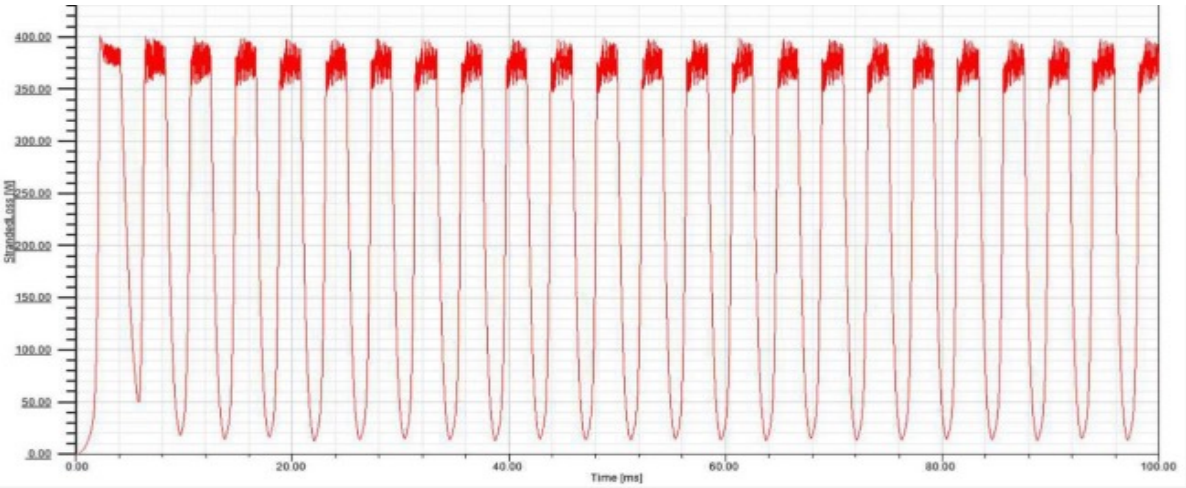

Figure 8. Co-simulation copper loss waveform

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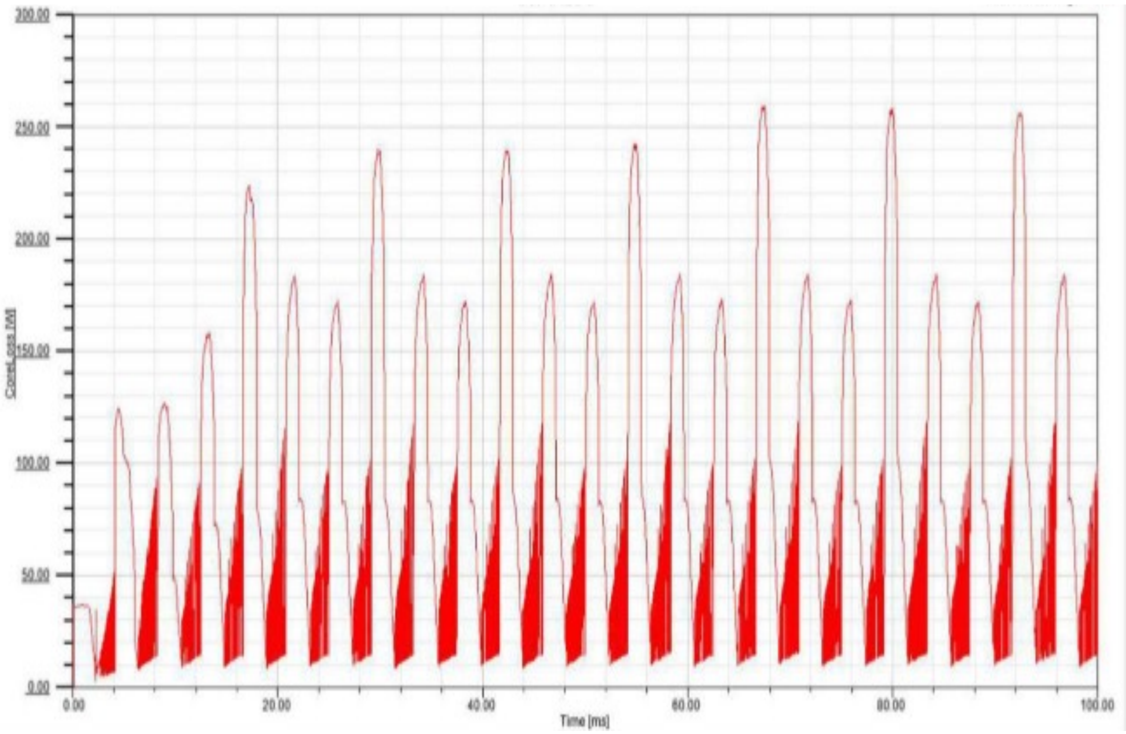

Figure 9. Co-simulation iron loss waveform

Results indicate a substantial power generation of about 2.6kW with an impressive efficiency rating of 85%. The overall power generation density and efficiency metrics validate the system's effectiveness. Incorporating wind speed as a dynamic input, the simulation emulates authentic operational conditions. Utilizing a periodic function and spanning a 5-second simulation period with two sampled periods, Figures 10 and 11 visualize the speed-time and motor power-time waveforms, showcasing a correlation between the motor's output power and speed waveform. Figures 10 and 11 establish a direct correlation between the motor's power output and the fluctuating wind speed. Notably, the motor demonstrates optimal power generation capabilities within the 150rpm to 350rpm range, indicating a successful and efficient design tailored to varying operational speeds. This comprehensive simulation unravels the DOSRG's robustness and efficiency across a spectrum of operating conditions, affirming its viability for practical applications.

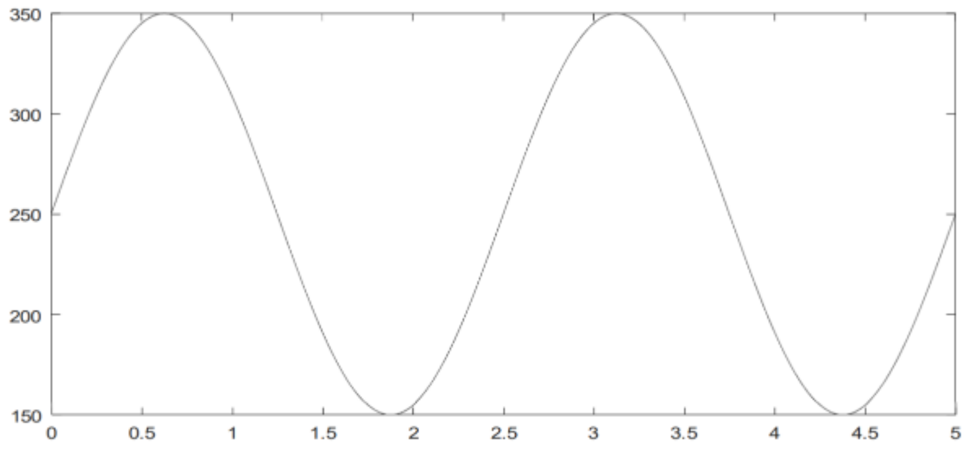

Figure 10. Speed-time waveform graph

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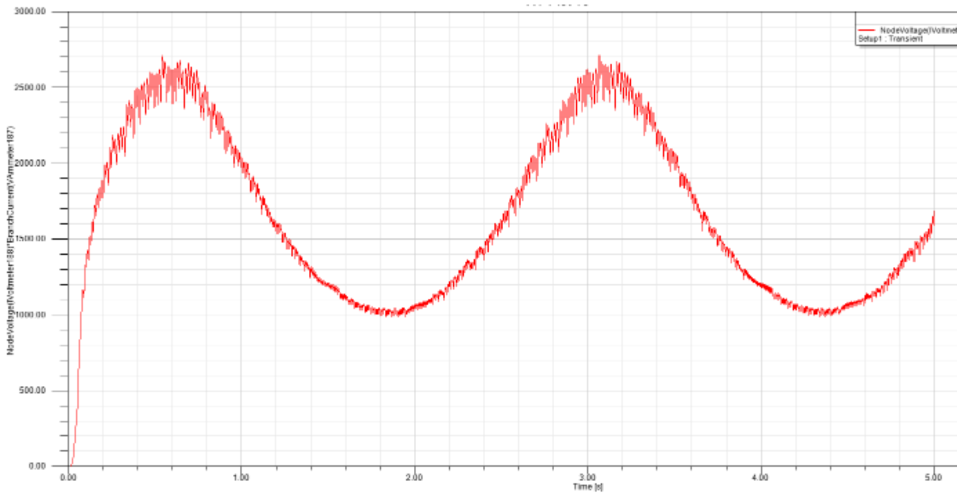

Figure 11. Motor joint simulation dynamic speed output power waveform diagram

CONCLUSION

In the field of renewable energy, the combined use of Maxwell and Simplorer for joint simulations proves to be a powerful tool in analyzing the intricate performance details of the motor's design. This collaborative simulation validates the motor's performance through angle position control and chopper control techniques. The simulation further strengthens confidence in the motor's capabilities by testing excitation and current-limiting processes. However, the true test comes with fluctuating wind speed patterns, where the simulation reveals the motor's adaptability through variable speed analysis. Operating efficiently within the dynamic range of 150 to 350 rpm, the motor excels in optimal power generation, especially within this range. This highlights the motor's ability to harness energy more effectively across varying operational conditions. The seamless interaction between the motor's design and simulated environmental changes showcases an impressive engineering achievement, reaffirming the motor's resilience and adaptability—essential traits in the unpredictable realm of renewable energy generation. The joint simulation tells a story of flexibility and reliability, showing how the motor adjusts to dynamic conditions. Each trial and wind speed variation underscores the motor's responsiveness and ability to capitalize on these changes. Beyond the simulation, this study offers a pathway to optimized motor designs suitable for the challenges of renewable energy. It emphasizes the importance of adaptability in the face of environmental unpredictability, providing a blueprint for future advancements in motor technology. Ultimately, the joint simulation stands as a testament to the motor's reliability, flexibility, and effectiveness, setting new standards for excellence in renewable energy systems and paving the way for more resilient and efficient motor designs to meet the growing demands of sustainable energy.

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