International Journal of Robotics and Control Systems
Vol. 4, No. 2, 2024, pp. 678-690
ISSN 2775-2658
http://pubs2.ascee.org/index.php/ijrcs

Comparative Electromagnetic Performance Analysis of Double Stator and Single Stator Superconducting Generators for Direct-Drive Wind Turbines

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ARTICLE INFO

Article history
Received April 08, 2024
Revised May 09, 2024
Accepted May 12, 2024

Keywords
Direct-Drive;
Superconducting Generator;
High Temperature Superconductors;
Wind Turbine

ABSTRACT

Superconducting synchronous generators, especially for 10-MW direct-drive wind power systems, are gaining prominence due to their lightweight, compact design, lowering energy generation costs compared to conventional generators. With the ability to generate high magnetic fields. various approaches are exist for designing such generators for example modular superconducting generators which allow for easier assembly, maintenance, and scalability by dividing the generator into smaller, interchangeable components and single stator which simplifying the generator's design and reducing manufacturing costs. This study introduces a novel concept of a double-stator superconducting generator alongside a conventional single-stator superconducting generator, aiming to investigate and contrast the electromagnetic performance of both machine types considering different number pole pairs. Booth of the machines has been designed and studied applying 2d finite element model (COMSOL Multiphysics). The compared machine parameters include: the flux linkage and electromagnetic torque. Our study and compression of the two machines reveal that the double stator superconducting generator is characterized by high electromagnetic torque compared to its single-stator counterpart. the analysis also reveals that increasing the pole pairs number leads to high electromagnetic torque and higher magnetic flux density.

1. Introduction

One of the most significant challenges facing electricity production nowadays is the rise in electric energy consumption, which increases the use of fossil fuels and pollutes the environment [1]-[5]. As a result, renewable energy technologies such as photovoltaic generation (PV) and wind generation have emerged to reduce reliance on fossil fuels and mitigate environmental degradation

[6]-[11]. Therefore, offshore wind power, as a clean and renewable energy source, has become the primary focus of wind power development [12]-[14]. In accordance with the development of the wind energy there is a growing trend towards large-scale wind generators which exceed 10MW, to reduce the cost per unit of offshore wind power [15]. One approach of these large-scale wind generators is direct-drive HTS wind generators which have been extensively researched due to their excellent electromagnetic performance. A comprehensive review of HTS applications in offshore wind generators is presented in [16], [17]. One of the most common structure for direct-drive HTS wind generators is the traditional synchronous machine with a single stator which has been explored by many researchers. However, recent research has explored alternative methods, including double-stator designs. For instance, a 10 MW dual-stator superconducting permanent magnet wind power generator was proposed in [18]-[21]. Most of the existing research focuses on either the electromagnetic characteristics of single stator or double stator generators which have stationary superconducting field coils as in [18]-[23], However, only a few researchers have explored methods to increase the torque density of superconducting generators by proposing different double-stator HTSG designs [25]-[28].

It's worth noting that the majority of existing studies on double stator HTS generators have focused on double stator permanent magnet HTS generators. Consequently, some previous research emphasizes that thermal constraints can exacerbate the degradation of the output torque in electric machines if not properly managed. Specifically, when a permanent magnet machine is equipped with superconducting conductors, it demonstrates increased output torque compared to a traditional copper-coiled counterpart, as reported in prior studies [29]-[32]. Nonetheless, the study presented in [33] introduces a double-stator PM machine with superconducting coils that offers improved reliability and enhanced output power compared to conventional single-stator superconducting machines. Furthermore, an in-depth analysis of the influence of design variables on the electromagnetic performance of PM machines have been described in [34]-[37]. Studies, as outlined in [25], [38]-[41] showed an inverse relationship exist between the aspect ratio of the machine and its corresponding magnetic loading. Many studies concentrated on the influence of pole number, pole ratio, and the diameter of the inner air gap on double-stator generators in terms of mass and cost of active materials [24], [42]-[45]. However, only a few researchers have explored methods to increase the torque density of superconducting generators by proposing different double-stator HTSG designs as in [46]-[50]. Hence, it's crucial to meticulously choose the design variables to enhance torque production and possibly cut costs. Existing literature predominantly delves into the electromagnetic traits of either single or double stator generators, with few studies directly comparing the two configurations. Moreover, many studies have limited scopes, focusing on specific applications or conditions, potentially overlooking performance disparities between single and double stator configurations across diverse scenarios. Additionally, there's limited research on the impact of design parameters on the generator performance. Given these factors, this study introduces a novel high-performance double-stator superconducting generator machine. It features AC windings on both the inner and outer stators. The study aims to investigate how the inclusion of an additional stator enhances the generator's torque density and flux linkage. Additionally, it compares this double-stator configuration with a single-stator model. The comparison considers the design parameter of pole pairs to examine how different pole pairs affect the electromagnetic torque and flux linkage in both configurations.

2. Method

Below is a flowchart highlighting the key components and analyses involved in comparing of single stator partially high temperature superconducting generator to double stator partially high temperature superconducting generator. Flowchart shown in Fig. 1.

2.1. Two High-Temperature Superconducting Generators Design

The two generators have been designed for a 10 MW direct-drive wind turbine. The superconductor selected for the design is a HTS. This type of superconductor operates at a higher range of cryogenic temperatures, exceeding those of all low-temperature superconductors (LTS). In this design, only the field winding employs HTS, while the armature winding is made of copper conductors operating at ambient temperature, akin to conventional synchronous generators. Consequently, this configuration can be classified as a partially superconducting generator, as illustrated in Fig. 2. The essential parameters of the generator design are detailed in Table 1. With all parameters identical for both designs. The sole difference lies in the number of pole pairs, which results in varying operating currents and generator shapes.

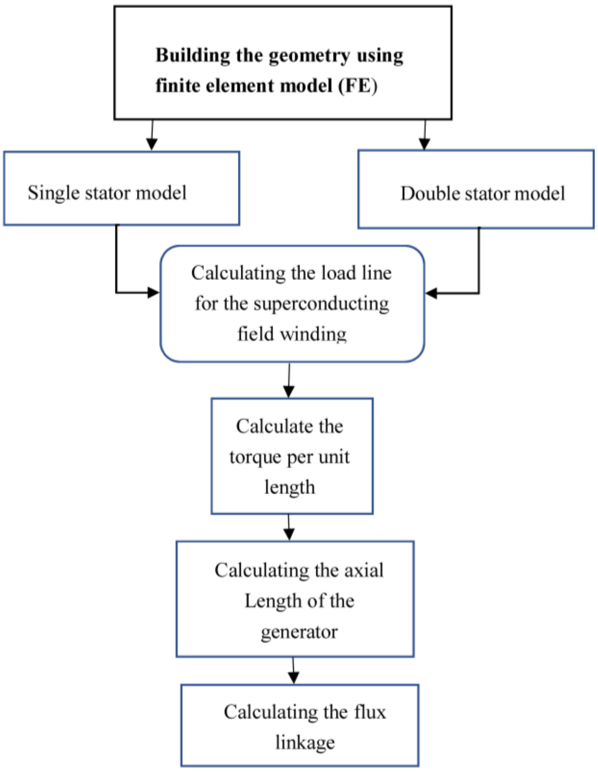


Fig. 1. Flowchart

Nonetheless, the number of pole pairs significantly influences the comparison results. The nominal power output is set at 10 MW, with an armature current density of 3 A/mm^2. The filling factor of the armature winding is 0.4, a typical value for rectangular copper conductors, accounting for appropriate twisting and transposing. To mitigate slotting effects, the number of slots per pole per phase is fixed at 4. This paper focuses on the design of double-stator armature windings wound with conventional copper wires, distinguished as the outer-stator windings and inner-stator windings, as depicted in Fig. 2 (b). Due to the spatial constraints imposed by the specialized dual-stator structure, the rotor core is omitted, as shown in Fig. 2 (b). While single generator stator model is shown Fig. 2 (a).

Table 1. Design parameters

Parameters	Double stator	Single stator	Values
Nominal power	-	-	10 MW
Rated speed	-	-	10 rpm
Number of phases	-	-	3
Number of pole pairs	-	-	4,12,20,24
Mechanical air gap length	-	-	6 mm
Armature bore diameter	-	-	3000
Armature current density	-	-	3A/mm^2
Armature Winding filling factor	-	-	0.4
Number of slots per pole per phase	-	-	4
height of rotor yoke	0	135	
height of inner stator yoke	135		
height of outer stator yoke	135		

2.2. Generators Design Structure

The geometry for the proposed HTS machine is illustrated in Fig. 3 and Fig. 4, and essential dimensional data are provided in Table 1 for both Model 1, which features a single stator, and Model 2, which incorporates a double stator. The sole distinction in geometrical parameters between these two models lies in the number of stators. We perform a comparative evaluation based on variations in pole pairs number, specifically (4, 12, 20, 24) pole pairs, to enhance efficiency. Furthermore, the air gap between the rotating field windings and each armature winding has been maintained at 30 mm to ensure sufficient space for thermal insulation and the refrigeration cooling system.

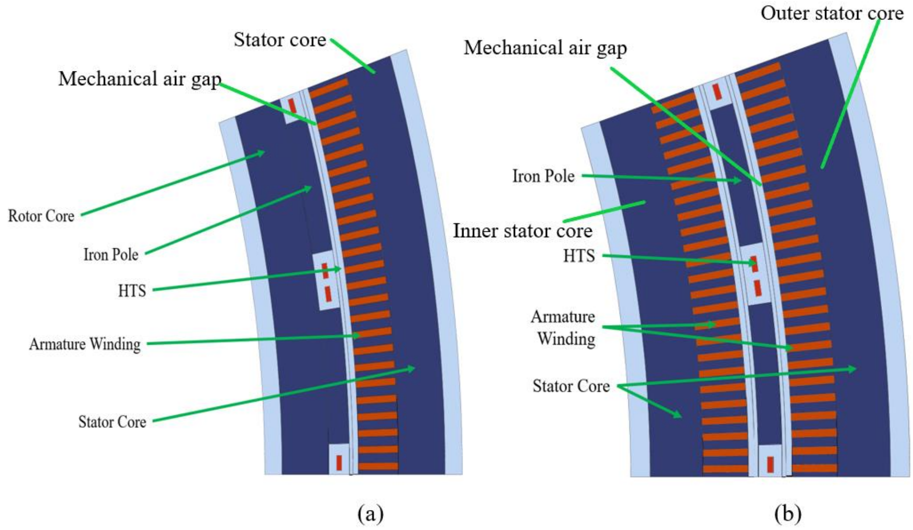


Fig. 2. General design of partially superconducting generator: (a) single stator, (b) double stator

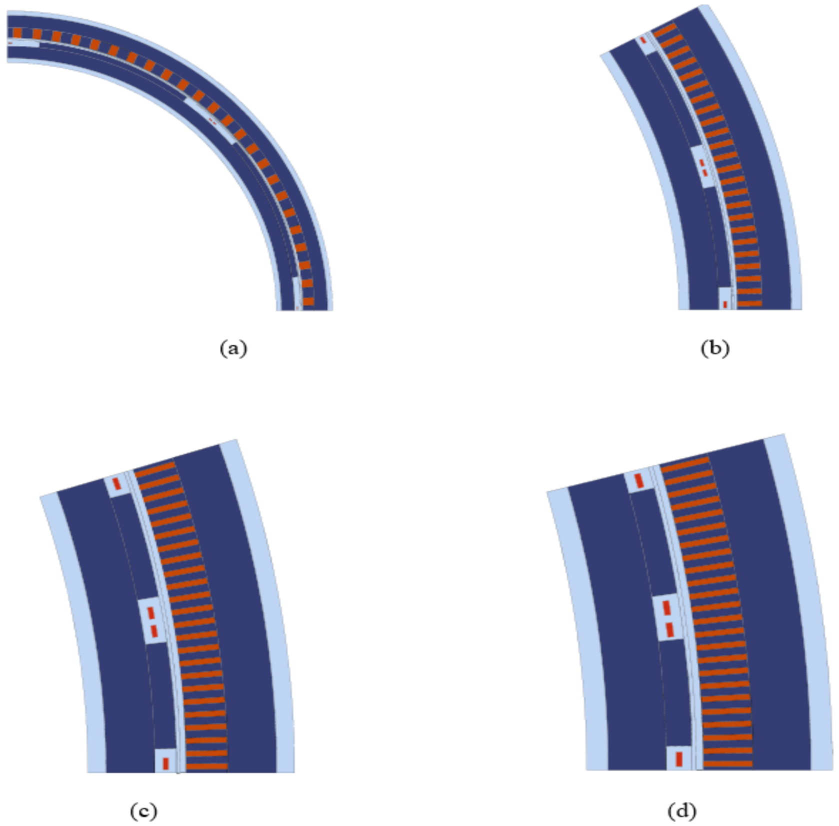


Fig. 3. General design of the partially superconducting single stator generator: (a) single stator 4 pole pair, (b) single stator 12 pole pair (c) single stator 20 pole pair (d) single stator 24 pole pair

2.3. Determination of the Operating Point of Field Winding

The operating current density of a superconducting generator is calculated from FE model and to determine the operating point of field winding currents, it is essential to construct a load line for each generator individually. For this purpose, distinct models are required for both single and double-stator configurations. In our analysis, we utilize HTS superconducting coils as flat tapes. It is essential to consider that any superconducting coil must maintain a current density lower than its critical current density to function as a superconducting coil. If the coil's current density surpasses the superconductor's critical current density, the coil will cease to operate as a superconducting coil. Information regarding the critical characteristics of the wire, typically supplied by the superconducting wire manufacturer and it's expressed in terms of critical current density (Je), which is a function of magnetic flux density (B), as depicted in Fig. 5.

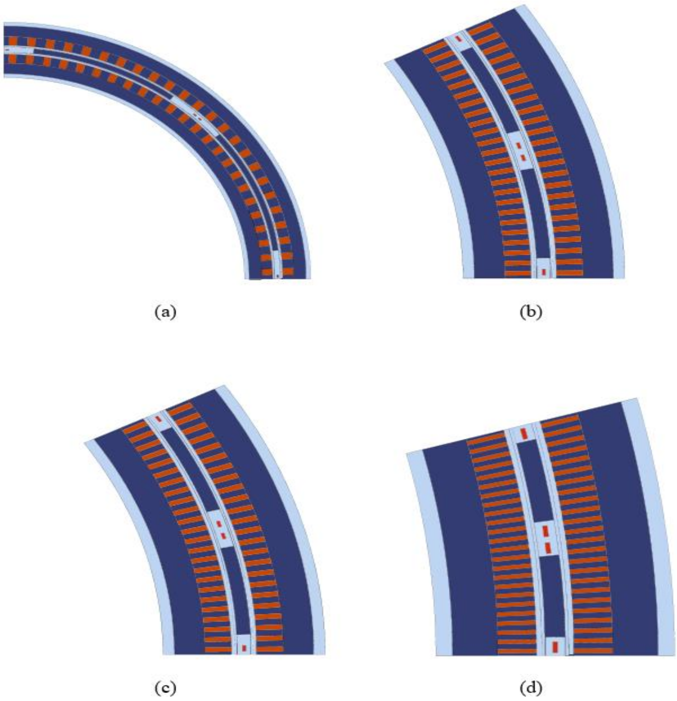


Fig. 4. General design of partially superconducting double stator generator: (a) double stator 4 pole pair, (b) double stator 12 pole pair (c) double stator 20 pole pair (d) double stator 24 pole pair

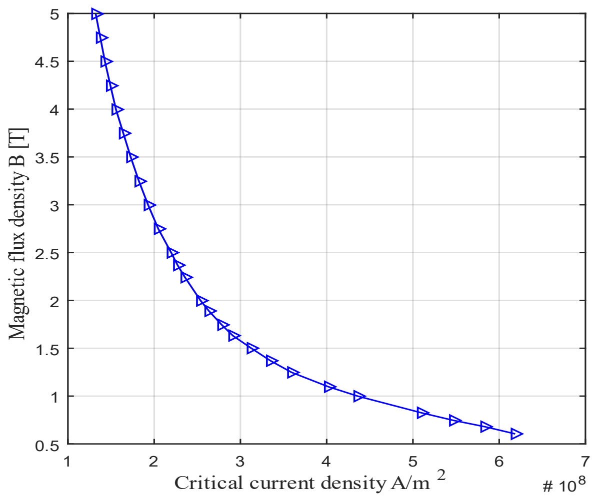


Fig. 5. Engineering critical current density Je as a function of the magnetic flux density B of the coil has been used in the field winding

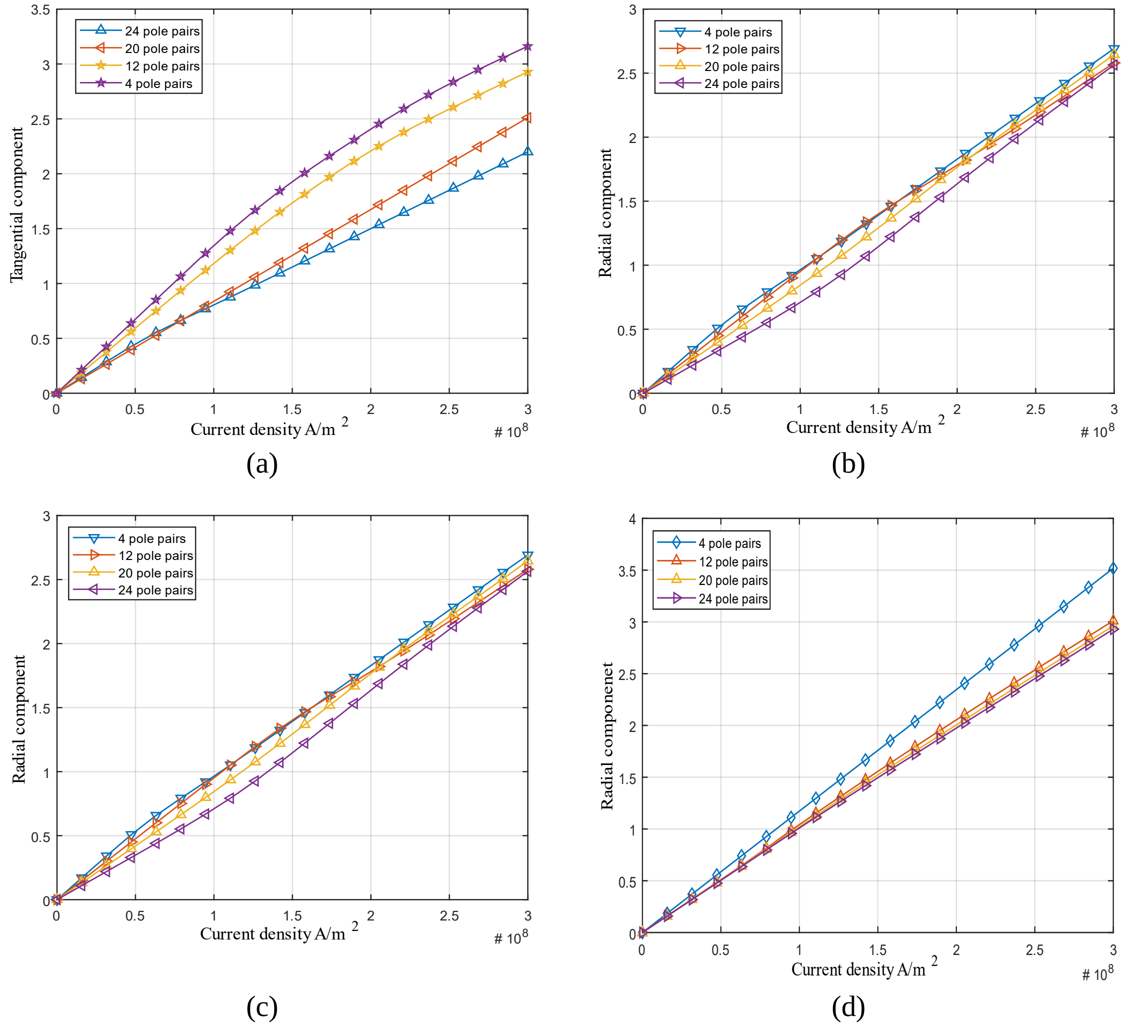


Fig. 6. Maximum magnetic field at the surface of superconducting field winding with respect to the current density (a) is single stator perpendicular component, (b) single stator radial component, (c) double stator perpendicular component and (d) double stator radial component

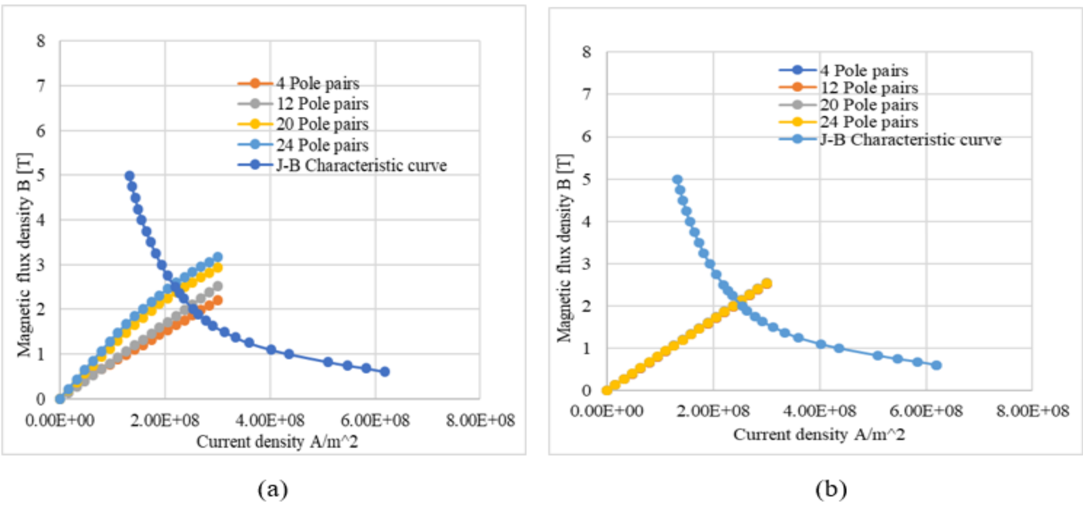


Fig. 7. Different excitation point for each of the five designs with respect to the current density flowing in a superconducting wire (a) is for single stator and (b) for double stator

After calculating the load lines showed in Fig. 6 we need to find the intersection point of the critical characteristic curve with the blue color and the load lines curves, we apply a uniform coil current density that is higher than the one needed for the superconducting coil after the end of the searching process we achieve the load line shown previously in Fig. 6 the intersection of the load line and the critical characteristic is considered stage of current density that allows the superconducting wire to be in superconducting state which mean that any small in increment in the current density after this rang will take the superconducting wire out of its super conducting state. Fig. 7 shows distinct load lines for each model relative to the current density flowing within the superconducting wire, and the exact excitation points.

3. Comparison Result

3.1. Magnetic Field Distribution

The magnetic flux density distribution and saturation behavior in single stator partially superconducting generators and double stator superconducting generators is varying with increasing pole pairs. With increasing pole pairs, the distribution of magnetic flux density within the single stator winding becomes more complex and it has created more non-uniform distribution of magnetic flux density within the stator winding, especially near the poles as shown in Fig. 8. In a double stator superconducting generator, the generator has two separate stator windings positioned on either side of the rotor. With increasing pole pairs, the interaction between the rotor's magnetic field and the two separate stator windings becomes more complex that’s why, the distribution of magnetic flux density within each stator winding in a double stator generator depends not only on the rotor's magnetic field but also on the arrangement and positioning of the stator windings. In our case in our case higher pole pair number has led to more intricate flux density distributions within each stator winding and between the two stator windings as shown in Fig. 9.

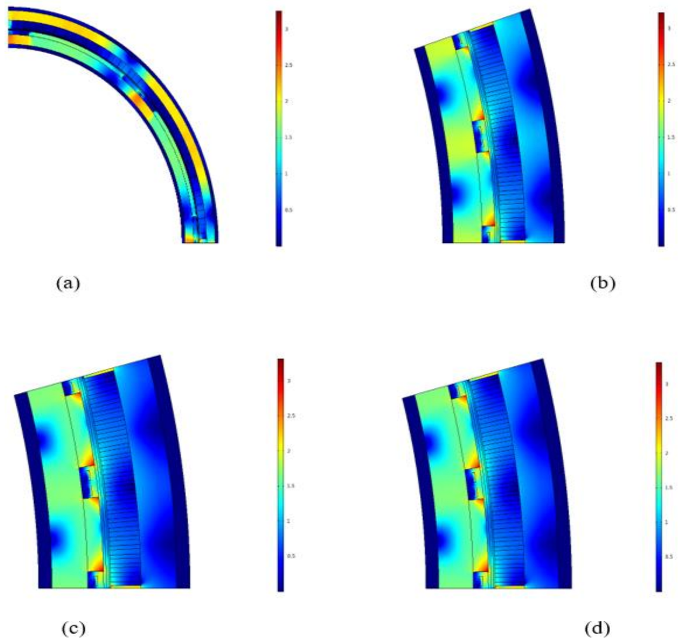
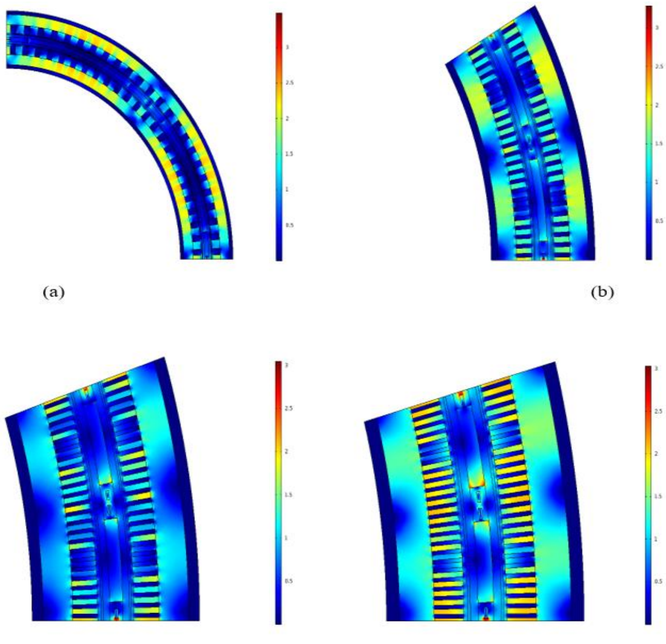


Fig. 8. Magnetic flux density distribution for single stator with different number of pole pairs (a) is for Single stator 4 pole pairs, (b) Single stator 12 pole pairs, (c) Single stator 20 pole pairs and (d)for Single stator 24 pole pairs

3.2. Electromagnetic Torque of Single Stator Double Stator

The electromagnetic torque for both the single stator and double stator machines has been calculated for four distinct sets, each with varying pole pairs configurations: (4, 12, 20, 24). In the case of the double stator machines, it was observed that as the number of pole pairs increased, the electromagnetic torque also increased. Notably, the highest recorded electromagnetic torque for the double stator set was 24.7 Mn/m, which occurred with 24 pole pair, while the lowest was 14.7 Mn/m with 4 pole pair, as depicted in Fig. 10. Similarly, the single stator sets exhibited a consistent trend in electromagnetic torque as observed in the double stator counterparts. The highest electromagnetic torque for the single stator machines was 15 Mn/m, occurring with 24 pole pair, while the lowest was 8.2 Mn/m with 4 pole pair, as demonstrated in Fig. 10. the comparison between the double stator and single stator generators in terms of electromagnetic torque showed that the double stator generators provided superior torque performance when considering machines of the same size.



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

Fig. 9. Magnetic flux density distribution for double stator with different number of pole pair (a) is for double stator 4 pole pair, (b) double stator 12 pole pair, (c) double stator 20 pole pair and (d)for double stator 24 pole pair

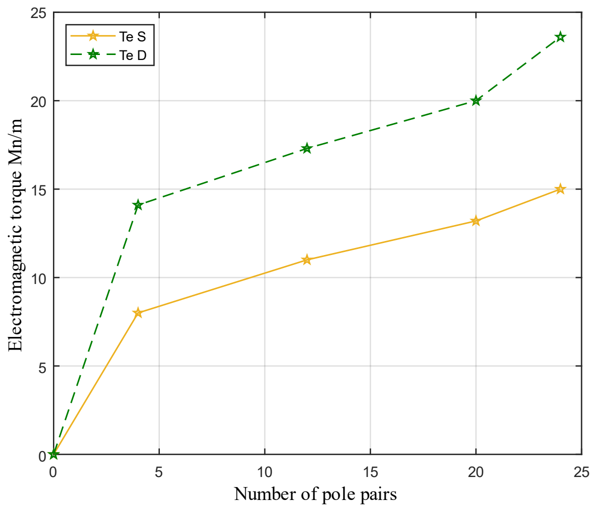
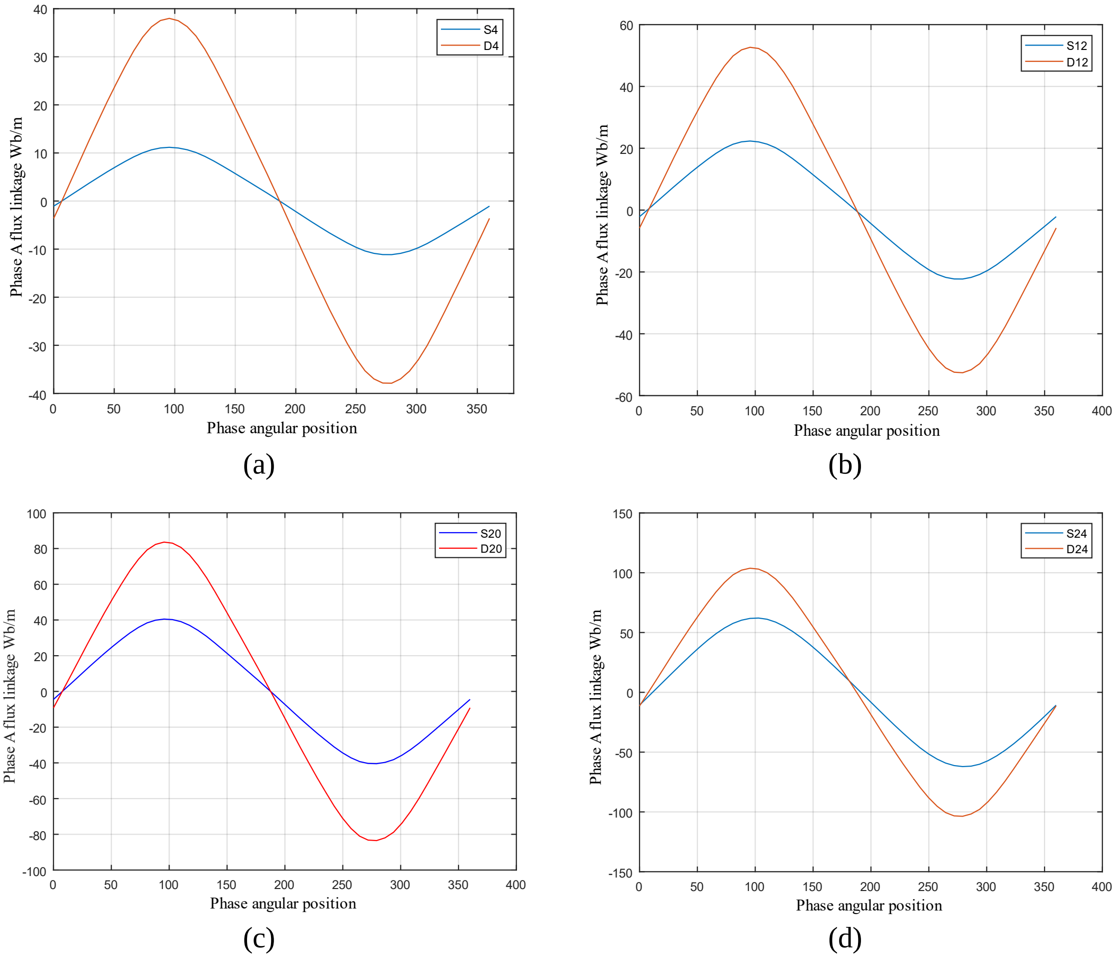


Fig. 10. Electromagnetic torque Peake values for single stator generator and double stator generator sets with respect to pole number pairs

From the results we can see that the double stator configuration exhibits higher torque production compared to the single stator generator. Because the presence of two stator windings allows for a stronger magnetic field interaction with the rotor, resulting in increased torque output. While single stator generators exhibit lower torque compared to double stator generators due to the absence of an additional stator winding. We can see that increasing the number of pole pairs in a double stator and single stator generator can further enhance torque production because more pole pairs allow for more complex magnetic field interactions, leading to increased torque.

3.3. Flux Linkage Double Stator and Single Stator Superconductor Generator

Phase A coil-flux linkage of the proposed machine that shown in Fig. 2 and Fig. 3, is calculated for both the single and double stator configurations using a 2D finite element model COMSOL Multiphysics. phase A coil-flux linkage for the four double stator and single stator design is illustrated in Fig. 11. The waveform is found to be purely sinusoidal. Among the tested configurations, the highest peak value was recorded for the double stator with 24 poles, measuring 104.6 Wb/m, while the lowest value was observed for the single stator with 4 poles, measuring 12.3 Wb/m. We can see that the presence of two stator windings in the double stator configuration leads to enhanced flux linkage compared to the single stator generator because the additional winding allows for greater control over the magnetic field distribution, resulting in increased flux linkage.



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

Fig. 11. Variation in phase A flux-linkage waveforms of each pole pairs combination (a) is for single and double stator 4 pole pair, (b) single and double stator 12 pole pair, (c) single and double stator 20 pole pair and (d) for single and double stator 24 pole pair

4. Conclusion

This paper comprehensively compares double stator and single stator HTS generators, focusing on torque and flux linkage variations with increasing pole pair numbers. Both generator types exhibit notable shifts in torque and flux linkage as pole pair numbers increase. Double stator generators reach peak flux linkage of 104.6 Wb/m with 24 pole pairs, while single stator generators peak at 66.7 Wb/m. Similarly, electromagnetic torque increases with pole pair numbers, peaking at 24.7 Mn/m and 15 Mn/m for double stator and single stator generators, respectively. The study also highlights that higher pole pair numbers in single stator generators result in less uniform flux density distribution and heightened magnetic saturation effects, posing operational challenges. Conversely, double stator generators exhibit a complex flux density distribution between stator windings. Overall, this analysis underscores the importance of considering torque and flux linkage characteristics in evaluating partially superconducting generator performance. The findings offer valuable insights for generator design and optimization, guiding advancements in high-efficiency electrical generation systems across various applications. Since the higher torque output and enhanced flux linkage observed in the double stator generators may translate to improved electromagnetic efficiency compared to single stator generators which, can result in reduced losses and improved energy conversion, leading to higher overall efficiency. Furthermore, the higher torque and flux linkage observed in double stator generators may contribute to greater stability and robustness, reducing the risk of performance degradation or failure under challenging operating conditions. Finally, further research is wanted to explore additional factors influencing such generator performance and to identify optimal design strategies tailored to specific industry needs.

Author Contribution: All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] M. A. A. Abdalla *et al.*, "Optimizing Energy Usage and Smoothing Load Profile via a Home Energy Management Strategy with Vehicle-to-Home and Energy Storage System," *Sustainability*, vol. 15, no. 20, p. 15046, 2023, https://doi.org/10.3390/su152015046.

[2] G. R. Sosa, M. Z. Falah, D. F. L, A. P. Wibawa, A. N. Handayani, J. A. H. Hammad, "Forecasting electrical power consumption using ARIMA method based on kWh of sold energy," *Science in Information Technology Letters*, vol. 2, no. 1, pp. 9-15, 2021, https://doi.org/10.31763/sitech.v2i1.637.

[3] M. Wang, D. Pan, M. A. A. Abdalla, H. Wang, F. Zuo and X. Sheng, "A Review of Robust State Estimation of Distribution Network," *2023 2nd Asian Conference on Frontiers of Power and Energy (ACFPE)*, pp. 475-481, 2023, https://doi.org/10.1109/ACFPE59335.2023.10455394.

[4] S. O. Effiom, P. C. O. Effiom, R. Akwagiobe, P. O. Odu, "Technical and economic appraisal for harnessing a proposed hybrid energy system nexus for power generation and CO2 mitigation in Cross River State, Nigeria," *Applied Engineering and Technology*, vol. 2, no. 2, pp. 153-175, 2023, https://doi.org/10.31763/aet.v2i2.1075.

[5] A. H. Bagdadee, Z. Li, M. A. A. Abdalla, "Constant &Reliable Power Supply by the Smart Grid Technology in Modern Power System," *IOP Conference Series: Materials Science and Engineering*, vol. 561, no. 1, p. 012088, 2019, https://doi.org/10.1088/1757-899X/561/1/012088.

[6] M. K. Salihu, "Optimization model for determining global solar radiation in the northeastern states of Nigeria using both meteorological and satellite imagery data," *Applied Engineering and Technology*, vol. 2, no. 2, pp. 75-92, 2023, https://doi.org/10.31763/aet.v2i2.1039.

[7] M. Abdallah, B. Mohammadi, H. Nasiri, O. M. Katipoğlu, M. A. A. Abdalla, M. M. Ebadzadeh, "Daily global solar radiation time series prediction using variational mode decomposition combined with multi-functional recurrent fuzzy neural network and quantile regression forests algorithm," *Energy Reports*, vol. 10, pp. 4198-4217, 2023, https://doi.org/10.1016/j.egyr.2023.10.070.

[8] N. M. S. Kumar, K. Hariprasath, N. Kaviyavarshini, K. Kavinya, "A Study On the Forecasting Bigmart Sales Using Optimized Data Mining Techniques," *Science in Information Technology Letters*, vol. 1, no. 2, pp. 52-59, 2020, https://doi.org/10.31763/sitech.v1i2.167.

[9] F. Kurniawan, S. Sulaiman, S. Konate, M. A. A. Abdalla, "Deep learning approaches for MIMO time-series analysis," *International Journal of Advances in Intelligent Informatics*, vol. 9, no. 2, pp. 286-300, 2023, https://doi.org/10.26555/ijain.v9i2.1092.

[10] S. O. Effiom, "Feasibility of floating solar photovoltaic systems (FSPVs) development in Nigeria: an economic cost appraisal case study," *Applied Engineering and Technology*, vol. 2, no. 2, pp. 60-74, 2023, https://doi.org/10.31763/aet.v2i2.1012.

[11] O. A. A. Mohammed, L. Peng, G. H. A. Hamid, A. M. Ishag, M. A. A. Abdalla, "Effective Energy Management Strategy with Model-Free DC-Bus Voltage Control for Fuel Cell/Battery/Supercapacitor Hybrid Electric Vehicle System," *Machines*, vol. 11, no. 10, p. 944, 2023, https://doi.org/10.3390/machines11100944.

[12] A. Ballarino *et al.*, "The BEST PATHS Project on MgB2 Superconducting Cables for Very High Power Transmission," *IEEE Transactions on Applied Superconductivity*, vol. 26, no. 3, pp. 1-6, 2016, https://doi.org/10.1109/TASC.2016.2545116.

[13] O. A. Abbaker, A. A. Ahmed, "Control of wind turbine for variable speed based on fuzzy-PID controller," *Journal of Engineering and Computer Science (JECS)*, vol. 18, no. 1, pp. 40-51, 2017, https://core.ac.uk/download/pdf/323246088.pdf.

[14] Z. Zheng, Q. Xie, C. Huang, X. Xiao and C. Li, "Superconducting Technology Based Fault Ride Through Strategy for PMSG-Based Wind Turbine Generator: A Comprehensive Review," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 8, pp. 1-6, 2021, https://doi.org/10.1109/TASC.2021.3101767.

[15] J. Muñoz-Antón, A. Marian, F. Lesur, C. -E. Bruzek, "Dichotomic decision optimization for the design of HVDC superconducting links," *Entropy*, vol. 22, no. 12, p. 1413, 2020, https://doi.org/10.3390/e22121413.

[16] R. Schiferl, A. Flory, W. C. Livoti and S. D. Umans, "High Temperature Superconducting Synchronous Motors: Economic Issues for Industrial Applications," *2006 Record of Conference Papers - IEEE Industry Applications Society 53rd Annual Petroleum and Chemical Industry Conference*, pp. 1-9, 2006, https://doi.org/10.1109/PCICON.2006.359715.

[17] D. Liu *et al.*, "Short-Circuit Characteristics of Superconducting Permanent Magnet Generators for 10 MW Wind Turbines," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-5, 2021, https://doi.org/10.1109/TASC.2021.3056996.

[18] O. Keysan, "Application of high-temperature superconducting machines to direct drive renewable energy systems, in: Electrical Drives for Direct Drive Renewable Energy Systems," *Elsevier*, pp. 219-252, 2013, https://doi.org/10.1533/9780857097491.2.219.

[19] A. Fithriyyah, T. Purwaningsih, S. Konate, M. A. A. Abdalla, "Mapping dengue vulnerability: spatial cluster analysis reveals patterns in Central Java, Indonesia," *Science in Information Technology Letters*, vol. 4, no. 2, pp. 109-122, 2023, https://doi.org/10.31763/sitech.v4i2.1203.

[20] M. A. A. Abdalla, G. Kalcon, A. Mohammed, "Design of Travelling Wave Relay for Protection of Transmission Lines," *International Journal of Research*, vol. 3, no. 4, pp. 29-41, 2017, https://doi.org/10.20431/2454-9436.0304005.

[21] N. Savvides *et al.*, "Effect of strain on ac power loss of Bi-2223/Ag superconducting tapes," *Physica C: Superconductivity*, vol. 306, no. 1-2, pp. 129-135, 1998, https://doi.org/10.1016/S0921-4534(98)00362-1.

[22] R. Köster and A. Binder, "Parametric AC Loss Study on 7 MW Fully Superconducting Direct-Drive Wind Turbine Generators With Concentrated Stator Winding," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, pp. 1-7, 2024, https://doi.org/10.1109/TASC.2023.3346352.

[23] R. Köster, A. Binder, "Eddy current loss estimation for direct drive wind turbine generators with superconducting excitation winding by numerical and analytical models," *International Journal of*

Numerical Modelling: Electronic Networks, Devices and Fields, vol. 36, no. 3, p. e3066, 2023, https://doi.org/10.1002/jnm.3066.

[24] A. Desikan, B. J. H. de Bruyn, D. C. J. Krop and E. A. Lomonova, "Modeling and Analysis of HTS Linear Motors in High-Dynamic Applications," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-9, 2023, https://doi.org/10.1109/TASC.2023.3262625.

[25] P. G. O'Brien, R. R. Taylor, "HTS synchronous machine critical current modelling and comparison with tests," *Journal of Physics: Conference Series*, vol. 1559, no. 1, p. 012135, 2020, https://doi.org/10.1088/1742-6596/1559/1/012135.

[26] S. I. A. Haroon, J. Qian, Y. Zeng, Y. Zou, D. Tian, "Extended State Observer Based-Backstepping Control for Virtual Synchronous Generator," *Electronics*, vol. 11, no. 19, p. 2988, 2022, https://doi.org/10.3390/electronics11192988.

[27] M. A. A. Abdalla, W. Min, W. Bing, A. M. Ishag, B. Saleh, "Double-layer home energy management strategy for increasing PV self-consumption and cost reduction through appliances scheduling, EV, and storage," *Energy Reports*, vol. 10, pp. 3494-3518, 2023, https://doi.org/10.1016/j.egyr.2023.10.019.

[28] P. P. Ferreira *et al.*, "Search for ambient superconductivity in the Lu-NH system," *Nature Communications*, vol. 14, no. 1, p. 5367, 2023, https://doi.org/10.1038/s41467-023-41005-2.

[29] V. K. Khanna, "Superconductive electronics for ultra-cool environments," *Extreme-Temperature and Harsh-Environment Electronics*, 2017, https://doi.org/10.1088/978-0-7503-1155-7ch12.

[30] J. W. Bray, "Superconductors in Applications; Some Practical Aspects," *IEEE Transactions on Applied Superconductivity*, vol. 19, no. 3, pp. 2533-2539, 2009, https://doi.org/10.1109/TASC.2009.2019287.

[31] D. Liu, T. Salmi and J. Lin, "Potential Performance of Fully Superconducting Generators for Large Direct-Drive Wind Turbines," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp. 1-5, 2023, https://doi.org/10.1109/TASC.2023.3255826.

[32] C. C. T. Chow, M. D. Ainslie, K. T. Chau, "High temperature superconducting rotating electrical machines: An overview," *Energy Reports*, vol. 9, pp. 1124-1156, 2023, https://doi.org/10.1016/j.egyr.2022.11.173.

[33] D. A. Korzekwa, J. F. Bingert, E. J. Podtburg, P. Miles, "Deformation processing of wires and tapes using the oxide-powder-in-tube method," *Applied Superconductivity*, vol. 2, no. 3-4, pp. 261-270, 1994, https://doi.org/10.1016/0964-1807(94)90012-4.

[34] D. K. Finnemore, K. E. Gray, M. P. Maley, D. O. Welch, D. K. Christen, D. M. Kroeger, "Coated conductor development: an assessment," *Physica C: Superconductivity*, vol. 320, no. 1-2, pp. 1-8, 1999, https://doi.org/10.1016/S0921-4534(99)00325-1.

[35] H. Karmaker, M. Ho and D. Kulkarni, "Comparison Between Different Design Topologies for Multi-Megawatt Direct Drive Wind Generators Using Improved Second Generation High Temperature Superconductors," *IEEE Transactions on Applied Superconductivity*, vol. 25, no. 3, pp. 1-5, 2015, https://doi.org/10.1109/TASC.2014.2375872.

[36] Y. Cheng *et al.*, "Comparison of Electromagnetic Performance of 10-MW HTS Double-Stator Flux Modulation Wind Generators With Different Topologies," *IEEE Transactions on Applied Superconductivity*, vol. 30, no. 4, pp. 1-7, 2020, https://doi.org/10.1109/TASC.2020.2975153.

[37] Y. Zhang, Y. Cheng, X. Fan, D. Li and R. Qu, "Electromagnetic Fault Analysis of Superconducting Wind Generator With Different Topologies," *IEEE Transactions on Applied Superconductivity*, vol. 31, no. 5, pp. 1-6, 2021, https://doi.org/10.1109/TASC.2021.3070924.

[38] O. Rahman, K. M. Muttaqi and D. Sutanto, "High Temperature Superconducting Devices and Renewable Energy Resources in Future Power Grids: A Case Study," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 2, pp. 1-4, 2019, https://doi.org/10.1109/TASC.2019.2895677.

[39] D. Liu, H. Polinder, A. B. Abrahamsen, X. Wang and J. A. Ferreira, "Comparison of superconducting generators and permanent magnet generators for 10-MW direct-drive wind turbines," *2016 19th International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1-6, 2016, https://ieeexplore.ieee.org/document/7837422.

[40] Y. Cheng, D. Li, W. Kong, R. Qu and F. Lin, "Electromagnetic Design of a Large-Scale Double-Stator Direct Driving HTS Wind Generator," *IEEE Transactions on Applied Superconductivity*, vol. 28, no. 4, pp. 1-5, 2018, https://doi.org/10.1109/TASC.2018.2803265.

[41] R. Qu, Y. Liu and J. Wang, "Review of Superconducting Generator Topologies for Direct-Drive Wind Turbines," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 5201108-5201108, 2013, https://doi.org/10.1109/TASC.2013.2241387.

[42] B. B. Jensen, N. Mijatovic, A. B. Abrahamsen, "Development of superconducting wind turbine generators," *Journal of Renewable and Sustainable Energy*, vol. 5, no. 2, 2013, https://doi.org/10.1063/1.4801449.

[43] D. Kostopoulos, D. Liu, G. Genani, H. Polinder, "Feasibility study of a 10 MW MgB2 fully superconducting generator for offshore wind turbines," *European Wind Energy Association*, 2013, https://repository.tudelft.nl/islandora/object/uuid%3A42184015-8cac-4be2-8084-a221744d0452.

[44] J. Wang, R. Qu and Y. Liu, "Comparison Study of Superconducting Generators With Multiphase Armature Windings for Large-Scale Direct-Drive Wind Turbines," *IEEE Transactions on Applied Superconductivity*, vol. 23, no. 3, pp. 5201005-5201005, 2013, https://doi.org/10.1109/TASC.2013.2241172.

[45] D. Liu, H. Polinder, A. B. Abrahamsen and J. A. Ferreira, "Topology Comparison of Superconducting Generators for 10-MW Direct-Drive Wind Turbines: Cost of Energy Based," *IEEE Transactions on Applied Superconductivity*, vol. 27, no. 4, pp. 1-7, 2017, https://doi.org/10.1109/TASC.2017.2668059.

[46] T. Sheahen, "Introduction to high-temperature superconductivity," *Springer Science & Business Media*, 1994, https://doi.org/10.1007/b115100.

[47] M. A. A. Abdalla, W. Min, A. H. Gomaa Haroun and M. Elhindi, "Optimal Energy Scheduling Strategy for Smart Charging of Electric Vehicles from Grid-Connected Photovoltaic System," *2021 7th International Conference on Electrical, Electronics and Information Engineering (ICEEIE)*, pp. 37-42, 2021, https://doi.org/10.1109/ICEEIE52663.2021.9616634.

[48] Y. Liu, R. Qu and J. Wang, "Comparative Analysis on Superconducting Direct-Drive Wind Generators With Iron Teeth and Air-Gap Winding," *IEEE Transactions on Applied Superconductivity*, vol. 24, no. 3, pp. 1-5, 2014, https://doi.org/10.1109/TASC.2013.2292309.

[49] L. Huang, B. Hu, M. Hu, C. Liu and H. Zhu, "Research on Primary Excitation Fully Superconducting Linear Generators for Wave Energy Conversion," *IEEE Transactions on Applied Superconductivity*, vol. 29, no. 5, pp. 1-5, 2019, https://doi.org/10.1109/TASC.2019.2903573.

[50] X. Zhu and M. Cheng, "Design and Analysis of 10 MW Class HTS Exciting Double Stator Direct-Drive Wind Generator With Stationary Seal," *IEEE Access*, vol. 7, pp. 51129-51139, 2019, https://doi.org/10.1109/ACCESS.2019.2911298.