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Article

The Application of All-Aluminum Electrical System in Wind Power

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Abstract: The purpose of this paper is to explore the application of an all-aluminum electrical system in the field of wind power. Driven by the global "dual carbon" goal, the wind power industry is developing rapidly as a key force in clean energy. In view of the lightweight, high strength, corrosion resistance and good conductivity of aluminum, this paper proposes an innovative all-aluminum electrical system solution, which applies aluminum to key components such as generators, cables, transformers and converter busbars to reduce the levelized cost of energy (LCOE) and enhance market competitiveness. In this paper, through in-depth research on the mechanical and electrical properties, connection technology and short-circuit tolerance of aluminum materials, the key technologies and innovation points of the core electrical components of the all-aluminum electrical system are comprehensively analyzed, and the product application market is planned in depth. The proposed system shows 30-year lifecycle viability through accelerated aging tests, outperforming conventional materials in total ownership cost metrics. These technical advancements position aluminum electrical systems as transformative solutions for next-generation wind farms, aligning with global decarbonization objectives while addressing industry pain points in cost containment and operational reliability across diverse geographical markets.The results show that the all-aluminum electrical system has established a leading technical position in the wind power industry, and its superior LCOE perfectly meets the needs of various wind power markets, showing broad application potential and prospects.

Keywords: Wind Power; All-Aluminum Materials Electrical System; Aluminum Materials; Cost Reduction and Efficiency; Technological Innovations

1. Introduction

In order to cater to the rapid development of the wind power industry under the "dual-carbon" target, wind turbine manufacturers are actively promoting the layout planning of their latest products [1]. In 2023, the average stand-alone capacity of domestic onshore wind turbines reached 5.4 MW, up 25.1% year-on-year, while the average stand-alone capacity of offshore wind turbines was 9.6 MW, up 29.4% year-on-year. The trend of large-scale offshore wind turbines is being strengthened, with onshore wind turbines of more than 6 MW already taking up nearly half of the market share. It is expected that by 2024, the main models will be further upgraded to 7–8 MW, and even 10 MW models will be widely used in the field of onshore wind power. In addition, the rapid decline in wind turbine prices has become an important feature of the wind power industry in 2023, and market competition is extremely fierce, for both onshore and offshore wind turbines [2].

With my country's "carbon peak" and "carbon neutral" goals [3], all countries are vigorously promoting the development of new energy sources and low-carbon electricity [4]. Wind power has gradually become an important part of the sustainable development strategies in many countries [5].

The National Energy Administration clearly pointed out in the "14th Five-Year Plan for Modern Energy System" that by 2025, the proportion of non-fossil energy power generation in China is expected to reach about 39%, and the proportion of electric energy in terminal energy will also reach about 30% [6–10]. This transformation will significantly increase the demand for the construction of renewable energy power systems such as wind power and photovoltaic power, and will also promote the rapid development of industrial energy in the fields of coal-to-electricity and new energy vehicles. Developments in these areas will inevitably lead to a surge in the consumption of copper resources.

However, China's copper resources are relatively scarce, accounting for only about 3% of the world's total reserves. Of these, copper resources are used in the power and electronics industries for about 21%. What's more serious is that more than 70% of China's copper ore resources rely on imports, resulting in an increasingly unbalanced supply and demand of domestic copper resources [11–15]. According to the copper material price chart provided by Shanghai Nonferrous Metals Network, we can clearly see that from September 2022 to September 2023, the price of copper materials has shown a clear upward trend. This large price fluctuation has put tremendous pressure on both the supply and demand sides of the transformer. In this context, the application of aluminum winding transformers is particularly important. It can not only effectively save limited copper resources, but also has obvious cost-benefit advantages. The promotion and application of this technology is fully in line with the strategic goal of sustainable development in China.

"Replacing copper with aluminum" is a technical policy to deal with the shortage of copper resources in China in the 1960s [16]. Against this backdrop, "replacing copper with aluminum" as a key cost reduction strategy shows great potential for application in the wind power industry [17–21]. Aluminum, with its lightweight density, low cost and good electrical conductivity, coupled with the abundance of resources, has become an ideal alternative to copper, effectively reducing the cost and weight of electrical components, thereby enhancing the economics and market competitiveness of wind power.

The all-aluminum materials electrical system, as an innovative wind power solution, applies aluminum to key components such as generators, cables, transformers and converter busbars, achieving the goals of cost reduction, weight reduction and competitiveness enhancement. In this paper, we will discuss the background, key technologies, innovations and market prospects of the all-aluminum materials electrical system and analyze its far-reaching impact on the wind power industry.It is predicted that the future application prospect of aluminum wire for electrical appliances will be broader [22].

To sum up, in the face of the opportunities and challenges of the rapid development of the wind power industry, the application of the all-aluminum electrical system has become an important way to reduce costs and improve efficiency. The goal of this paper is to comprehensively discuss the key technologies, innovations and market application potential of all-aluminum electrical systems, and provide new solutions for the sustainable development of the wind power industry. The contribution of this paper is to propose an innovative all-aluminum electrical system scheme, which provides strong support for the technological progress and cost reduction of the wind power industry through in-depth analysis of the performance advantages of aluminum materials and their application in wind power equipment.

2. Background on the Development of All-Aluminum Materials Electrical Systems

2.1. Current Status of Wind Power Industry Development

In the first half of 2024, copper prices experienced a sharp rise, soaring from an average of 69,000 yuan per ton at the end of 2023 to a high of 87,000 yuan per ton in the first half of 2024, an increase of 26%.In comparison, aluminum material prices peaked at only 21,000 yuan per ton during the same period. As can be seen from these data, the price of copper materials is almost four times that of aluminum materials. In view of the scarcity of copper resources in China and the abundance of aluminum materials, the country has launched an energy strategy of "replacing copper with aluminum".

Currently, China's wind power industry is developing rapidly, with installed capacity increasing and technology levels improving. Nevertheless, the cost of electricity is still high, which limits the wider penetration of wind power.

In order to reduce the cost of electricity and promote wind power to achieve grid parity, wind power machine manufacturers are actively exploring various ways of technological innovation and cost reduction. In this process, aluminum has become the key to cost reduction and efficiency improvement in the wind power industry due to its cost-effectiveness and resource advantages.

2.2. The Need to "Replace Copper with Aluminum"

Although copper material occupies a core position in electrical equipment, its high cost and limited resources have become the bottleneck of cost reduction and efficiency in the wind power industry. In contrast, aluminum stands out for its light density, low cost and excellent electrical conductivity, and its relative abundance of resources makes it an ideal choice to replace copper. The use of aluminum can significantly reduce the cost and weight of electrical components, thereby improving the economics and market competitiveness of wind power.

In 2024, when the price of wind power continues to go down and the price of copper remains high, the development and industrialization of all-aluminum materials electrical systems is particularly urgent. This will not only lead to technological innovation within the wind power industry but also produce a significant reduction in the cost of electrical components of the whole machine, providing strong support for the market competitiveness of the company's products.

After the completion of project validation and promotion in the domestic market, these successful demonstration projects will provide strong evidence and confidence for the expansion of the overseas market, further consolidating the company's leading position in the global wind power field.

2.3. Advantages of All-Aluminum Materials Electrical Systems

Aluminum exhibits a number of significant advantages in electrical components, making it one of the materials of choice in the manufacture of electrical products. Aluminum has excellent electrical conductivity, although not as good as copper, but its density is only one-third that of copper, making it lighter in mass for the same volume. This characteristic makes aluminum electrical equipment lighter to transport and install, especially in applications where weight reduction is required, such as wind turbine tower loads.

Aluminum's high thermal conductivity is also a major benefit, allowing it to quickly dissipate heat generated during operation, helping to maintain stable equipment temperatures, which in turn improves efficiency and extends service life. In addition, the dense oxide film formed on the surface of aluminum gives it excellent corrosion resistance, ensuring stable performance in a wide range of environmental conditions.

Ease of processing is another advantage of aluminum, which can be easily formed by casting, extruding, bending, etc., and is suitable for the manufacture of housings and structural components for a variety of electrical equipment. Aluminum also provides good electromagnetic shielding, superior to many other metals, which is critical for reducing electromagnetic interference (EMI) and improving the performance of electrical equipment.

Sustainability is another key feature of aluminum. As a recyclable material, the recycling process is low in energy consumption and has a low environmental impact, and the use of recycled aluminum in the manufacture of electrical equipment helps to reduce resource consumption and environmental pollution.

In the wind power sector, aluminum is widely used in key electrical components such as generators, cables, transformers, and converter busbars, bringing multiple advantages such as cost reduction, weight reduction, and improved product competitiveness. The price of aluminum is lower than that of copper, which can effectively reduce the cost of electrical components and improve the economy of wind power. At the same time, the density of aluminum is less than that of copper, which can significantly reduce the weight of electrical components, reduce transportation and installation costs, and improve the transportation and installation efficiency of wind power. The advantage of the all-aluminum materials electrical system is to ensure the same performance with copper electrical equipment, but also has a significant cost advantage, which can significantly enhance the market competitiveness of wind power products [23].

3. Key Technology of All-Aluminum Materials Electrical System

The all-aluminum materials electrical system is composed of an aluminum winding generator, an aluminum transformer, an aluminum alloy cable (low-voltage aluminum alloy twisted cable, a low-voltage aluminum alloy cable in the tower section, and a medium-voltage aluminum alloy cable in the tower section), and an aluminum bar for the converter. The following are the key technical items of the all-aluminum materials electrical system.

3.1. Aluminum Winding Generator Development

The aluminum winding generator is a key component of the all-aluminum materials electrical system, and its development process needs to overcome a number of technical difficulties.

3.1.1. Optimization and Performance Testing of Aluminum Magnet Wire Materials

The selection of aluminum magnet wire materials is the primary task of aluminum generator research and development. In the selection process, factors such as conductivity, mechanical strength, corrosion resistance and cost of the material need to be comprehensively considered. Through performance testing and comparative analysis of different aluminum magnet wire materials, the most suitable materials for wind turbine applications can be screened. The performance test mainly includes the test of conductivity, tensile strength, yield strength, elongation and corrosion resistance. Through testing, it can be ensured that the selected material can meet the long-term stable operation needs of the generator in harsh environments.

3.1.2. Design and Manufacture of Aluminum Winding

Aluminum winding is one of the key components of the aluminum generator, and its design and manufacturing quality directly affect the performance and life of the generator. In the design and manufacturing process of aluminum winding, it is necessary to solve the problems of arrangement, insulation, fixing and protection of aluminum wire winding. At the same time, it is also necessary to consider the connection between the aluminum wire winding and the copper wire to ensure the reliability of the connection point and excellent electrical performance. In order to achieve this goal, advanced manufacturing processes and technical means, such as precision winding, laser welding, and cold pressing connection, are required to ensure the quality and performance of aluminum windings.

3.1.3. Research on Copper-Aluminum Transfer Technology

Due to the great difference in the conductivity and mechanical properties of aluminum and copper, the research of copper-aluminum transfer technology is particularly important in the research and development process of aluminum generators. The main purpose of copper-aluminum transfer technology is to achieve a reliable connection of the aluminum winding to the copper conductor while ensuring the electrical properties and mechanical strength of the connection point. In the research process, it is necessary to explore different connection methods and process parameters, such as welding processes and cold pressing joining processes, etc., and verify and optimize them through experiments to ensure the reliability and stability of the transition point.

3.1.4. Performance Testing and Optimization of Aluminum Winding Generators

After the design and manufacture of aluminum winding generators is completed, comprehensive performance testing and optimization is required. The performance test mainly includes the test of electromagnetic performance, mechanical properties and insulation performance. Through the test, the operating status, performance parameters and existing problems of the generator can be understood, which can provide a basis for subsequent optimization and improvement. In the optimization process, it is necessary to make targeted improvements and optimizations for the problems found in the test, such as adjusting the winding structure, optimizing the insulation material, and improving the heat dissipation mode, so as to improve the performance and stability of the generator.

We carry out type tests for copper winding and aluminum winding generators according to the requirements of IEC 60034-1:2022 «Rotating electrical machines - Part 1: Rating and performance» standards, and the key test items meet the requirements of the standard, so the cost of aluminum winding generators is more economical under the same performance conditions. See **Table 1** for detailed test items.

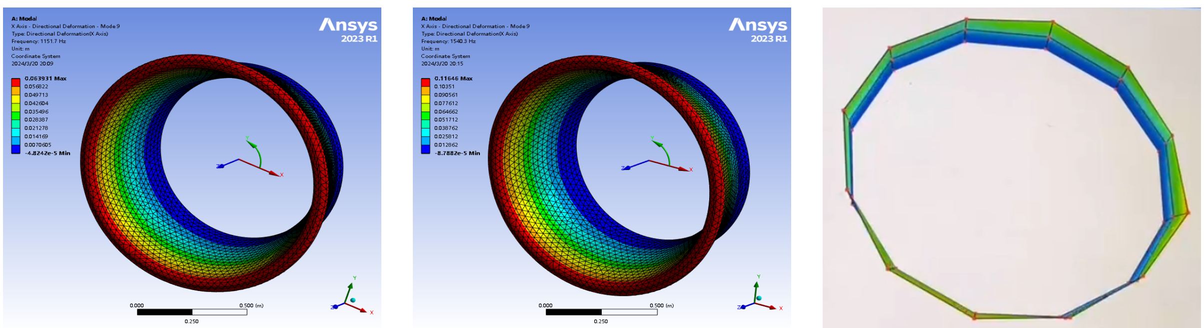
Table 1. Key test items for copper winding and aluminum winding generators.

Test	Test Requirements
Immersion test	The coil is immersed in water, the insulation resistance is measured, the insulation resistance is 1000 V test, the insulation resistance >500 MΩ
Short-circuit shock	Number of tests per phase: 3 times Duration(s): 0.5 10%
Winding dimensional stability test	After the temperature rise stabilizes, it lasts for 50 h and drops After measuring the end windings at room temperature in the axial direction and the amount of dimensional change in the radial direction.
Insulation heat resistance rating	Single-point temperature resistance level test
Electrothermal aging	2*Un 150 °C

3.1.5. Modal Test of Stator End of Aluminum Winding Generator

Modal analysis of the stator end of the aluminum winding generator is one of the important means to ensure the stable operation of the generator [24, 25]. Modal analysis can help understand the vibration characteristics and natural frequencies of the stator end of the generator and provide a basis for subsequent vibration control and structural optimization. When performing modal analysis, advanced testing and analysis methods, such as accelerometers, hammers, and modal analysis software, are required to obtain accurate vibration data and modal parameters. Through the analysis results, the vibration characteristics and weak links of the stator end of the generator can be understood, which can provide a reference for subsequent improvement and optimization. The simulation results are detailed in **Figure 1**.

Three cross-sections were selected from the inside to the outside along the axial direction at the end of the stator, and 12 measuring points were uniformly arranged along the circumferential direction of each cross-section, with a total of 36 measuring points. Three piezoelectric single-axis accelerometers are mounted at each of the three measuring points, with the mounting surface perpendicular to the radial direction of the motor, to measure the radial vibration component. A hammer with a piezoelectric transducer is struck at intervals four times at a fixed position, recording the signal data of the hammer and each accelerometer, aligning the data of the four strikes and processing them equally. The sensor mounting position is changed, tapping at the same position, and the test is repeated until all measurement points are traversed. Finally, the analysis software is used to process the data, decompose the mode shapes of each order, establish a geometric simplified model of the stator end, and set the end close to the core as a fixed constraint. In the modal analysis software, the mode shapes and frequencies of each order mode at the end of the stator are simulated and analyzed.



(**a**) (**b**) (**c**)

Figure 1. End modal test: (**a**) Copper (1152 Hz); (**b**) Aluminum (1540 Hz); (**c**) Measured (203 Hz).

The resonance frequencies of each order mode are mainly related to the geometry and material properties. Under the condition of consistent geometry, the frequency is proportional to , where is the modulus of elasticity of the material and is the density of the material. Therefore, when the geometry is the same, the natural frequency of the aluminum end is higher than that of the copper end.

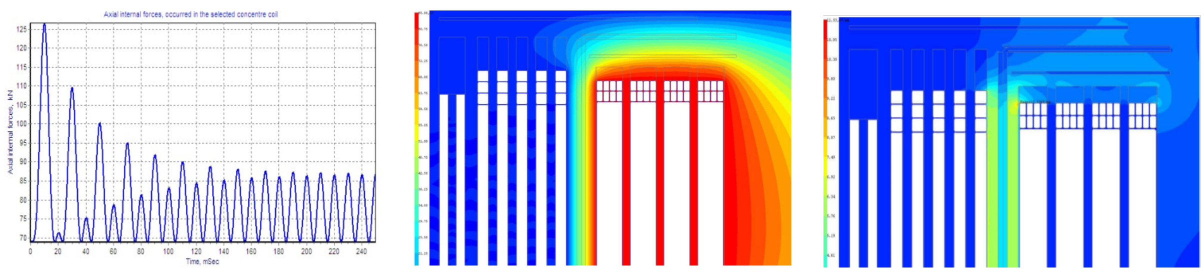
Through the development and testing of these key technologies, the performance and reliability of aluminum-wound generators will be significantly improved, thus laying a solid foundation for the development of all-aluminum materials electrical systems.

3.2. Aluminum Transformer Development

Aluminum transformers play a critical role in all-aluminum materials electrical systems. From the perspective of manufacturing costs, if the manufacturing costs after reducing the rated power of the copper winding are still higher than those of the aluminum winding transformer with the same rated power, the use of aluminum is more economical [26]. The resistivity of aluminum transformers is 170% of that of copper, the density is 30% of that of copper, the weight of the same resistance is only 51% of that of copper, and the price of aluminum is only 35%–40% of that of copper, thus achieving good energy-saving effects, low product costs, and obvious energy-saving and consumption-reducing effects. The key technical challenges to be overcome during their development include .

3.2.1. Design and Manufacture of Aluminum Winding Coil

The winding coil is one of the core components of the aluminum transformer, and its design and manufacturing quality directly affects the performance and life of the transformer. In the design and manufacturing process of aluminum winding coils, it is necessary to solve the problems of coil arrangement, insulation, fixing and protection [27]. At the same time, factors such as the heat dissipation performance and mechanical strength of the coil also need to be considered. Through the simulation of the electric field of the transformer, the field strength distribution can be determined, The simulation results are detailed in **Figure 2**. In order to achieve this goal, advanced manufacturing processes and technical means, such as precision winding, laser welding, and hot press forming, are required to ensure the quality and performance of the coils.



(**a**) (**b**) (**c**)

Figure 2. Aluminum transformer simulation: (**a**) The high-voltage wire cake is axially stressed during the short circuit process; (**b**) Contour of potential distribution; (**c**) Contour of field strength distribution.

3.2.2. R&D of Laminated Iron-Core All-Aluminum Box Transformer Products

The R&D of laminated iron-core all-aluminum box transformer products is one of the key points of R&D of aluminum transformers. The laminated iron core structure has excellent electromagnetic properties and mechanical strength, which can meet the long-term stable operation needs of transformers in harsh environments. In the process of research and development, it is necessary to solve the problems of the manufacturing process of the stacked iron core, the winding process of the coil, and the selection of insulating materials. At the same time, it is also necessary to test and optimize the performance of the stacked iron-core all-aluminum box transformer to ensure that it meets the needs of the wind power system.

3.2.3. Research and Optimization of Aluminum Transformer Manufacturing Process

The manufacturing process of aluminum transformers is one of the important factors affecting their performance and cost. In the process of research and optimization of the manufacturing process, it is necessary to explore different manufacturing processes and technical means, such as laser welding, cold pressing connection, and hot press forming, and verify and optimize through experiments to ensure the stability and reliability of the manufacturing process. At the same time, it is also necessary to optimize the cost control and efficiency improvement of the manufacturing process to reduce the manufacturing cost of aluminum transformers and improve production efficiency.

3.2.4. Aluminum Transformer Performance Testing and Optimization

After the design and manufacture of aluminum transformers are completed, comprehensive performance testing and optimization are required. The performance test mainly includes the test of electromagnetic performance, mechanical properties, and insulation performance. Through the test, the operation status, performance parameters, and existing problems of the transformer can be understood, which provides a basis for subsequent optimization and improvement. In the optimization process, it is necessary to make targeted improvements and optimizations for the problems found in the test, such as adjusting the coil structure, optimizing the insulation material, and improving the heat dissipation mode, to enhance the performance and stability of the transformer.By adjusting the composition of the prepared liquid aluminum, controlling the sensitive element composition, and micro-alloying, a high conductivity duralumin alloy with better properties was obtained [28].

We carry out type tests for copper winding and aluminum winding transformers according to the requirements of the IEC60076-11:2018 «Power transformers -Part 11:Dry-type transformers» standard, and the key test items meet the requirements of the standard, so the cost of aluminum winding transformers is more economical under the same performance conditions. See **Table 2** for detailed test items.

Table 2. Key test items for copper winding and aluminum winding transformers.

Test	Test Requirements
No-load loss	0.6 + 10%
Short-circuit impedance and load loss	t: 120 °C Z(%): 10.0 P(kw): 72 ± 10% P(kW): 87
Partial discharge test	Three-phase measurement Applied voltage (kV): 1.3 Ur Duration (min): 3 Discharge (pC): ≤10
Temperature rise test	In the AF state, the temperature rise limit of the winding (K): 85
Short-circuit withstand test	Number of tests per phase: 3 times Duration(s): 0.5 10%
Lightning impulse test	Full Wave (kV): 170 ± 3%

3.2.5. Research on the Adaptability of the Application Environment of Aluminum Transformer

The application environment of aluminum transformers in wind power systems is relatively harsh, so it is necessary to study the adaptability of their application environment. The research content mainly includes the performance change and stability of aluminum transformers in different temperatures, humidity, salt spray, and other environments. Through experiments and tests, we can understand the adaptability and performance changes of aluminum transformers in different environments and provide references for subsequent improvement and optimization. At the same time, aluminum transformers can also be designed and optimized according to the needs of the application environment to improve their adaptability and reliability.

Through continuous research and improvement of these key technologies, the performance of aluminum transformers will be significantly improved, thus providing strong support for the reliability and efficiency of all-aluminum materials electrical systems.

3.3. Aluminum Cable Development

Aluminum alloy cables play a critical role in all-aluminum materials electrical systems, and the key technical challenges to be addressed in their development include.

3.3.1. Structural Design of Aluminum Alloy Conductors:

Study and optimize the structural design of aluminum alloy conductors, and select appropriate conductor structures to ensure that the cables can meet the expected performance requirements.

3.3.2. Torsional Performance of Aluminum Alloy Cables

In-depth investigation of the performance of aluminum alloy cables in torsional conditions, through rigorous testing and verification to ensure that the cable can adapt to the torsional stress generated by wind turbines in operation.

3.3.3. Aluminum Alloy Cable Crimping/Butting Process

Research and improve the aluminum alloy cable crimping and butting process, through testing and verification, to ensure the reliability of the connection and excellent electrical performance.

Through the continuous research and improvement of these key technologies, the performance of aluminum alloy cables will be significantly improved, thus providing strong support for the reliability and efficiency of all-aluminum materials electrical systems.

3.4. Converter Aluminum Row Development

The comparison of the parameters of copper bars and aluminum bars is as follows **Table 3**:

Table 3. Comparison of parameters between copper and aluminum bars.

	Test	Copper Bars	Aluminum Bars
Mechanical properties	Tensile strength	113.8 MPa	220–270 MPa
	Elongation	30%	30–45%
	Yield strength	53.9 MPa	60–80 MPa
Electrical properties	DC resistivity	0.0279 IACS%	0.0172 IACS%
	Electrical conductivity	61.8 Ω mm^2 m^{-1}	100 Ω mm^2 m^{-1}

- The elongation at break of aluminum alloy conductors and copper conductors is basically the same, which can effectively avoid the shortcomings of poor mechanical strength and easy breaking of pure aluminum.
- The yield strength of aluminum alloy conductors and copper conductors is basically the same, so the creep performance of aluminum alloy conductors is close to that of copper conductors, alleviating the problem of fast creep deformation of aluminum alloy.
- In order to solve the problem of overlap between copper bars and aluminum bars, it is found that the surface of the aluminum bar needs to be tinned or nickel-plated in practical applications, and the lap of copper bars and aluminum bars can also be realized by using a copper-aluminum transition piece. The external wiring of the converter is still connected by copper bars, and all of them are tin-plated, eliminating the electrochemical corrosion problem of the lap surface.

As a core component of the all-aluminum materials electrical system, the key technical challenges to be addressed in the development of the converter aluminum row include:

- Aluminum row grade selection: Select the appropriate aluminum row grade to ensure that the selected material can meet the performance requirements of the converter operation.
- Individual performance testing of aluminum rows: Conduct a comprehensive performance evaluation of the aluminum rows, including mechanical properties, process characteristics and electrical conductivity, in order to verify whether they meet the performance standards of the converter.
- Research on the special characteristics of aluminum rows for converter applications: In-depth investigation of the special performance requirements of aluminum rows for converter applications, and through testing and verification, ensure that the aluminum rows can meet the specific performance requirements of the converter.

Through the continuous research and improvement of these key technologies, the performance of aluminum rows for converters will be significantly improved, thus providing strong support for the reliability and efficiency of all-aluminum materials electrical systems.

4. Innovative Highlights of the All-Aluminum Materials Electrical System

The aluminum winding generator adopts an innovative molding bracket and end hoop combination support design. This structure not only solves the motor end fixing and lead transfer fixing problems but also significantly improves the impact resistance of the motor end and enhances the overall mechanical stability.

In the development of aluminum transformers, taking into account the power stability performance of the stacked core aluminum winding box variable coil, the design does not simply use the traditional copper winding round length structure and replace the material. Instead, it synthesizes the needs of cost and structural strength, innovatively choosing a coil shape similar to an ellipse, and improved the hardness of the coil conductor, and taking measures such as auxiliary fabrication processes to ensure that the mechanical strength of the coil is met.

The design of the aluminum alloy cable focuses on meeting the special requirements of wind turbines for torsional performance. Through the innovative design of the conductor structure, it is ensured that the cable can withstand torsional stress in the operation of the unit while maintaining good electrical performance and mechanical strength.

The design innovation of the aluminum row of the converter is reflected in solving the long-term dependence on copper rows, which not only reduces the direct material cost of the converter but also improves the economy of the whole system. The reliability and efficiency of the converter's aluminum rows are ensured by the selection of suitable aluminum materials and the optimization of the design.

These innovations not only represent a breakthrough in the design of all-aluminum materials electrical systems, but also show the great potential of aluminum in electrical components, opening up new paths for sustainable development and cost reduction in the wind power industry.

5. Market Outlook for All-Aluminum Materials Electrical Systems

In 2024, wind power prices continue to dip, as do the high prices of copper materials in the environment. All-aluminum materials electrical systems are very necessary, not only only to form a a technology leader in the wind power industry but also to bring objective cost reductions to the overall electrical component costs, providing strong support for the company's product market. The all-aluminum materials electrical system has obvious cost and performance advantages and broad market prospects in the field of wind power.

5.1. Onshore Wind Power Market

The onshore wind power market has a strong demand for large-scale, low-cost electrical systems. From January to March 2024, the domestic new wind power installed capacity reached 15.5 GW (+49%). From January to February, there were still 23 projects delayed due to the end-of-year rush to install, impacting grid connections, while in March, the single-month new installed capacity was 5.6 GW (+23%). The year total wind power installed capacity for 2024 is expected to grow further.In wind, the past few years, tenders for onshore wind have approached 100 GW, and it is expected that the installed capacity for 2024 will reach 80 GW. At the same time, the development of wind power in rural areas and the further expansion of large-scale projects will bring incremental demand.

5.2. Offshore Wind Power Market

At the beginning of 2024, Zhejiang's "14th Five-Year Plan" for offshore wind power was approved, including 8.5 million kilowatts of the provincial management sea wind projects and 8 million kilowatts of state management sea wind projects. The requirements state that by the end of 2025, 2 million kilowatts of both provincial and state management projects must be connected to the grid. The development of deep-sea wind power is supported by the state to promote GW-level parity demonstration projects. On October 18, 2023, the National Energy Board issued a notice "on the organization of renewable energy development pilot demonstration notice" [29], which put forward to support for large-capacity wind turbines for nearshore and offshore applications, and support for deep-sea offshore wind demonstration, with project scales required to be at least 1 GW.

5.3. "Thousands of Villages Harnessing Wind Action" Launched, Accelerating Distributed Wind Power Advancement

On March 25, 2024, the National Development and Reform Commission (NDRC), the Energy Bureau, and the Ministry of Agriculture and Rural Development (MARD) jointly issued the Notice on Organizing and Carrying out the "Thousands of Villages and Ten Thousand Villages Harnessing the Wind Action", which opens up space for the development of distributed wind power: the theoretical space is close to 10,000 GW, with boundary conditions restricting the expected lower limit to 500 GW. The scale of new demand in the next few years is expected to reach 20–40 GW per year.

6. Summary and Outlook

The all-aluminum materials electrical system perfectly fits the needs of the market for wind power in rural areas, large wind turbines, wind power base projects, and deep and distant sea applications, coinciding with the "14th Five-Year Plan" for wind power development and the 2035 Vision Outline, accurately aligning with the needs of the target market. The system will provide strong support for the industrialization of large-capacity units on land and sea, help the strategy of rural revitalization, and enhance the competitiveness of products in the wind power markets.

Meanwhile, the strategy of "replacing copper with aluminum" not only responds to the macro goal of energy saving and emission reduction but also has a significant effect in practical application. Aluminum transformers, for example, have an all-aluminum structure that reduces material costs, including copper, iron, oil and others, by about 5 to 10% compared to all-copper products, while also offering a low cost and high performance advantages. The all-aluminum products of Grade 1 energy-efficiency class can save electricity up to 465,000 kW over their life cycle, equivalent to saving 232.5 tons of standard coal, reducing CO_2 emissions by about 580 tons, and lowering direct running costs by 232,500 yuan.

In addition, the all-aluminum materials electrical system positively responds to the national energy strategy of carbon neutrality and carbon peak, effectively reducing China's consumption of copper resources for strategic energy materials. The promotion and application of the system greatly reduce the cost of electricity in the wind power industry and significantly decreases the amount of copper cables used in wind power, thus accelerating the realization of China's carbon neutrality and peak carbon goals and significantly reducing the consumption of copper resources.

Although this paper has achieved remarkable results in the research of all-aluminum electrical systems, there are still some limitations. First of all, aluminum is better than most metals in terms of electrical conductivity, but still inferior to copper, which may limit some applications that require high conductivity. Secondly, the welding and joining technology of aluminum is more complex than that of copper, and needs to be further optimized to improve the reliability and stability of the system. In addition, the long-term operational performance and environmental adaptability of the all-aluminum electrical system need to be verified by more actual operation data.

In view of the above limitations, future work can be carried out from the following aspects: first, continue to develop high-performance aluminum materials to improve their conductivity and mechanical strength; Second, optimize the welding and joining process of aluminum materials to reduce manufacturing costs and improve system reliability; Third, strengthen the long-term operation monitoring of the all-aluminum electrical system, accumulate actual operation data, and provide a basis for system optimization and improvement. At the same time, with the continuous development of the wind power industry, it is necessary to further explore the application potential of all-aluminum electrical systems in other renewable energy fields in the future.

The research and development of the all-aluminum materials electrical system and its industrialization process not only promote the continuous innovation of wind power technology but also facilitate the ongoing progress of technology and the continuous expansion of the market. Additionally, it helps the wind power industry to form a complete industrial chain, including equipment manufacturing, installation, operation, and maintenance, further promotes promoting the upgrading and development of related industries and improving the ecological circle of the upstream and downstream industry chain of wind power. The successful application of this system is of great significance in promoting the sustainable development of the wind power industry and enhancing China's competitiveness in the global wind power field.

Author Contributions

Conceptualization, L.W., W.Z., and Z.W.; methodology, L.W.; software, W.Z., and Z.W.; validation, L.W., and Z.W.; formal analysis, W.Z.; investigation, L.W., W.Z., and Z.W.; data curation, L.W., W.Z., and Z.W.; writing—original draft preparation, L.W., and Z.W.; writing—review and editing, L.W.; visualization, L.W.; supervision, L.W.; project administration, L.W.; funding acquisition, L.W. All authors have read and agreed to the published version of the manuscript.

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