Exploration of Methods for Coupling and Integration of Green Electricity in Aluminium Smelter

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Abstract

Aluminium electrolysis has a substantial demand for electrical energy. The rational and effective integration of green electricity into aluminium smelters both aligns with policy, and reduces the amount of electricity purchased from the grid, decreases carbon emissions effectively. This approach serves as an effective means to assist the aluminium industry in achieving the dual goals of "carbon peak and carbon neutrality" as well as dual control over energy consumption. Furthermore, many aluminium smelters are located near regions with well-developed or developing green energy industries generation, such as wind power and photovoltaic power generation, which can provide favourable conditions for the application of green electricity. This paper explores methods for the coupling and integration of green electricity in aluminium smelters and proposes optimization suggestions for the current stabilization strategy of the rectification system.

Keywords: Aluminium electrolysis, Green electricity, Coupling and integration, Current stabilization strategy.

1. Introduction: Necessity of Green Power Coupling and Integration in Aluminium Smelters

Since the beginning of the 21st century, China has significantly increased investments and production capacity in renewable energy, driven by the government's heightened emphasis on environmental protection, sustainable development, and international climate commitments. As an energy-intensive sector, the aluminium electrolysis industry requires substantial electricity input, with power consumption being the primary source of carbon emissions during production.

Current data indicate that coal-fired power dominates the electrical supply for aluminium production in China, while renewable sources such as wind and photovoltaic (PV) energy account for a minimal share. Producing one tonne of aluminium emits approximately 1.8 tonnes of CO_2, with the industry's total emissions reaching 438 million tonnes in 2023 – about 5 % of China's net CO_2 emissions. This highlights the sector's immense potential for emission reduction.

Moreover, aluminium production demands consistent and large-scale power supply, particularly in regions with unstable electricity availability or volatile pricing. Integrating wind and solar power has thus become an inevitable trend. Notably, most aluminium plants are located in areas abundant in renewable resources, creating favourable conditions for localized green power consumption. Adopting region-specific renewable energy solutions not only aligns with national decarbonization policies but also reduces reliance on grid electricity, cuts carbon emissions, and supports the industry's dual-carbon and energy efficiency control goals.

However, wind and solar power face challenges such as intermittency, unpredictability, and instability. Without effective integration methods, these issues can lead to power supply fluctuations and low utilization efficiency in aluminium plants. Therefore, developing tailored green power coupling and consumption strategies which consider the unique power demands of aluminium production and the characteristics of wind/PV generation is essential.

1.1 Power Supply Characteristics of Aluminium Electrolysis

As energy-intensive facilities, aluminium electrolysis plants have consistently ranked among the largest electricity consumers in regional grids [1]. The power load of these plants primarily consists of DC power for electrolytic cells and AC power for auxiliary systems including flue gas purification, compressed air stations, and casting workshops. Notably, DC power consumption accounts for over 95 % of the plant's total electricity demand. For instance, a typical 500 000 t/a aluminium electrolysis plant has total approximately 6.65 TWh power consumption per year, including about 6.4 TWh DC power consumption with electrical costs constituting 40–50 % of total production expenses.

Furthermore, under China's "Dual Carbon" environmental goals (commitment to peak carbon dioxide before 2030 and achieve carbon neutrality by 2060) and industrial adjustments [2], increasingly stringent energy consumption limits per unit product have been imposed on aluminium producers. This has placed high-energy-consumption plants at risk of being phased out as obsolete capacity.

The production process employs molten salt electrolysis, requiring three key materials: alumina, fluoride salts, and carbon anodes. The necessary DC power is supplied by rectifier stations. In electrolysis cells, dissolved alumina undergoes redox reactions with carbon anodes under electrical current to produce molten aluminium. Once electrolytic cells are started and enter normal production, they require a reliable, continuous, and stable DC power supply. If the DC current decreases during production, the cell temperature will drop, leading to reduced output. Prolonged power interruptions may cause a complete shutdown, or even result in solidified aluminium in the cell, damage to the electrolytic cell equipment, and in severe cases, permanent scrapping. Therefore, the DC power supply system for aluminium electrolysis must meet the requirements of Grade I power loads.

The rectifier station is a critical power supply facility in an aluminium smelter, responsible for converting AC power from the external grid into DC power, providing the full DC supply for the electrolytic cells.

1.2 Challenges in Applying Green Power Supply to Aluminium Electrolysis

As previously established, aluminium electrolysis production imposes stringent requirements on power supply stability. A sudden power interruption that cannot be promptly restored may cause severe damage to both production and equipment—particularly to the DC electrolysis system. Such events can significantly reduce electrolytic cell lifespan and even lead to complete system failure. Consequently, both the DC electrolysis system and critical auxiliary production systems must be designed to meet Grade I power load standards.

Photovoltaic (PV) power generation systems, primarily composed of solar panels and inverters, generate electricity that heavily depends on weather conditions such as solar irradiance and ambient temperature. Similarly, wind power systems, consisting of turbines, generators, transmission systems, power converters, and towers, are also subject to natural factors like wind speed and direction. Furthermore, without effective energy dispatch and utilization, significant curtailment of solar and wind power may occur, reducing the overall efficiency of renewable energy usage.

system's injected current magnitude, the system selects between master-slave coordinated control (total adjustment) or distributed independent control (partial adjustment) as follows:

a) Master-slave coordinated control：The photovoltaic (PV) system's injected current is subtracted from the current stabilization system's setpoint value.
b) Distributed independent control：The PV system's output current is divided by the number of operational rectifier units to obtain the deduction value per rectifier, which is then subtracted from each unit's current setpoint value.

Furthermore, significant variations exist in PV output current volatility due to regional climate differences and photovoltaic system configurations. When PV DC-coupled current fluctuations exceed ±5 % of the aluminium electrolysis potline current, the following measures are recommended to enhance current stabilization performance:

1) Coordinated control strategy upgrade: Implement constant-power voltage regulation for current stabilization [3].
2) Utilize thyristor-based rectification elements to achieve superior dynamic response and current stabilization performance.
3) Integrate flexible aluminium electrolysis production technology by deeply coupling the PV DC power supply system with the electrolytic cell's flexible production process to enhance energy efficiency.

4. Conclusions

Under China's "Dual Carbon" goals (commitment to peak carbon dioxide before 2030 and achieve carbon neutrality by 2060), integrating green electricity into aluminium smelters and coupling it with flexible consumption not only aligns with national decarbonization directives but also significantly reduces grid power purchases and optimizes the plant's specific energy consumption metrics. Globally, an increasing number of aluminium plants have successfully integrated renewable energy (primarily photovoltaic and wind power) into their production processes, achieving significant operational and environmental benefits [4–5]. For example, the aluminium smelter in Huolinhe, Inner Mongolia has successfully implemented a wind-PV-energy storage hybrid power supply system to provide electricity for its production. Aluminium smelters in Yangzhonghai Yunnan, Qingtongxia Ningxia and other regions have successfully implemented DC-coupled photovoltaic power supply systems for their production. However, the inherent intermittency and variability of certain renewable energy sources (such as wind and solar PV generation) necessitate the implementation of flexible power supply strategies and the development of the ways of coordinated current stabilization specifically designed to accommodate the characteristics of green electricity. Through optimized control parameters, enhanced regulation response speed, intelligent energy dispatch, and strategic deployment of customer-side energy storage and so on, it mitigates production instability in aluminium electrolysis caused by power fluctuations, improves green electricity utilization efficiency, achieves "Dual Carbon" goals [6].

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