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Application of Energy-Saving Optimization Technology for Coal Mine Power Supply Systems

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Abstract: The coal mine power supply system serves as the "lifeblood" of mine production, accounting for 60% to 80% of the mine's total energy consumption. Issues such as equipment oversizing, low power factor, severe harmonic pollution, and irrational peak-valley electricity usage indicate significant energy-saving potential. This paper systematically analyzes the main energy consumption points and their causes in coal mine power supply systems, proposing an integrated energy-saving optimization framework based on reactive power compensation, harmonic mitigation, transformer economic operation, variable-frequency speed regulation, and peak-valley electricity management. Dynamic reactive power compensation can increase the power factor to above 0.95, while variable-frequency speed regulation achieves energy savings of 20% to 35% for fan and pump loads. Comprehensive energy-saving measures can yield an overall energy reduction of 15% to 25% in mine power supply systems.

Keywords: Coal mine power supply; Energy saving optimization; Reactive power compensation; Variable frequency speed regulation; Harmonic control

Introduction

Coal mining is a high-energy-consumption industry, and the power supply system, as the driving force behind mine production, has an operational efficiency that directly impacts both the economic benefits of enterprises and the achievement of national "dual carbon" goals. In recent years, the rapid development of power electronics and intelligent control technologies has provided technical support for energy conservation in coal mine power supply systems. This paper systematically elaborates on the principles and applications of energy-saving optimization technologies for coal mine power supply systems from five dimensions: reactive power compensation, harmonic control, economic operation of transformers, variable frequency speed regulation, and electricity management.

1. Analysis of Energy Consumption Characteristics and Issues in Coal Mine Power Supply Systems

1.1 Power Supply System Structure and Energy Consumption Composition

Coal mine power supply systems typically employ dual-circuit power supply lines and a hierarchical radial distribution structure, with voltage levels spanning multiple tiers, including 110kV, 35kV, 10kV, 6kV, and 1140V, 660V, 380V. The surface substation steps down grid electricity and transmits it to the underground central substation, which then distributes power through district substations to various electrical equipment. Major power loads include: ventilation fans (accounting for 20% to 30% of total mine energy consumption), drainage pumps (15% to 25%), hoists (10% to 20%), mining equipment (15% to 25%), transport equipment (10% to 15%), air compressors (5% to 10%), and auxiliary equipment (approximately 5%). Energy consumption analysis reveals that fan and pump loads—characterized by continuous operation, high power, and frequent load fluctuations—are key targets for energy optimization. Transformer no-load losses, line losses, and additional losses caused by reactive power also constitute significant components of energy consumption.

1.2 Major Energy Consumption Issues and Their Causes

The issue of high energy consumption in coal mine power supply systems can be categorized into five types. First, equipment oversizing and light-load operation. To meet short-term peak load demands, transformers and motors are generally selected based on maximum operating conditions, resulting in a common scenario where daily operating load rates are below 50%. No-load losses of transformers can account for over 30% of total losses. Second, low power factor. The extensive use of asynchronous motors in underground coal mines results in a natural power factor typically ranging from 0.6 to 0.8. A low power factor not only increases line losses but also reduces the output capacity of transformers, leading to additional power factor adjustment fees imposed by electricity authorities [1]. Third, severe harmonic pollution. Non-linear loads such as frequency converters, soft starters, and rectifier equipment generate significant harmonics. Harmonic currents cause additional heating, insulation aging, and metering errors. Measurements indicate that harmonics can increase transformer losses by 10% to 20%. Fourth, outdated speed regulation methods. Many coal mine fans and pumps still use dampers or valves for regulation, resulting in throttling losses as high as 30% to 50%, leading to substantial energy waste. Fifth, inefficient electricity management. The absence of time-of-use electricity strategies results in a high proportion of equipment operation during peak hours. Additionally, the lack of online monitoring and energy consumption analysis systems makes it difficult to quantify and identify energy-saving potential. Systematically addressing these issues requires the comprehensive application of various energy-saving technologies.

2. Key Technologies for Energy Saving and Optimization in Power Supply Systems

2.1 Reactive Power Compensation Technology

Reactive power compensation is the most direct method to improve the power factor and reduce line losses in coal mine power supply systems. Coal mine reactive power compensation should adhere to the principle of "graded compensation and local balance," with compensation devices installed at the underground central substation, mining area substation, and high-capacity equipment terminals. For surface substations, high-voltage static var generators (SVG) are employed, featuring a response time of less than 5 milliseconds, enabling continuous reactive power regulation and maintaining the power factor on the 110kV side above 0.95. In underground power supply systems, due to humid conditions and space constraints, explosion-proof dynamic reactive power compensation devices are preferred, with thyristor-switched capacitors (TSC) combined with static var generators (SVG) as the core components. Dynamic compensation can track reactive power fluctuations in real time, preventing overcompensation or undercompensation. In practical applications, after installing fast reactive power compensation devices near impact loads such as shearers and scraper conveyors, the power factor increased from 0.72 to 0.93, line current decreased by 18%, and annual energy savings reached over 300,000 yuan. The determination of compensation capacity requires reactive power balance calculations based on measured load data, typically configured at 20% to 40% of the transformer capacity.

2.2 Harmonic Control Technology

Harmonics generated by non-linear equipment not only increase power loss but also interfere with protection devices and communication systems. Coal mine power supply systems adopt a combined approach of passive and active filtering for harmonic mitigation. Passive filter devices, composed of reactors and capacitors connected in series, are designed to target characteristic harmonics such as the 5th and 7th orders. They also provide reactive power compensation and are suitable for scenarios where harmonic sources are fixed and harmonic content remains stable. Active power filters (APFs) dynamically cancel harmonic components by detecting harmonic currents in real-time and generating inverse compensation currents. While APFs offer superior compensation performance, their higher cost makes them more suitable for areas with concentrated frequency converters. After installing a 200A active filter in an underground substation of a coal mine, the total harmonic distortion rate decreased from 12.5% to 3.8%, transformer winding temperature dropped by 6°C, and transformer losses were reduced by approximately 12%. Filtering devices should be installed near harmonic sources to prevent harmonic currents from propagating over long distances in power supply lines. Additionally, energy-efficient transformers with a sufficient K-factor should be selected to enhance their resistance to harmonics [2].

2.3 Transformer Economic Operation Technology

Coal mine power supply systems have a large number of transformers with high total capacity, making transformer economic operation a key approach to energy conservation. The core of economic operation lies in optimizing transformer operation modes and load distribution. For substations with dual-transformer operation, the economic operating range should be determined based on load variation patterns: when the total load is below 60% of a single transformer's rated capacity, one transformer should be automatically switched off to reduce no-load losses; when the load exceeds 80% of a single transformer's capacity, the second transformer should be activated. Taking two 1000kVA transformers as an example, switching off one during light-load periods can save 300 to 500 kWh of electricity per day. Energy-efficient amorphous alloy transformers should replace outdated S7 and S9 series transformers, as amorphous alloy transformers reduce no-load losses by 60% to 70% compared to S9 models. For equipment with significant seasonal load variations (such as transformers for ground heating boiler rooms), power should be completely cut off during non-heating seasons. The transformer economic operation decision system enables intelligent management by monitoring real-time load data, automatically generating switching strategies, and remotely controlling circuit breakers.

2.4 Variable Frequency Speed Control Technology

Variable frequency speed control is the most effective energy-saving technology for loads such as coal mine fans and water pumps. According to the similarity laws of fluid machinery, flow rate is proportional to rotational speed, while power is proportional to the cube of rotational speed. When the flow demand drops to 80%, the theoretical power required is only 51.2% of the rated power. After applying variable frequency speed control to equipment such as main ventilation fans, auxiliary ventilation fans, drainage pumps, and air compressors in coal mines, the electricity saving rate generally reaches 20% to 35%. The following points should be considered when selecting a variable frequency speed control system: the capacity of the frequency converter should be one grade higher than the motor capacity to accommodate voltage fluctuations and overload conditions in underground coal mines; input reactors and output filters should be installed to suppress harmonics and reduce damage to motor insulation caused by du/dt; for long-distance power supply (exceeding 100 meters), output reactors should be added to compensate for the effects of distributed capacitance in long cables. In gas outburst mines, the frequency converter must be of the flameproof and intrinsically safe type and comply with relevant explosion-proof standards. In addition to energy-saving benefits, variable frequency speed control enables soft starting of motors, reducing mechanical and electrical shocks, extending equipment lifespan, and lowering maintenance costs.

2.5 Peak and Valley Electricity Usage and Smart Management

Coal mines should align with production realities by scheduling non-continuous operations such as drainage, backfilling, and material preparation during off-peak hours (typically from 23:00 to 07:00 the next day), while maintaining only safety ventilation and drainage during peak hours. After implementing a strategy of off-peak drainage and peak-hour shutdowns for maintenance at one mine, annual electricity costs were reduced by approximately 18%. An online energy efficiency monitoring platform for the power supply system has been established, with smart meters and power quality analyzers installed in key distribution circuits to collect real-time parameters such as voltage, current, power factor, harmonics, and demand. The platform features functions for energy consumption data analysis, anomaly alerts, and energy-saving potential assessment, automatically generating shift-based, daily, weekly, and monthly energy consumption reports. It benchmarks historical data to identify periods and equipment with abnormal energy usage. After integrating the energy efficiency management platform with the production scheduling system, ventilation and drainage plans can be dynamically adjusted based on the progress of mining faces, enabling on-demand power supply and avoiding unnecessary energy consumption.

3. Comprehensive Energy-Saving Solution Design and Benefit Analysis

3.1 Comprehensive Energy-Saving Solution Architecture

Energy-saving optimization of coal mine power supply systems should follow a systematic process of "monitoring and diagnosis—solution design—implementation and retrofitting—effect verification."

Step 1: Conduct an energy consumption survey of the power supply system, performing continuous monitoring for one week on lines at various voltage levels, transformers, and major electrical equipment to collect basic data such as load curves, power factors, and harmonics.

Step 2: Based on the monitoring results, assess the energy-saving potential, calculate the theoretical electricity-saving capacity at each stage, and determine the priority for retrofitting. Typically, reactive power compensation and variable frequency speed control have the shortest payback periods and should be implemented first, followed by transformer replacement and intelligent management [3].

Step 3: Develop a comprehensive energy-saving plan that integrates measures such as reactive power compensation, harmonic mitigation, variable frequency retrofitting, economic operation of transformers, and intelligent monitoring, ensuring that interactions between subsystems are avoided. For example, active filters should be installed in areas with concentrated frequency converters to prevent harmonic interference with the normal switching of reactive power compensation devices.

Step 4: Implement the retrofitting in phases, starting with easier tasks before moving to more complex ones, and prioritizing surface installations over underground ones to ensure safe power supply during the retrofitting period.

Step 5: After the retrofitting is completed, conduct an effect verification for no less than three months, measuring the actual electricity-saving rate and comparing it with the expected target.

3.2 Energy Saving Benefit Analysis

Taking a modern coal mine with an annual output of 3 million tons as an example for energy-saving benefit calculation. The main electrical equipment of the mine includes: 2 main ventilation fans (400 kW × 2), 3 main drainage pumps (500 kW × 3), 4 air compressors (250 kW × 4), 1 hoist (800 kW), and mining equipment with a total power of approximately 2,500 kW. The annual total electricity consumption is about 80 million kWh. After implementing comprehensive energy-saving retrofits, reactive power compensation increases the power factor from 0.78 to 0.95, and the line loss rate decreases from 10% to 7%, resulting in an annual electricity saving of approximately 2.4 million kWh. After installing frequency converters on the main ventilation fans and drainage pumps, with a comprehensive electricity saving rate calculated at 25%, the annual electricity saving is about 6 million kWh. After optimizing transformer operation, no-load losses are reduced by about 30%, resulting in an annual electricity saving of approximately 400,000 kWh. After optimizing peak and off-peak electricity usage adjustments, the average electricity price decreases by about 0.05 yuan/kWh. Based on an annual electricity consumption of 80 million kWh, the annual electricity cost saving is about 4 million yuan. The total annual electricity saving from the above measures is approximately 8.8 million kWh. At an electricity price of 0.65 yuan/kWh, the annual energy-saving benefit is about 5.72 million yuan. The total investment for the retrofits is approximately 8 million yuan (including frequency converters, reactive power compensation devices, active filters, intelligent monitoring systems, etc.), with a payback period of about 1.4 years. Additionally, the energy-saving retrofits can reduce carbon emissions by approximately 7,500 tons per year, providing significant environmental benefits.

3.3 Safety and Operational Precautions

Energy-saving retrofitting of coal mine power supply systems must prioritize safety. When installing frequency converters underground, explosion-proof products should be selected, and their cooling methods must match the underground environmental conditions (water-cooled types are preferred). The switching devices for reactive power compensation equipment should employ zero-crossing switching technology to avoid operational overvoltage. Before putting harmonic suppression devices into operation, a system impedance analysis should be conducted to prevent parallel resonance and harmonic amplification. During the energy-saving retrofitting period, live work is strictly prohibited in gas accumulation areas such as mining faces [4]. After the retrofitting is completed, the short-circuit capacity and protection settings of the power supply system should be recalculated and re-adjusted to ensure selective coordination of protection devices at all levels. For power supply systems utilizing a large number of power electronic devices, online power quality monitoring devices should be installed to monitor indicators such as harmonic distortion rates and voltage flicker in real time, preventing protection malfunctions or equipment damage caused by power quality issues. Additionally, a regular inspection system for energy-saving equipment should be established, and vulnerable components such as filter capacitors and power modules of frequency converters should be replaced periodically according to the manufacturer's requirements.

Conclusion

Energy conservation optimization of coal mine power supply systems is a crucial measure for reducing coal production costs and responding to national energy-saving and emission-reduction policies. This paper systematically analyzes the energy consumption characteristics and root causes of issues in coal mine power supply systems, and elaborates on the energy-saving optimization technology framework from five dimensions: reactive power compensation, harmonic control, economic operation of transformers, variable frequency speed regulation, and peak-valley electricity consumption management. Energy-saving retrofitting of coal mine power supply should adhere to the principles of systematic planning and phased implementation, advancing in an orderly manner while ensuring safety. Currently, there remains significant room for improvement in the digitalization and intelligence levels of coal mine power supply systems. In the future, further exploration should focus on energy efficiency optimization decision-making systems based on big data analysis and artificial intelligence algorithms, enabling adaptive energy-saving operation of power supply systems and providing technical support for the green and low-carbon transformation of coal mines.

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