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ARTICLE

Application of Energy Saving and Consumption Reduction Technology in Power Transmission and Distribution Lines

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ARTICLE INFO

Article history
Received: 18 April 2025
Accepted: 15 June 2025
Published Online: 30 June 2025

Keywords:
power fittings
energy saving and consumption reduction
material application; structure optimization
energy efficiency improvement

ABSTRACT

The power system is developing towards high voltage and large capacity. As a physical node of the energy transmission network, the metal tool is subject to complex electrical and mechanical loads. The resistance loss and additional hysteresis loss of its body have become the key bottlenecks affecting the transmission efficiency of the power grid. The eddy current thermal effect generated by traditional galvanized steel tools in alternating electromagnetic field environment leads to significant energy consumption accumulation, and the unstable contact resistance at the contiguous part aggravates the risk of non-uniform temperature rise of the conductor. The engineering application of new aluminum alloys and carbon fiber composites breaks the inherent electromagnetic characteristics of metal materials, and combines the research and development of surface treatment and structural lightweight technology to build an energy-saving technology matrix from material conductivity optimization to structural form redesign. This research system aims to solve the inherent bottleneck of energy consumption in the metal link in the transmission and distribution lines, and provides scientific basis for improving the economic indicators of electricity transmission and system reliability.

1. Introduction

The power transmission and distribution network carries the core functions of power transmission, and its line energy loss directly affects the economics and environmental benefits of power supply. Electrical metal tools play an irreplaceable role in ensuring the mechanical strength and electrical connectivity of the line. The ineffective energy consumption caused by resistance effect and electromagnetic induction during operation of conventional metal tools has not been fully paid attention to for a long time. The application of aluminum alloys and composite materials has significantly improved the conductivity of the metal tool, and combined with the eddy current suppression structural design, the electromagnetic conversion loss can be reduced from the source. Improved

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DOI: http://doi.org/10.26549/frae.v8i1.33839

coating process effectively suppresses the increase in contact resistance caused by metal surface oxidation. Integrated design reduces material usage while ensuring mechanical strength, forming a multi-dimensional energy-saving effect. Together, these technologies constitute a technical system for energy consumption control of power tools [1].

2.Overview of electric appliances

(I) Definition and classification of power equipment

Electric power metal tools specifically refer to basic components used to connect, fix and protect various components in overhead transmission and distribution lines. This type of metal accessories constitutes the physical framework for the installation and operation of the power grid. Its classification system is based on functional realization. The connecting tool undertakes the series connection task between the drape clamps or tension clamps. The connecting tool specializes in handling repair operations and daily connection needs after wire damage (see Figure 1). Protective tools focus on the safe operation protection field of key equipment such as insulators to avoid corona discharge and mechanical damage affecting system stability. The wire pulling tool exerts structural anchoring function at the base of the tower to maintain the overall structural stress balance. Each type adopts differentiated material formulas and structural forms based on specific physical characteristics and functional goals. For example, the model size in the tension string group is related to the vibration characteristics of the conductor, and the inclination parameters of the overhang line affect the safety margin of the air bias. These standardized technical specifications jointly build the basic structure of electric power tools.

(II) The role of power tools in power transmission and distribution lines

Electric power tools essentially play the role of adhesive in the grid structure, connecting the dispersed wires and insulators into a continuous transmission corridor. The tension-resistant wire clip accurately controls the conductor tension distribution against the uncertain effects of wind loads, and the overhang combination maintains the conductor trajectory in the vertical direction to reduce the probability of dancing accidents (see Table 1). The conductor connection tube maintains the transmission cross-sectional area unchanged when repairing the broken strand defect, thereby ensuring stable electrical performance. The anti-vibration hammer targets the metal fatigue hazards formed by breeze oscillation and extends the service cycle of the conductor. The mechanical connection system composed of this type of metal components ensures the structural integrity of the line when it encounters extreme weather. The physical characteristics of its conductive contact surface directly determine the line loss level. The accumulation of oxide layer on the metal surface may lead to an abnormal increase in contact resistance. The edge electric field control capability of the metal design is related to the electric field distribution of the insulator string surface, and is related to the total corona loss and the radio interference level. These multi-dimensional functions are nested together to ensure the long-term and reliable operation of power transmission and distribution systems.

3.Energy-saving and consumption-reducing technology of electric tools

(I) New material application technology

The current innovation in power metal materials focuses on the coordinated optimization of conductive mechanism and mechanical properties, and aluminium alloy materials have become the mainstream trend to replace traditional cast iron. Due to the characteristics of the relative permeability approaching 1, the aluminum alloy member significantly reduces the hysteresis loss in the alternating magnetic field, and its body resistivity decreases, so that the intrinsic impedance of the current transmission path can be compressed. The application of carbon fiber reinforced composite materials in the field of overhanging wire clips shows unique advantages. This non-metallic material completely avoids the conditions for forming closed magnetic circuits and fundamentally eliminates the inherent eddy current thermal effects of ferromagnetic materials. The polymer composite conductive material acts as a transition layer at the metal joint node. Its specific carrier concentration distribution mode can effectively harmonize the potential step phenomenon between different metals and reduce the carrier scattering probability of the connection interface. This type of material solution verifies the temperature rise suppression capability in the ±800kV ultra-high voltage project, and the overall linear loss rate of the transmission corridor shows structural improvement. The practice of metal-based ceramic composites in heavily corroded areas shows that the oxide film generated in-situ on the surface simultaneously solves the dual issues of chemical corrosion protection and contact resistance stability.

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(III) Surface treatment technology

Microarc oxidation technology forms a micro-scale ceramic protective layer in the application of tension-resistant wire clip surfaces. This α-Al_2O_3 crystal structure controls the surface contact resistance drift rate to three thousandths per month while maintaining the substrate conductivity. Cold spray pure copper coating treatment carried out molecular-level recombination of the current-carrying surface of the equipment line clamp. SEM observations showed that the optimal growth of the copper grain orientation (110) surface increased the carrier mobility by 1.5 times. The practice of graphene composite coating in the isolation switch contacts has attracted attention. Raman spectroscopy analysis has confirmed that the phonon scattering cross-section of the material interface is reduced, and the temperature rise of the contact point is reduced by about 28K compared with the traditional silver plating scheme. The diamond-like carbon film prepared by plasma-enhanced chemical vapor deposition covers the outer surface of the wire-supporting tube. Its negative electron affinity characteristics significantly inhibit the corona starting voltage, and the corona loss reduction of more than 80% is achieved in an altitude of 2,000 meters. Ion implantation technology performs selective doping of metal grain boundaries, and the corrosion current density of steel U-shaped hanging rings treated with boron ion beam drops by nearly an order of magnitude.

(IV) Integration and Lightweight Technology

The topological optimization-driven structural weight reduction is reconstructing the metal tool design paradigm. The V-shaped string connection frame designed based on the finite element topological analysis results can reduce the mass by 30% while maintaining the equivalent structural stiffness. The multi-physical field coupling design integrates the drainage plate and anti-halo ring function. This integrated structure has a measured field strength distortion rate of 56% in the 220kV substation application. The internal stress distribution state of aluminum alloy overhanging wire clips produced by precision casting process combined with topological optimization algorithm is more than 30% better than that of traditional sand castings. Laser additive manufacturing technology realizes active regulation of the internal lattice structure of the metal tool, and the functional gradient material design forms a progressive intensity distribution in the anchoring area of the tension-resistant line clamp, and the fatigue life test data in this area is four times higher. The truss hollow structure of the tension-resistant wire clip of carbon fiber composite material makes the eddy current loss approach the theoretical zero point, and the weight index is only one-third of the traditional forged steel parts. The vibration monitoring of a coastal wind power transmission line shows that its resonance frequency offset is reduced by about 15Hz.

4.Application of energy-saving and consumption-reducing technology in power transmission and distribution lines

(I) Application in transmission lines

The transmission line engineering comprehensively evaluates the conductivity and environmental adaptability index of metal materials selection, and the creep-resistant high-conductance aluminum alloy tension-resistant wire clips have completely replaced the traditional forged cast iron models in heavy ice-zone lines.The wire connection parts are preferred to use the integral sleeve formed by friction stir welding process, and the internal electric field distribution of the metal tool is repeatedly corrected by the finite element calculation model to approach the ideal state.The overhang string group adopts a nonlinear damper configuration scheme, and structural dynamic analysis verifies that the design converts breeze resonance energy into heat three times more efficiently than traditional anti-vibration hammers. The acceleration sensor monitoring record of the Gobi wind field in Qinghai confirms that this strategy effectively curbs the development of conducting line bending strain.The composite insulator integrated

pressure equalization ring assembly assembled at the cross-burst part of the transmission tower. The design target of this structural design is locked in a use scenario in an altitude of 3,000 meters. Multiphysics simulation shows that its surface maximum field strength is controlled within 80% of the critical corona starting threshold.The adaptive deflection mechanism of the drainage plate allows the current transmission path to maintain the contact pressure during the thermal expansion and contraction of the line. The infrared thermal image data in the high-temperature area of Guangdong show that the temperature rise of the connection point remains below the standard limit of about 35%.The concept of full life cycle guides innovation in operation and maintenance management. The drone is equipped with a metal tool temperature map collected by high-precision infrared thermal imager to construct a predictive maintenance model. The statistics of operation faults in Zhejiang power grids reflect that this technology has reduced the shutdown of the metal tool failure by nearly 40%.

(II) Application in distribution lines

The dense distribution characteristics of distribution line networks require lightweighting and weather resistance of the metal tools to be considered as priority factors. Waterproof puncture lines made of silicon-aluminum composite materials show excellent performance in coastal chemical areas.This type of wire clip body structure design integrates the concept of sealed chambers, and the electrochemical corrosion rate caused by moisture penetration is suppressed within the engineering allowable threshold range.Low-voltage branch lines generally use T-shaped groove clamps with integral die-casting. The internal pressure self-regulating module offsets the telescopic deformation of the conductor caused by seasonal temperature differences. The distribution operation and maintenance records in North China show that the frequency of loose faults of this type of metal has dropped by nearly 70%.The cable clamp of cold-shrinkage composite material equipment is used in the downline of the distribution station area. The stress memory characteristics of polymer materials provide continuous radial pressure. The long-term monitoring of Sichuan salt spray area proves that the oxidation degree of the joint remains above 90% of the new installation standard.The copper-aluminum transition terminals of the underground cable branch box adopt vacuum diffusion welding technology interface metallurgical combined state eliminates the microarc phenomenon caused by potential difference, and the Shanghai Urban Power Grid Power Quality Monitoring System detected that the background harmonic component decreased by about 30 basis points.The insulated wire connection points of the medium voltage line are designed to be covered shielding layer, and the simulation of high-frequency electromagnetic field confirms that this structure reduces the induction loss of adjacent metal components to about 35% of the original amount.The wire puncture clamp operation tool is equipped with a digital torque control system, and the installation quality traceability database shows that the optimization amplitude of the contact resistance discrete coefficient of the connection point is more than 40%.The power distribution automation transformation project adopts a functionally integrated intelligent metal system, and the wedge-shaped tension wire embedded in the micro current sensor is sandwiched in the Fujian smart distribution network to achieve automatic positioning accuracy error of the energy consumption hot spots.

Conclusion

Engineering practice has proved that the energy-saving technology of power tools needs to run through the entire chain of material selection, structural design, processing, manufacturing and operation and maintenance. Aluminum alloys and composite materials innovate the selection strategy of metal conductive dielectrics, and design optimization of hyperbolic drainage plates and other designs weaken the distortion effect of electromagnetic field distribution. The surface microarc oxidation treatment of the metal tool creates a double protective barrier, which not only maintains the body's conductive characteristics but also blocks the resistance deterioration process induced by environmental erosion. Topological weight reduction and functional integration strategies significantly reduce the energy consumption of additional loads, and lightweight components reduce the load load burden of the tower foundation structure. It is recommended that subsequent technical research and development focus on theoretical breakthroughs in designing asymmetric electromagnetic field metal tools, explore the engineering adaptation solutions of nanocrystalline metal-based composite materials, and strengthen the iteration of corrosion protection technology in coastal industrial areas. It is urgent to develop embedded perception intelligent metals in the distribution automation scenario to build a predictive control mechanism for energy consumption hotspots.

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