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Permanent Magnet Driving Technology and its Application Status in The Field of Mining Equipment

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Abstract: Against the dual background of the "Dual-Carbon" strategy and mine intelligent transformation, traditional AC asynchronous motor drive systems suffer from low operational energy efficiency, insufficient intelligence, and excessive energy consumption, which cannot meet the green and efficient development requirements of modern mines. With the advantages of high energy-saving efficiency, compact structure and high control accuracy, permanent magnet driving technology has become a core technology for the intelligent upgrading of mining equipment. This paper systematically compares the performance differences between traditional AC asynchronous drive and permanent magnet driving technologies. Focusing on key mining equipment, including mine hoists, material conveyors, crushing and grinding devices, and flotation equipment, it comprehensively analyzes the engineering application status, structural optimization schemes and technological breakthroughs of permanent magnet driving technology, and summarizes its innovative achievements in high-voltage and high-power adaptation, extreme heavy-load condition adaptability, and multi-motor cooperative intelligent control. Considering the harsh mining environments characterized by high dust, humid corrosion and impact loads, the key technical bottlenecks including irreversible demagnetization of permanent magnets, high-voltage insulation protection, structural adaptation and operational stability are clarified. Finally, the future development trends are prospected. Further intelligent integration, development of ultra-high-power equipment, optimization of permanent magnet materials and motor structures, and expanded application in full-range mining equipment can construct a full-process intelligent drive system, providing technical support for the green and low-carbon upgrading of intelligent mines.

Keywords: Permanent Magnet Driving Technology; Mining Equipment; AC Asynchronous Motor; Permanent Magnet Synchronous Motor; Intelligent Mine.

1. Introduction

Driven by the comprehensive advancement of intelligent construction in China's coal mines, high-efficiency and intelligent drive technologies for mining equipment have become one of the core technical bottlenecks urgently requiring breakthroughs in the industry[1]. At present, drive systems for key underground mining and transportation equipment generally adopt conventional AC asynchronous motor driving schemes, including mainstream equipment such as shearer cutting units, roadheader cutting mechanisms, belt conveyors, scraper conveyors and mine hoists. Subject to the long-term low-speed and heavy-duty operating conditions of mining equipment, AC asynchronous motors cannot directly match load demands and must be equipped with reduction transmission devices for condition adaptation. To satisfy the high-torque output requirement during heavy-load startup, considerable motor power margin is normally reserved in engineering type-selection. Consequently, the matching degree between normal operating conditions and rated conditions of motors is extremely low. Motors frequently operate under low-efficiency and high-energy-consumption states, accompanied by drawbacks such as poor speed-regulation performance and insufficient intelligent adaptability[2]. Such conventional driving modes not only restrict the overall operational efficiency of coal mining but also cause substantial electric-energy loss, which is inconsistent with the development philosophy of green, intelligent and efficient mines.

Compared with AC asynchronous motors, permanent-magnet synchronous motors achieve excitation by means of rare-earth permanent magnets and generate stable permanent magnetic fields without additional excitation current. They can greatly improve power factor, transmission efficiency and load adaptability, presenting prominent energy-saving benefits. Meanwhile, the air-gap magnetic density produced by permanent magnets on the rotor is insensitive to air-gap parameter fluctuations, enabling stable low-speed high-torque output. It well fits the operating characteristics of mining equipment featuring heavy-load startup and continuous low-speed operation, and effectively addresses performance defects of conventional driving equipment. Furthermore, China ranks first globally in rare-earth resource reserves, providing unique resource support for the research, development and large-scale application of permanent-magnet drive technologies in mining sectors. Despite remarkable technical advantages, permanent-magnet motors saw extremely limited practical deployment in mining equipment in the early stage due to harsh and complicated mine operating environments. Mining machinery runs persistently under severe conditions characterized by heavy-load impact, high humidity, heavy dust and strict explosion-proof requirements. The commonly-used Nd-Fe-B permanent-magnet material has a maximum operating temperature of merely 150 ℃ with poor temperature resistance, and its performance tends to degrade easily under operational temperature rise [3]. Rare-earth cobalt permanent-magnet materials with superior high-temperature tolerance come at high costs, which considerably increases equipment retrofitting and operation-maintenance expenses and hinders the popularization of permanent-magnet drive technologies in mines.

In recent years, the iterative upgrading of power-electronic devices and continuous improvement of modern intelligent control theories have greatly promoted the innovation and maturation of high-power permanent-magnet motor technologies. Permanent-magnet drive technologies have realized large-scale industrial applications in numerous fields including aerospace, rail transit and wind power generation[4]. It also provides solid technical support and broad application prospects for intelligent upgrading of mining equipment empowered by such technologies. On this basis, this paper sorts out the technical characteristics of conventional drive and permanent-magnet synchronous motor variable-frequency drive technologies, systematically analyzes the application status of permanent-magnet drive technologies in key equipment such as mine hoists, conveyors, crushing-grinding and flotation facilities, and summarizes future development trends of permanent-magnet drive technologies for mining equipment, so as to offer references for technical upgrading of mining machinery.

2. Characteristics of Conventional Drive Technologies

After long-term development, conventional drive technologies have formed three mainstream schemes with respective technical principles and application scopes:

Hydraulic coupler soft-start technology: Power is transmitted via fluid medium between the motor and reducer, and startup buffering is realized by flow properties of the medium. This scheme features low cost; nevertheless, its startup process cannot be precisely controlled. It is only applicable to small-size conveying equipment with a belt width below 1 m, and medium loss tends to cause efficiency decline.

CST (Controlled Start Transmission) technology: It integrates both speed reduction and soft-start functions. The wet clutch is regulated by an electro-hydraulic control system to achieve smooth belt-speed variation. It exhibits excellent power-balancing performance under multi-drive conditions and is widely adopted for large-scale conveying equipment. However, it suffers from frequent lubricant replacement and high annual maintenance costs.

Asynchronous-motor variable-frequency driving technology[5]: The output frequency is adjusted by frequency converters to flexibly set startup curves and operating speeds. With the maturation of explosion-proof frequency converters, its voltage level reaches 3300 V and single-drive power exceeds 1000 kW. Restricted by motor structure, reducers and couplings are still required, and the overall transmission efficiency is approximately 89%.

The three conventional schemes share common problems such as long transmission chains, prominent energy loss or high maintenance costs, and can hardly meet the dual requirements of energy conservation and intelligence in coal mines.

3. Characteristics of Permanent-Magnet Synchronous Motor Variable-Frequency Driving Technology

3.1. Core Technical Principle

The core of permanent-magnet drive lies in the coordination between permanent-magnet synchronous motors and variable-frequency control. The motor rotor is excited by high-performance rare-earth permanent-magnet materials. Rotating magnetic fields are generated when currents pass through stator windings, which drive synchronous rotation of the rotor through electromagnetic coupling without extra excitation current. Combined with advanced algorithms such as vector control and model predictive control, precise regulation of torque and rotating speed can be realized. Adopting direct-drive or semi-direct-drive structural design, motors can be directly connected to loads, which thoroughly simplifies multi-link transmission chains of conventional drive systems.

Two mainstream technical schemes are formed for different application scenarios. The direct-drive scheme completely eliminates intermediate components such as reducers and suits low-speed high-torque working conditions. The semi-direct-drive scheme embeds planetary reduction mechanisms. While retaining high-efficiency performance, it reduces equipment dimensions and adapts to complicated sites with limited installation space.

3.2. Core Performance Advantages

Remarkable energy-saving performance: The rated efficiency of permanent-magnet motors exceeds 96%, and the maximum system transmission efficiency can reach 98.5%. Compared with conventional asynchronous-motor driving schemes, an energy-saving ratio of 10%-30% is achieved, which can significantly cut power consumption for mines during long-term operation. The energy feedback function recovers braking energy to power grids for further improvement of energy utilization efficiency.

Compact and lightweight structure: Direct-drive / semi-direct-drive structures remove reducers, couplings and other components, greatly reducing equipment weight and footprint. Easy transportation and installation lower capital investment and space occupation, which is especially suitable for narrow underground roadways and other special environments.

Outstanding control accuracy and reliability: Adopting full-vector control and other technologies, rotating-speed control error is less than 0.1%, and dynamic torque response time is shorter than 10 ms. Soft startup & soft stop and self-adaptive load adjustment can be accomplished. Reduced fault points cut maintenance workload by more than 68%, and the maximum bearing grease-filling interval reaches 22 000 h, greatly improving continuous operation capacity of equipment.

Adaptable safety protection performance: Through structural optimization and improved protection processes, protection class up to IP55 or higher can be realized, with favorable dust-proof, moisture-proof and shock-resistant capabilities to adapt to extreme underground mine conditions of high humidity, heavy dust and intense impact.

4. Application Status of Permanent-Magnet Driving Technologies in Mining Equipment

4.1. Hoisting Equipment

As the "throat-type" equipment of mines, hoisting machines impose stringent requirements on safety reliability and energy-saving benefits. With the advancement of control technologies, hoisting systems driven by variable-frequency-regulated AC motors have gradually replaced conventional DC-motor-driven systems. Currently,

mine hoists are evolving toward high-power and high-efficiency synchronous-motor-driven technologies. As a high-performance driving motor, the permanent-magnet synchronous motor (PMSM) has attracted increasing research attention and begun to find practical applications in mine hoists.

Huang et al.[6] performed electromagnetic simulation and parameter optimization for an outer-rotor permanent-magnet direct-drive hoist, providing theoretical support for the permanent-magnet retrofitting of heavy-load hoisting equipment. The Gaozhuang Coal Mine under Zaozhuang Mining Group[7]. applied a permanent-magnet direct-drive system to a gangue-hill winch. Master-slave following control was adopted to realize torque and speed balance, which greatly improved mechanical transmission efficiency and remarkably reduced maintenance workload Researchers from Taiyuan University of Technology[8] investigated the variable-frequency speed-regulation system for an outer-rotor permanent-magnet hoist. An integrated structure combining an outer-rotor permanent-magnet synchronous motor and the hoist drum was employed, featuring a simplified transmission system, stable operation and low noise (Figure 1). TAN from China University of Mining and Technology developed a full-series variable-frequency intelligent control technology for ultra-high-power mine hoists [9], which has reached the world-leading level.

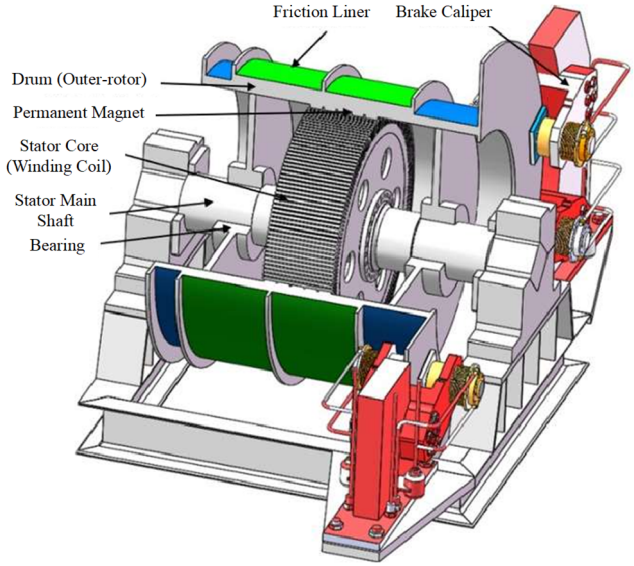


Figure 1. Configuration of permanent-magnet outer-rotor hoist [8]

4.2. Conveying Equipment

Belt conveyors are core mine transportation equipment that deliver coal and various bulk materials by means of frictional traction generated between the belt and driving pulleys. Owing to the inherent overload self-protection characteristic originating from the belt-drive property of belt conveyors, the probability of irreversible demagnetization of permanent magnets can be greatly reduced. This enables permanent-magnet synchronous motors (PMSMs) to operate consistently within high-efficiency, stable and reliable working ranges. Meanwhile, PMSMs feature low-speed and high-torque output characteristics, which are highly compatible with the operating conditions for material transportation of belt conveyors.

The 10 kV permanent-magnet direct-drive integrated machine (Figure 2) developed by Zhongjiate realizes the three-in-one integration of frequency converter, motor and monitoring device. It addresses key technical challenges including underground high-voltage insulation and high-efficiency heat dissipation, and delivers high speed-control accuracy and strong anti-interference capability, while simplifying the complicated structure of conventional driving systems[10]. Researchers from China University of Mining and Technology together with Beijing Baizheng Chuangyuan Co., Ltd. proposed an integrated intelligent direct-drive and tensioning system based on PMSMs. A multi-motor multi-point driving scheme at the head and middle sections of the conveyor is adopted. Both the driving system and tensioning system take PMSMs as power sources and share one integrated control system. This technology has been successfully applied in multiple coal mines such as Gaojialiang Coal Mine of Ordos Haohua Clean Coal Co., Ltd.[11]. ZHANG[12] established a mechanical-electrical coupling dynamic model for an all-permanent-magnet driven belt conveyor integrating "permanent-magnet direct-drive + permanent-magnet tensioning + coordinated control" in MATLAB/Simulink. Underground field tests verified that the all-permanent-magnet driven belt conveyor can not only realize intelligent driving and tensioning, but also substantially cut power consumption, representing a vital development trend for future belt-conveyor driving technologies(Figure 3). On this basis, HAO et al.[13] proposed an active-disturbance-rejection synchronization control strategy, which can further improve the anti-interference performance, control accuracy and synchronization performance of belt conveyors, and is more conducive to the stable operation of multi-motor-driven belt conveyors.

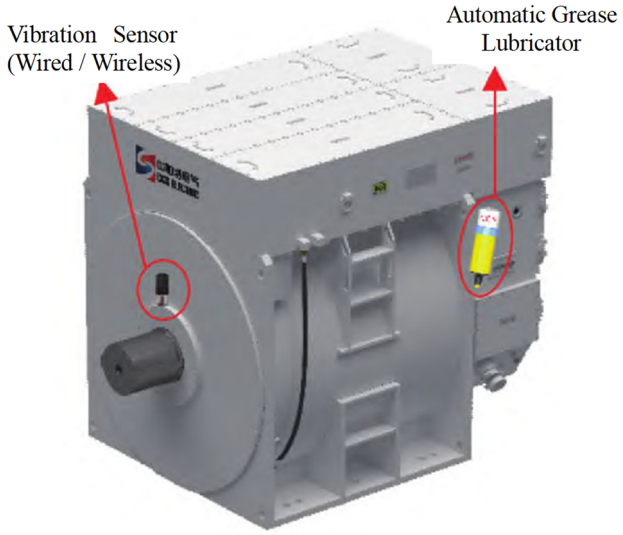


Figure 2. Intelligent 10kV permanent magnet direct-drive integrated machine[10]

The scraper conveyor serves both as the running track for the shearer and the core transportation equipment for coal on the working face. Its driving section has long relied on three technical solutions: TTT, CST, and variable-frequency driving with asynchronous motors. All these solutions adopt AC asynchronous motors as power sources and suffer from respective limitations. Thanks to its advantages including low-speed high-torque output, superior energy-saving performance and high power factor, the permanent-magnet synchronous motor (PMSM) has motivated researchers to explore permanent-magnet direct-drive technologies for scraper conveyors in recent years, aiming to break through the

performance bottlenecks of conventional driving schemes.

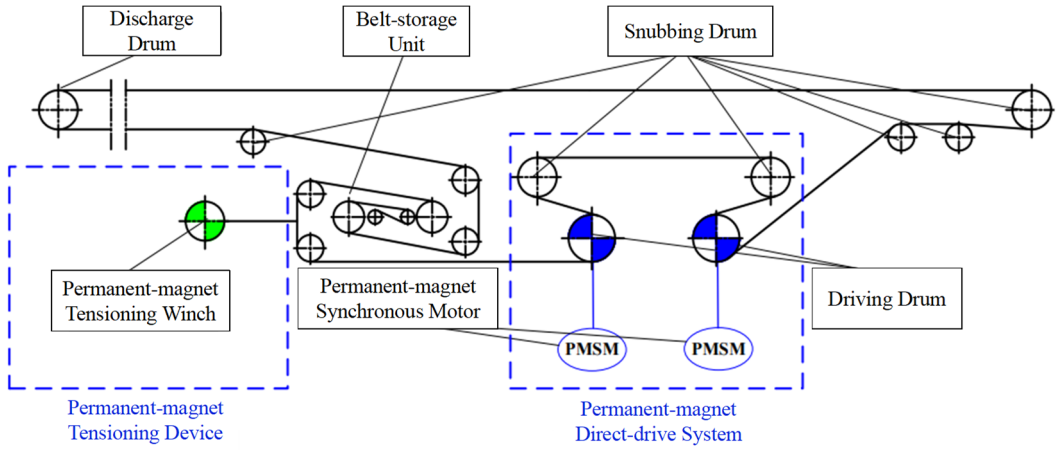


Figure 3. Design scheme of full permanent-magnet drive system[12]

To address the problem of excessive radial dimension in direct-drive schemes, the research team led by Academician GE's innovatively[14] proposed a permanent-magnet semi-direct-drive system (Figure 4). By adopting a built-in planetary gear reduction mechanism for speed reduction and torque amplification, the system reduces equipment volume and protects permanent magnets from impact loads. Its transmission efficiency is improved by more than 16.3 % compared with traditional asynchronous-motor drives. Validated by multi-condition bench tests, this technology provides a new pathway for upgrading conveying equipment in fully-mechanized mining working faces. WANG et al.[15] established an electromechanical coupling model for the permanent-magnet direct-drive system in MATLAB/Simulink.

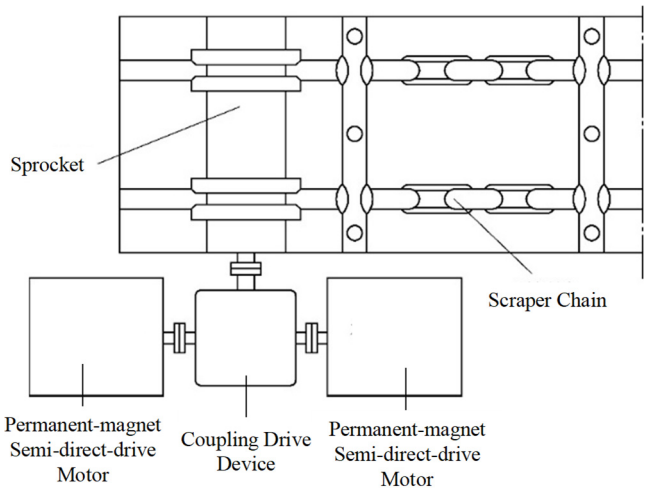


Figure 4. Parallel-connected permanent magnet semi-direct drive system for scraper conveyor [14]

Real-time control over the operating states of PMSMs at both the head and tail sections is realized according to load variations, which mitigates overload impacts on the chain. LU et al.[16] designed a composite sliding-mode control method based on load characteristics for the permanent-magnet direct-drive system of scraper conveyors, enhancing the intelligence level of the driving system. YANG et al.[17] proposed a permanent-magnet semi-direct-drive motor suitable for scraper conveyors, in which the reducer and permanent-magnet motor are integrated within a single cabinet. While maintaining high transmission efficiency, the failure rate of the transmission system is reduced. SHU[18] derived dynamic equations for the gear transmission system of the permanent-magnet semi-direct-drive scraper conveyor, laying a theoretical foundation for the engineering application of permanent-magnet driving technologies for scraper conveyors.

4.3. Crushing, Grinding and Flotation Equipment

Crushing equipment includes jaw crushers, cone crushers, high-pressure roller presses, vertical mills and tower mills. Such equipment generally operates under intermittent working conditions characterized by severe transient impact loads and high dust concentration. The industry has formed a unified technical route dominated by permanent-magnet semi-direct-drive systems, supplemented by permanent-magnet direct-drive for small-size light-load fine-crushing equipment. Relevant researches are collaboratively carried out covering complete-set equipment development, structural protection and heat dissipation, intelligent control, and industrial retrofitting verification.

HE et al.[19] established a field-circuit coupling simulation model for the permanent-magnet semi-direct-drive roller press, quantified the buffering and vibration-reduction effect of single-stage planetary gears under ore impact loads, and proposed a general dynamic analysis method for heavy-duty permanent-magnet equipment, which provides theoretical simulation support for the structural design of semi-direct-drive high-pressure roller presses. YANG et al.[20] conducted researches on structural optimization of semi-direct-drive roller presses and low-cost retrofitting of existing equipment. Motor vibration-damping structures, shaft-current protection structures and elastic buffering retrofitting schemes were designed respectively. Moreover, selection criteria for permanent-magnet drives of roller presses with different power ratings were formulated, specifying that concentric integrated semi-direct-drive layout is preferred for large-scale roller presses with power above 2000 kW. WANG et al.[21] proposed a composite speed-regulation strategy based on the MC-CMAC neural network to optimize the speed-loop control of permanent-magnet synchronous motors. Compared with

conventional PI control, this strategy greatly suppresses drastic speed fluctuations induced by abrupt changes in ore hardness, and is suitable for the development of variable-load variable-frequency control systems for crushers. Vertical mills and tower mills suffer from relatively mild load fluctuations. SHI[22] and DING[23] verified through industrial tests that ring-type permanent-magnet direct-drive can eliminate multi-stage transmission losses, with the system efficiency improved by 10%–18%. HAO et al.[24] built a co-simulation model of electromagnetic field and control system to optimize harmonic eddy-current losses of the motor. The matched air-water composite heat-dissipation scheme keeps the permanent-magnet temperature stably below 120 ℃. Meanwhile, the patented permanent-magnet direct-drive mill structure with flexible vibration-damping base[25] isolates grinding-induced shocks from transmitting to the motor, thus prolonging the service life of magnetic steels.

Grinding is the most mature industrialized procedure for permanent-magnet drive applications in mineral processing, which consists of ring-type permanent-magnet direct-drive for large-scale ball mills and permanent-magnet semi-direct-drive for medium-and-small-sized mills as well as vertical tower mills.

Through field retrofitting tests on ball mills, WU et al.[26] verified that low-speed permanent-magnet direct-drive can significantly reduce transmission losses and cut operation-and-maintenance costs. Aiming at the manufacturing challenges of high-power split ring-type direct-drive motors, WANG et al.[27] performed finite-element-based verification of stator strength and modal resonance, and addressed risks concerning transportation, installation and resonance of permanent-magnet equipment for large-scale mills. DOU et al.[28] quantitatively evaluated the payback period of permanent-magnet direct-drive retrofitting from the perspective of economic assessment, providing decision-making data for mine-equipment upgrading (Figure 5).

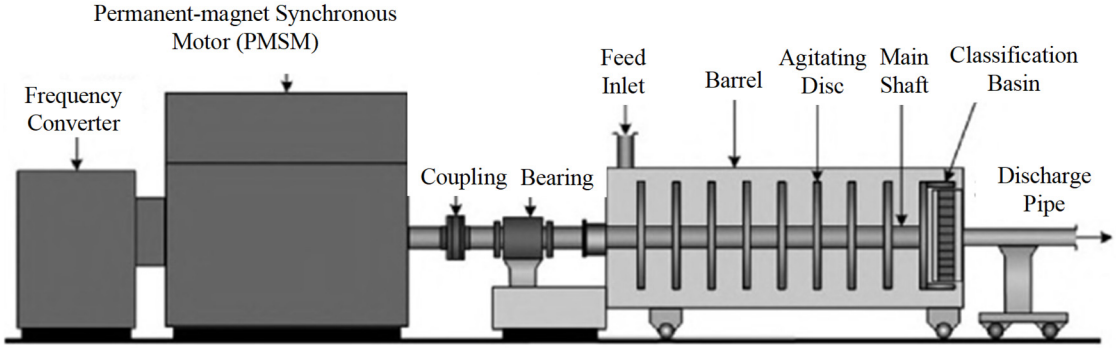


Figure 5. Schematic diagram of permanent-magnet direct-drive IsaMill[28]

Flotation equipment is featured by low-speed continuous stirring and slightly fluctuating loads. Permanent-magnet coaxial direct-drive is the mainstream solution, together with auxiliary permanent-magnet brushless-driven reagent-dosing equipment.

BAO et al.[29] systematically analyzed typical faults of conventional belt-driven flotation machines, including belt abrasion, bearing damage and large transmission loss. A complete low-speed PMSM direct-drive system was designed, eliminating belts and gearboxes. Industrial tests show that equipment failure rate decreases substantially and comprehensive energy-saving rate exceeds 15%（Figure 6）. LU et al.[30] proposed an AEPSO-optimized non-singular terminal sliding-mode control algorithm to improve the synchronous control accuracy of multi-tank flotation units, whereby the speed deviation is restricted within ±0.5 %. This stabilizes flotation liquid level and reduces reagent consumption. For the reagent delivery link supporting flotation, LIU[31] developed the BRFS multi-frequency magnetic-isolation permanent-magnet brushless reagent-dosing machine. Free of vulnerable mechanical-sealing components and resistant to reagent corrosion, it embeds a PID flow self-correction module to realize accurate quantitative dosing. It can be connected to the intelligent scheduling platform for mineral processing, achieving full permanent-magnet coverage for flotation auxiliary equipment. LI et al. [32] analyzed the high-energy-consumption and high-failure-rate problems of conventional asynchronous belt-driving systems for mine flotation and leaching stirring equipment. The advantages of PMSMs, i.e., low-speed high-torque output and high power factor, were illustrated. Two stirring-drive schemes, permanent-magnet direct-drive and semi-direct-drive, were compared. It is pointed out that high-humidity corrosive environment and alternating loads in mineral processing may easily cause irreversible demagnetization of permanent magnets. Optimization measures such as sealing-anticorrosion treatment and on-line magnetic-flux monitoring were put forward. It is concluded that permanent-magnet drive will become the mainstream upgrading direction for mine stirring equipment.

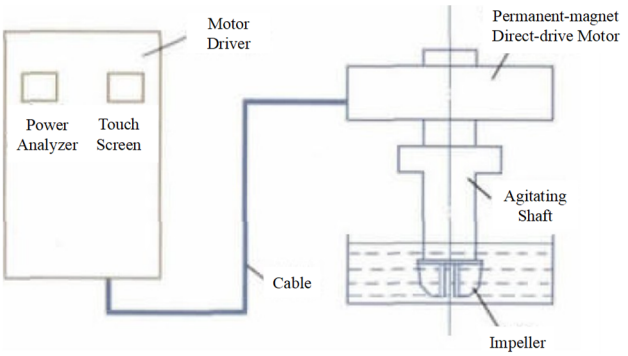


Figure 6. Schematic diagram of permanent-magnet direct-drive system for flotation machine [29]

5. Prospect of Permanent-Magnet Driving Technology for Mining Equipment

(1) Focus on in-depth intelligent integration to promote the linkage between permanent-magnet drive systems and mine intelligent platforms. Functions including real-time monitoring, remote operation-maintenance and early fault warning shall be integrated to realize dynamic matching between drive parameters and process requirements, supporting the construction of "unmanned mines".

(2) Target the demands of ten-million-ton-scale mines to develop ultra-high-power permanent-magnet drive equipment with power above 3 MW. Break through the limitations of extreme parameters such as high voltage, high speed, and low-speed high-torque, so as to expand application boundaries.

(3) Further develop high-reliability permanent-magnet driving technologies to prevent demagnetization of permanent magnets under environments of high temperature, current oscillation and chemical corrosion, as well as operating conditions of heavy load and abrupt load variation. Specifically, rare-earth-free permanent-magnet materials and high-temperature-resistant permanent magnets should be developed to reduce costs and demagnetization risks. Meanwhile, motor topological structures shall be optimized to further improve power density and anti-impact capability.

(4) Aiming at multi-field promotion in mines, extend the application scope from existing equipment to a full range of mine machinery including shearers, roadheaders, mine fans and drainage pumps. Develop intelligent mine equipment based on permanent-magnet drive systems that cover the whole procedures of mining, transportation and processing, thus laying a critical equipment foundation for the construction of smart mines.

References

[1] Bao, J. S., Liu, Q., & Ge, S. R., et al. (2020). Research status and development trend of intelligent technologies for mine transportation equipment. Intelligent Mine, 1(1), 78–88.

[2] Ge, S. R., Bao, J. S., & Cao, G. H. (2015). Mining transportation technology and equipment. China Coal Industry Publishing House.

[3] Sun, X. B., Zheng, Y., & Guo, H. C. (2022). Research and Application Development of Modern Permanent Magnet Motor Technology. Modern Manufacturing Technology and Equipment, 58(3), 153–155.

[4] Wang, J. S., Xu, R., & Sun, Y. Z. (2016). Overview of the development of permanent magnet synchronous motor. Science and Technology & Innovation, (16), 5–6.

[5] Zhang, L. (2015). Comparative analysis and application prospect of permanent-magnet synchronous motor variable-frequency drive technology and traditional drive technology for coal mine belt conveyor. Electronics World, (16), 194–195.

[6] Huang, L. P., Jiang, L., Luo, Z. P., et al. (2023). Design and optimization of direct-drive permanent magnet synchronous motor for mine hoisting based on PB test and BBD response surface method. Mining & Processing Equipment, 51(10), 23–33.

[7] Chen, H. L., Cheng, Y. S., Wang, F., et al. (2024). Research and Application of Intelligent Permanent Magnet Direct Drive Technology on Gangue Hill Hoisting Machine. Modern Industrial Economy and Informationization, 14(04), 111–113+117.

[8] Zhang, L. N. (2021). Research on the control system of external rotor permanent magnet elevator [Doctoral dissertation]. Taiyuan University of Technology.

[9] Tan, G. J., He, F. Y., & Xu, Z. O. (2019). Low-cost, high-reliability fully digital control system of direct current hoist of mine. In International Conference on Control & Automation. IEEE.

[10] Zhao, Z. H. (2026). Application of permanent-magnet direct-drive system for belt conveyor in intelligent fully-mechanized mining working face. Energy and Energy Conservation, (01), 97–99+131.

[11] Ge, S. R., Yang, X. L., Bao, J. S., et al. (2019). Complete technology of permanent-magnet intelligent drive and tensioning for long-distance heavy-duty belt conveyor [Research report]. China Coal Technology Appraisal No.JX17.

[12] Zhang, L. (2021). Research on electromechanical coupling dynamics of all permanent magnet driving belt conveyor [Doctoral dissertation]. China University of Mining and Technology.

[13] Hao, J. W., Bao, J. S., Ge, S. R., et al. (2021). Active disturbance rejection synchronous control strategy of permanent magnet motor drive system for belt conveyor. Electric Machines & Control Application, 48(9), 1–9.

[14] Zhang, L., Hao, J. W., Bao, J. S., et al. (2022). Control Strategy and Dynamic Behavior of Full permanent Magnet Driving Belt Conveyor. Journal of Mechanical Engineering, 58(21), 134–147.

[15] Wang, Y. Y., Bao, J. S., Ge, S. R., et al. (2020). Simulation and experimental study on electromechanical coupling model of permanent magnet direct drive system for scraper conveyor. Journal of China Coal Society, 45(6), 2127–2139.

[16] Lu, E., Li, W., & Yang, X. F. (2017). Composite sliding mode control of a permanent magnet direct-driven system for a mining scraper conveyor. IEEE Access, 5, 22399–22408. https://doi.org/10.1109/ACCESS.2017.2726848.

[17] Yang, X. L., Zu, H. B., & Li, B. C. (2016). Low-speed semi-direct-drive permanent-magnet drive system for scraper conveyor (Chinese Patent No. CN201620156767.8). 2016-07-27.

[18] Shu, Z. L. (2019). Research on dynamic characteristics of permanent magnet motor semi-direct drive scraper conveyor [Doctoral dissertation]. China University of Mining and Technology.

[19] He, Z. X., Wang, X. J., Kong, Y. J., et al. (2025). Electromechanical coupling modeling and characteristic analysis of permanent magnet semi-direct drive system. Computer Integrated Manufacturing Systems, 31(9), 3411–3421.

[20] Yang, G., Cai, S. M., Chen, W., et al. (2025). The Efficiency Testing and Application Research of the Permanent-Magnet Semi-Direct Drive Transmission System. Mechanical Research & Application, 38(6), 122–125.

[21] Wang, D. L., & Pan, F. (2025). Speed regulation control of permanent-magnet synchronous motor based on MC-CMAC. Manufacturing Automation, 47(7), 100–107.

[22] Shi, J. (2022). Application and research of permanent magnet direct drive motor in coal vertical mill. Cement, (9), 77–79.

[23] Ding, L. (2022). Application practice of permanent-magnet synchronous direct-drive motor in raw material vertical mill classifier. China Cement, (9), 95–97.

[24] Hao, Z. L., Cheng, X., & Zhang, B. Y. (2025). Design and Loss Analysis of Direct Drive Permanent Magnet Synchronous

Motor of Mill Based on Joint Simulation. Electric Machines & Control Application, 52(12), 1327–1337.

[25] Shang, Q. G., Zhang, B. Y., & Feng, G. H. (2024). Permanent-magnet motor direct-drive vertical mill with vibration-damping mechanism (Chinese Patent No. CN202110299125.9). 2024-06-14.

[26] Wu, L. Q., & Peng, P. Z. (2022). Application of low-speed direct-drive permanent-magnet synchronous motor in ball mill. Plant Maintenance Engineering, (24), 87–88.

[27] Wang, L., Yan, Y. Y., & Li, H. S. (2026). Structural Strength Simulation and Analysis on Permanent-Magnet Direct Drive Motor for Large Split Ball Mill. Explosion-proof Electric Machine, 61(2), 37–40+52.

[28] Dou, Z. Y., Wang, D. X., & Ren, T. (2025). Economic Analysis of Isa Mill System Based on Permanent Magnet Direct Drive. Mechanical Engineer, (9), 77–80+88.

[29] Bao, Y. Q., Deng, W., & Zou, W. H. (2013). Development of permanent-magnet direct-drive system for flotation machine. Electrotechnical Application, 32(23), 56–59.

[30] Lu, W. H., Ruan, H. D., & Zeng, X. F. (2022). Research on Non-singular Terminal sliding Mode Control of PMSM for Large Flotation Machine Optimized by AEPSO Algorithm. Copper Engineering, (4), 81–87.

[31] Liu, G. Y., Li, C. W., & Zhao, J. J. (2024). Development and application of BRFS multi-frequency magnetic drive dosing machine. China Mining Magazine, 33(S1), 252–257.

[32] Li, Q. Z., Liu, Z. B., & Xie, D. H. (2023). Application and discussion of permanent-magnet motor in mine stirring system. China Plant Engineering, (S1), 88–90.