

Study on the application of permanent magnet synchronous motors in underground belt conveyors

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Abstract. This paper analyzes and compares the advantages and disadvantages of several kinds of drive devices of belt conveyors from the angle of energy saving, and summarizes the application advantages and using problems of permanent magnet motor variable frequency drive system in belt conveyors. An example is given to demonstrate the energy saving effect of this system compared with other driving methods. This paper points out the application prospect of permanent magnet motor variable frequency drive system on belt conveyors and other large mining machines in coal mine. This paper is aimed to provide the design direction for the designer and the choice basis for the user on belt conveyor.

1. Introduction

After the integration of coal resources, China's coal mine production capacity has been greatly improved, and small and scattered production capacity has been phased out. For example, in Shanxi Province known for the coal production, the lowest production capacity of a single mine cannot be less than 300,000 tons, and the minimum production capacity standards have been gradually enhanced. Less than 600,000 tons of the production capacity of the mine coal will soon be eliminated this year, which has greatly promoted the development of the coal mine to the direction of large-scale and modernization. It improves the comprehensive benefits of mine production that the large, efficient, highly automated equipment has been input and used. Belt conveyor has gradually become the preferred equipment for coal transportation in coal mines, because of its simple structure, convenient installation, high efficient transportation, and other advantages. It has become the starting point and the foothold of designers and users to improve the stability and efficiency of equipment operation. The research on the belt conveyor mainly focuses on the dynamic characteristics, monitoring technology, starting characteristics, power balance, component reliability and service life, etc. [1]. All these make belt conveyor continuously turn to the direction of far distance, large volume, high speed, large dip angle, and high load development [2]. The whole system is toward the direction of high performance, high life, and the best operation of low energy consumption technology has become a hot topic of domestic and foreign scholars.

2. Energy-saving operation of belt conveyor

Belt conveyor working principle is shown in figure 1: the conveyor belt 3 is rotated around the transmission drum 1 and the turnabout drum 2 to form a closed ring, and the drive unit 4 drives the



transmission drum 1 to rotate, and the conveyor belt is continuously running in one direction depending on the friction between the drum surface and the conveyor belt, and the material on the conveyor belt is continuously transported from the loading end to the unloading end. The efficient and energy-saving operation of belt conveyor is mainly determined by its drive mode. The first energy-saving operation of belt conveyor is realized by reasonable optimization of the starting and running control mode of the conveyor motor [3], and 10% -50% of the energy savings can be achieved [4]; another way to save energy is to optimize or design the structure of the motor, which essentially improves the motor performance [3], 2% -8% of the energy savings can be achieved [4].

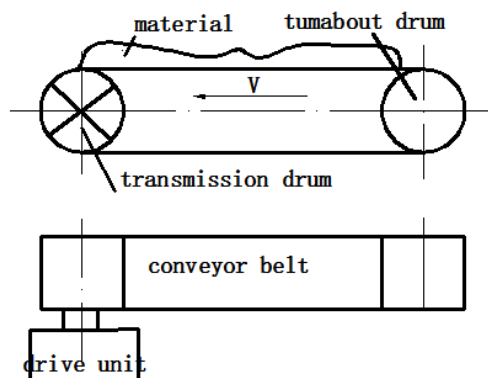


Figure 1. Working principle diagram of belt conveyor.

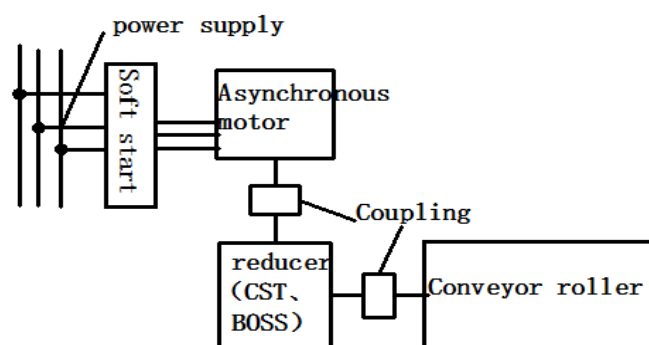


Figure 2. Schematic diagram of asynchronous motor drive system of belt conveyor.

2.1. Optimize start-up and control methods

The driving system of belt conveyor is generally composed of AC motor + connecting device + reducer + drive roller, as shown in figure 2. There are two categories of the optimization methods in start and control performance of the driving system, one is the use of electrical control circuit between electric power supply and the motor, such as adding step-down starting circuit, initiating device, soft starting switches, and inverters, etc.; the other is the use of different application of mechanical or hydraulic speed regulating device between motor and drive roller, such as the commonly used speed-type hydraulic coupler, slip clutch, CST, BOSS and other devices [5]. The better performance of starting and controlling device is the inverter and CST, and the inverter is more prominent in control performance [3]. Because of its complex structure, high maintenance costs, relatively high price and occupying larger space and so on, the application scope of CST is mainly concentrated on the places of the mining area of the groove and inclined shaft hoisting where has the advantage of the transportation convenience and the large installation space, while the frequency of converter is distributed in the mining area, roadway and inclined shaft hoisting and other kinds of the environment. Take the example of Erkuang Coal Mine in Yangquan Coal Industry (Group) CO., LTD, the whole mine has two levels, and the two main incline wells that are all promoted by the powerful belt conveyor. In the coal transportation system from coal mining working face to ground, the delivery is all using belt conveyor. Among 23 belt conveyors of 8 mining areas (not including the mining area of the groove), there are 10 using inverters with large power and long distance transportation. The others use soft starting switch and hydraulic coupler to start and control. In the lane transport and inclined well, there are 14 belt conveyors, among which one drive device is CST; one conveyor that can operate for a longer time and a shorter distance uses hydraulic coupler; four that run the shorter distance using the way of direct starting, and the remaining eight conveyors all use converters. Therefore, it can be seen that the application of converter as drive device in belt conveyor is approved. The inverter not only has a good speed performance and rich communication functions, but also can make the motor in the best power output through the speed matching, and achieve the energy saving in the operation.

2.2. Use high performance motors

Optimizing the system operation through the control strategy can improve the system efficiency to a certain extent, but it cannot compensate for the energy loss caused by the low efficiency of the design of the motor itself. Therefore, the use of high-performance motors is another way to achieve energy-saving operation of belt conveyors. There are many efficient energy-saving motors such as rare earth permanent magnet motors, high efficiency three-phase cage induction motors, switched reluctance motors, etc. [6]. Although they are a little expensive, for example, the efficiency of three-phase cage induction motors is 3% higher than that of ordinary motors, and the cost is higher than 25%-30%, and the efficiency of super-efficient cage induction motors is 5% higher than that of ordinary motors, and the cost is higher than 40%-60% [4]; the price of a permanent magnet motor is about 3-10 times as much as that of the asynchronous AC motor, as shown in table 1, it is much better than the AC motor in energy saving. Especially the rare earth permanent magnet motor, it has the advantages of simple structure, small loss, high efficiency and high power density because of the magnetic field generated by the permanent magnet, without the excitation winding and the excitation power supply, and with the improvement of the thermal stability of permanent magnet materials and corrosion resistance, and further development of power electronic technology, In the aspect of energy efficiency, rare earth permanent magnet motor shows the superiority of electric excitation motor, and it is more and more used in coal transportation belt conveyor in energy saving reconstruction of coal mine.

Table 1. Energy loss and various cost calculation for two configurations.

| | Traditional drive system | Permanent Magnet Synchronous Variable Frequency Drive System |
|---------------------------------------|-----------------------------------|--|
| Drive motor parameters | 2×250 kW Asynchronous motor | 2×250 kW Permanent magnet motor |
| Motor efficiency,% | 80 | 93 |
| Reducer efficiency,% | 85 | None |
| Hydraulic coupler efficiency,% | 90 | None |
| Coupling efficiency,% | 96 | 96 |
| Total efficiency of transmission,/% | 58.8 | 89.3 |
| Drum power, kW | 209.1 | 209.1 |
| Total input power, kW | 340.9 | 269 |
| 5 years' electricity consumption, kWh | 1963584 | 1549440 |
| 5 years' electricity bill, yuan | 1963584 | 1549440 |
| 5 years' maintenance fee, yuan | 5000000 | 250000 |
| Equipment purchase cost, yuan | 150000 | 1600000 |
| Total cost of running time, yuan | 7113584 | 3174440 |
| Saving power(kWh) /cost, yuan) | 414144/3939144 | |

2.3. Permanent magnet motor variable frequency drive system

Whether the optimization of the starting control system or the use of efficient motor will greatly improve the efficiency of belt conveyor system, and achieve better energy efficiency. Combining two energy saving modes can form the permanent magnet variable frequency drive system, as shown in figure 3, that is, the use of permanent magnet motor + inverter drive system to replace the previous drive control system, the maximize energy saving effect can be achieved in the whole system by adding two energy saving benefits.

The permanent magnet motor used in the belt conveyor is a built-in rotor magnetic circuit structure. The rotor surface places the rat cage winding, and the motor's starting relies on the asynchronous interaction starting torque between rotor conducting bar and the stator rotating magnetic field, which is known as asynchronous start of permanent magnet synchronous motor. Permanent magnet motor and

frequency converter are combined to form permanent magnetic variable frequency drive system. Through sensor-less vector control method, the starting control of belt conveyor and frequency conversion speed regulation are realized. The rotor of the motor is directly connected with the roller shaft of the belt conveyor, and the deceleration part in the prior drive mode is omitted. The schematic diagram of the drive system is shown in figure 2, and this drive is also known as direct drive. It not only has the advantage of transducer control, but also has the advantage of permanent magnet motor. It is the best drive system of the belt conveyor with optimal driving performance at present.

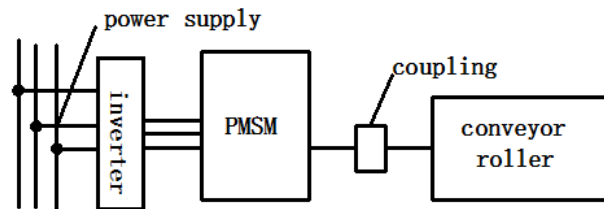


Figure 3. Schematic diagram of permanent magnet motor variable frequency drive system.

2.3.1. Advantages of permanent magnet motor drive system. Taking the application of SSJ-120 belt conveyor as an example, the advantages of using permanent magnet motor drive system are demonstrated.

- Simplified driving structure. The basic structure of permanent magnet motor variable frequency drive system is shown in figure 3. The motor is driven by the power converter through the inverter, and the permanent magnet motor is directly connected with the roller of the belt conveyor through the coupling. Compared with the traditional driving method, as shown in figure 2, the mechanical transmission link with soft start and speed regulation is reduced.
- Higher transmission efficiency and obvious energy saving benefits. SSJ-120 type belt conveyor is driven by two 250 KW three-phase asynchronous motors with 80% efficiency, and replaced by 2 sets of 250 kW permanent magnet motor with 93% efficiency in 2012. These two kinds of configuration of energy loss and various cost calculation is shown in table 1.

It can be seen from table 1 that the total efficiency of the permanent magnet drive system is about 30% higher than that of the original drive system. This is not only because of the permanent magnet motor using permanent magnet to generate the main magnetic field, and there is no exciting current, and power factor approximation is 1, so the rotor loss and the stator loss are small, which makes the motor itself have high efficiency, but also because of its simple drive system and transmission link is less; In the running time of the motor for five years, compared with the traditional driving system, the total cost saving of the permanent magnet synchronous variable frequency drive system is 3939144 yuan or 588,000 USD, which has obvious energy-saving benefit; $\{(1600000-150000)/[(1963548+5000000)-(1549440+25000)]/5\} \times 12 = 16.14$, that is, the installation cost of more than the traditional driving system can be recovered after 16.14 months of operation, and the efficiency can be highlighted by continuing operation.

Tables 2 and 3 of 160 kW and 315 kW permanent magnet motor drive system energy saving analysis is shown that under the same load and running time, the permanent magnet motor capacity is bigger, and the energy saving benefits are more obvious. Compared with the traditional driving system, the permanent magnet drive system can choose the motor with smaller capacity when driving the same load [7]. Combined with tables 1-3, it also can be seen that the permanent magnet drive systems generally need to experience about 8-17 months running time, energy-saving benefit and installation cost can balance, the greater the power, the shorter the time to recover the cost of installation, the more obvious energy conservation benefit. As compared to the traditional asynchronous motor + CST driven system, its energy saving rate reaches 22.3% [8].

Table 2. 160 KW energy-saving analysis of permanent magnet drive system (1000 KAV, primary voltage of 10000V and secondary voltage of 690 V).

| Test motor type | Motor input technical data | | | | | Analog load (generator output technical data) | | | | | Same load output, input power difference |
|--|----------------------------|--|-------------------|-------------|--------------|---|-------------------|-------------------|-------------|-------------|--|
| | Supply voltage | Operating voltage | Operating current | Input power | Power factor | Supply voltage | Operating voltage | Operating current | Input power | Analog load | |
| Permanent magnet drive system | 710 | 599 | 13.5 | 13.03 | 0.93 | 605 | 0 | 0 | 0 | No load | 6.67 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 705 | 33.6 | 19.69 | 0.48 | 605 | 0 | 0 | 0 | No load | |
| Permanent magnet drive system | 710 | 599 | 81.2 | 78.35 | 0.93 | 592 | 85.4 | 78.8 | 1 | half load | 14.83 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 704 | 89.9 | 93.17 | 0.85 | 589 | 85.8 | 78.8 | 1 | half load | |
| Permanent magnet drive system | 710 | 598 | 163.9 | 156.18 | 0.92 | 604 | 160.4 | 150.9 | 1 | full load | 36.21 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 704 | 179.3 | 192.39 | 0.88 | 604 | 160.1 | 150.8 | 1 | full load | |
| Saving electricity costs (10,000 yuan/year) | 26.0712 | Same power output, the permanent magnet motor and the ordinary three-phase asynchronous motor power difference 36.21 kW, calculate according to 360 days per year, 20h a day, 1 yuan per kWh: $36.21 \times 360 \times 20 = 26.0712$ | | | | | | | | | |
| Overhaul costs (10,000 yuan/year) | 7.26 | Overhaul maintenance cost: (2 sets traditional motor+2 sets reducer+2 sets+hydraulic coupler) cost price*30%=(12+13+3.2)*30%=8.46; | | | | | | | | | |
| Replacement costs(10,000 yuan/year)) | 21.7 | (Permanent magnet motor drive system)cost price*1%=(2*60)*1%=1.2 Replacement costs: 2 sets motor per year+1 set reducer per year+2 sets+hydraulic coupler 2 per year=12+6.5+3.2=21.7 | | | | | | | | | |
| Labour charges (10,000 yuan/year) | 10 | (Car labour charges+Maintenance labour charges)*2 persons=10 | | | | | | | | | |
| Total: (yuan/year) | 65.0312 | Time of cost recovery: permanent magnet motor drive system $60 \times 2 - (\text{traditional motor } 6 \times 2 + \text{reducer } 6.5 \times 2 + \text{hydraulic coupler } 1.6 \times 2) = 91.8$; $(91.8 / 65.0312) \times 12 = 16.9$, that is, the cost can be recovered in 16.9 months | | | | | | | | | |

Table 3. 315 KW Energy saving analysis of permanent magnet drive system (1000 KAV, primary voltage of 10000 V, secondary voltage of 690 V).

| Test motor type | Motor input technical data | | | | | Analog load (generator output technical data) | | | | | Same load output, input power difference |
|---|----------------------------|--|-------------------|-------------|--------------|---|-------------------|-------------------|-------------|-------------|--|
| | Supply voltage | Operating voltage | Operating current | input power | power factor | Supply voltage | Operating voltage | Operating current | input power | Analog load | |
| Permanent magnet drive system | 710 | 595 | 35.6 | 34.12 | 0.93 | 590 | 0 | 0 | 0 | No load | 10.93 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 709 | 56.2 | 45.05 | 0.65 | 590 | 0 | 0 | 0 | No load | |
| Permanent magnet drive system | 710 | 594 | 170 | 162.65 | 0.93 | 595 | 171.7 | 159.2 | 1 | half load | 37.86 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 709 | 188.8 | 200.51 | 0.86 | 587 | 174.7 | 159.9 | 1 | half load | |
| Permanent magnet drive system | 710 | 591 | 336 | 319.86 | 0.93 | 590 | 341 | 313.4 | 1 | full load | 84.63 |
| Asynchronous motor + reducer + hydraulic coupler | 710 | 709 | 396.3 | 404.49 | 0.83 | 589 | 341 | 313 | 1 | full load | |
| Saving electricity costs (Ten thousand yuan/year) | 60.9336 | Same power output, the permanent magnet motor and the ordinary three-phase asynchronous motor power difference 36.21 KW, calculate according to 360 days a year, 20 hours a day, 1 yuan per kilowatt hour: $84.63 \times 360 \times 20 = 60.9336$ | | | | | | | | | |
| Overhaul costs (Ten thousand yuan/year) | 28.1 | Overhaul maintenance cost: (2 sets traditional motor+2 sets reducer+2 sets+hydraulic coupler) cost price*30%=(32+64+5)*30%=30.3; permanent magnet motor drive system) cost price*1%=(2*110)*1%=2.2 | | | | | | | | | |
| Replacement costs (Ten thousand yuan/year) | 69 | Replacement costs: 2 sets motor per year+1 set reducer per year+2 sets+hydraulic coupler 2 per year=32+32+5=69 | | | | | | | | | |
| labour charges (Ten thousand yuan/year) | 10 | (Car labour charges+Maintenance labour charges)*2 persons=10 | | | | | | | | | |
| Total: (Ten thousand yuan/year) | 168.0336 | Time of cost recovery: permanent magnet motor drive system $110 \times 2 - (\text{traditional motor } 16 \times 2 + \text{reducer } 32 \times 2 + \text{hydraulic coupler } 2.5 \times 2) = 119$; $(119/168.0336) \times 12 = 8.5$, that is, the cost can be recovered in 8.5 months | | | | | | | | | |

- Realize soft start and big starting torque. Through the inverter control starting, the inverter output frequency of permanent magnet motor changes from 0 to the operating frequency

when starting, and the motor rotates synchronously following the frequency of the inverter output, therefore, without instantaneous high current, there will not be the bad impact on the grid; slow uniform starting lowers the maximum tension of belt and roller, reducing the impact on the idler, frame and other mechanical structures. Permanent magnet synchronous motor drive system can constantly output the starting torque, which is 2.8 times of rated load torque, but under the same power conditions, the starting torque is 55% of the rated load torque by using asynchronous motor drive system. In order to meet the starting torque, it is necessary to increase the motor capacity, and in the normal operation, it will waste more electricity, just as “a big horse pulls a small carriage”.

- Multimachine power balance. If the system uses the form of multiple permanent magnet motor drive, it can achieve multimachine power balance, to avoid multi-motor output imbalance caused by reduced motor life, burned and waste of electricity through the converter master-slave control mode.
- Reducing the system transformer capacity and volume. The structural characteristics of the permanent magnet motor determine its own high power factor that can be approximated as 1. In the case of the same power demand, compared with the asynchronous motor system, it can be driven with a smaller capacity motor, so the required capacity of the transformer will be reduced correspondingly.

Due to the use of inverter power supply, the use of high-frequency power supply can greatly reduce the size of the transformer.

2.3.2. Main problems in the operation of variable frequency drive system of the permanent magnet motor. Electromagnetic interference. As the frequency conversion to start the permanent magnet motor, the inverter control mode is the use of sine pulse width modulation (SPWM), but the output voltage is non-sinus, hence, it will generate a lot of time harmonics that the motor current contains a large number of harmonic components, which not only causes the increase of the motor's current and loss, the reduction of efficiency and power factor, but also with the increase of the motor power, this effect is more serious, and interferes with the adjacent electrical equipment [10]. It is possible to reduce the influence of harmonics by adding various harmonic suppression devices, such as AC reactors, DC reactors, filters, and other reactors. The effective control of interference can also be achieved by rational wiring and effective isolation.

- Irreversible demagnetization. Permanent magnet motor's temperature stability is poor. When designing or using it improperly, under too high (NdFeB permanent magnet) or too low (ferrite permanent magnet), the permanent magnet motor is possible to produce irreversible demagnetization or misconduct with the impact of the current generated by the armature reaction or in the chemical corrosion, severe mechanical vibration and the use of time and other comprehensive factors. Consequently, the motor performance is reduced, or it is even impossible to use. All these reduce the reliability of motor operation [9]. To prevent the demagnetization, the first one is to take good cooling measures, because for the motor using on the underground belt conveyor, it has explosion-proof demand, the best way is the water-cooling; the second is to use the optimal motor structure for preventing demagnetization, as the results show when the maximum demagnetization point of the permanent magnet of the motor that has rotor with pole shoe structure is the highest, the anti-demagnetization ability is the strongest [10].

3. Conclusions

From the perspective of the application place, permanent magnet motor variable frequency drive system which has been put into use is mainly used for the modification and the new gate road, tunneling faces, inclined shaft hoisting, etc. And in the mining area and poor conditions of the alley, the use of permanent magnet motor variable frequency drive system has a certain limit. On the one hand, it is because of its stand-alone volume and weight, so underground transportation is not

convenient, and the inverter also needs to occupy the corresponding chamber as the installation space; on the other hand, the coupler, reducer, asynchronous motor and other equipment that have been put into use are still in service, and are playing a corresponding role. From the application of power, because of its high price, the advantages in the use of low-power belt conveyor are not more obvious than in the large conveyor, so the use rate in permanent magnet drive system in small and medium-sized belt conveyor is very low. From the use effect of permanent magnet drive system, it can be trouble-free within a year, therefore, it greatly reduces the failure rate of belt conveyor drive system, ensures the belt conveyor running time and efficiency, and lightens the labor intensity of the maintenance and repair workers, so the permanent magnet drive system is very popular among the workers.

Through the comparison with the traditional driving system and the analysis of the advantages and disadvantages of practical application, it shows that the permanent magnet motor variable frequency drive system is much better than other drive control systems in the market, whether it is startup control, maintenance, failure rate and energy saving benefit. And through hardware and software settings, permanent magnet motor variable frequency drive system can not only realize the single or multimachine control, but also achieve the energy saving of the whole transportation system according to the optimal power matching speed. Through controlling the communication port of the system, combined with the monitoring system, it can achieve remote control of equipment, and further facilitate the realization of mine transportation system automation. Especially from the long-term operation effect of view, it is the best cost-effective driving system. This driving system is the design direction of the designers and the preferred choice of the users.

In short, the permanent magnet drive systems with the improving of the single coal mine production, the needs of national energy-saving and effect-raising driven, the advancement of mine automation level, the system performance further improving, will gradually replace other drive way and become a main drive system of the belt conveyor, will also be applied to the other large coal mining equipment such as scraper conveyor, fan, water pump, etc.

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