A New Linear Motor Driven MagTrack System

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Abstract:

In cooperation with China Coal, Magplane Technology, Inc. designed and led building of a 1km-long MagTrack demoline using a new third-generation permanent magnet linear synchronous motors at the campus of Zhangjiakou Mining Machinery Co. Ltd since 2013. After three years of manufacture, construction, and testing, two trains of coal-loaded six-capsules can be operated independently and fully demonstrated with all the functions of MagTrack systems, including loading, unloading, starting/stopping, switching, and 10 degree upslope climbing. The successful cycling running of 1km linear motor driven MagTrack system in Zhangjiakou was approved by China Machinery Industry Union and National Energy Administration as technical achievement in January 2016. This paper will describe the overall design and test results of new MagTrack system.

1. Introduction

A new capsule transportation system using linear synchronous motors, called MagTrack, developed by Magplane Technology, Inc. is invented to replace trucks and railways for hauling materials from the mine to the rail head, power plant or processing plant with reduced operating cost and energy consumption. Globally, coal is the third most heavily mined material after sand and gravel. According to a report from the World Coal Institute, up to 70% of the cost of coal is transportation costs [1]. Transportation of coal by truck uses large quantities of diesel fuel, which is energy inefficient, costly and a source of local pollution. Significant maintenance is also required for the trucks and for the road infrastructure. Transportation of coal by rail requires circuitous routes in hilly terrain and limitations on mining within 500m of the rail right-of-way often block access to significant reserves of coal.

Fig. 1. A 1st-generation 270m long pipeline demoline in Lakeland, Florida.

Figure 1 shows the 1st-generation linear synchronous motor driven pipeline prototype constructed and demonstrated in 2001 at the IMC-Agrico Company in Lakeland, Florida [2-3]. The prototype demonstration line used a 270m-long 60cm diameter cylindrical fiberglass tube, and included a 60m long accelerator/decelerator section, a switch, and load and unload stations. The test vehicle traversed back and forth at speeds up to 18m/s. As shown in Figure 1, the 2.4m long wheelbase vehicle used six-wheel assemblies at each end of a rotating hopper, and had a payload capacity of 270kg.

Fig. 2. A 2nd-generation 70m-long oval demonstration in Baotou, China.

Figure 2 shows the 2nd-generation 70m-long pipeline system demonstrated in Baotou, China in 2009 [4-5]. Based on the Florida prototype pipeline system, we have made a series of innovations on the pipeline system, including replacing the on-board North-South magnet array and the backiron with Halbach-arrayed permanent magnets and also putting non-continuous linear motor windings inside the pipe to decrease the gap between propulsion magnets and linear motor windings by half. The two changes together increased the motor propulsion force per Ampere by several times.

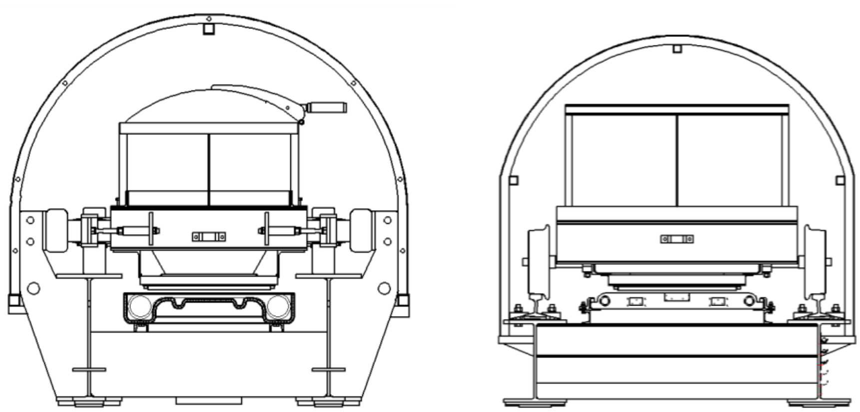

Fig. 3. A new 3rd-generation MagTrack system with the U-type guideway (left) or traditional rails (right).

Based on the Baotou pipeline prototype system, a series of innovations had been made to increase the coal transport capacity from 3 to 10 million ton/year, which presents a challenge for the motor deign and guideway structure. The most significant technical innovation is to replace the previous I-type hanging rail system underneath the top of pipe with the traditional rails or the U-type guideway with guidance wheels attached on two sides of each capsule in order to improve the stiffness of structure as shown in Figure 3.

2. 1 km Zhangjiakou Demonstration Line

Fig. 4. A new 3rd-generation 1km-long MagTrack demoline in Zhangjiakou, China.

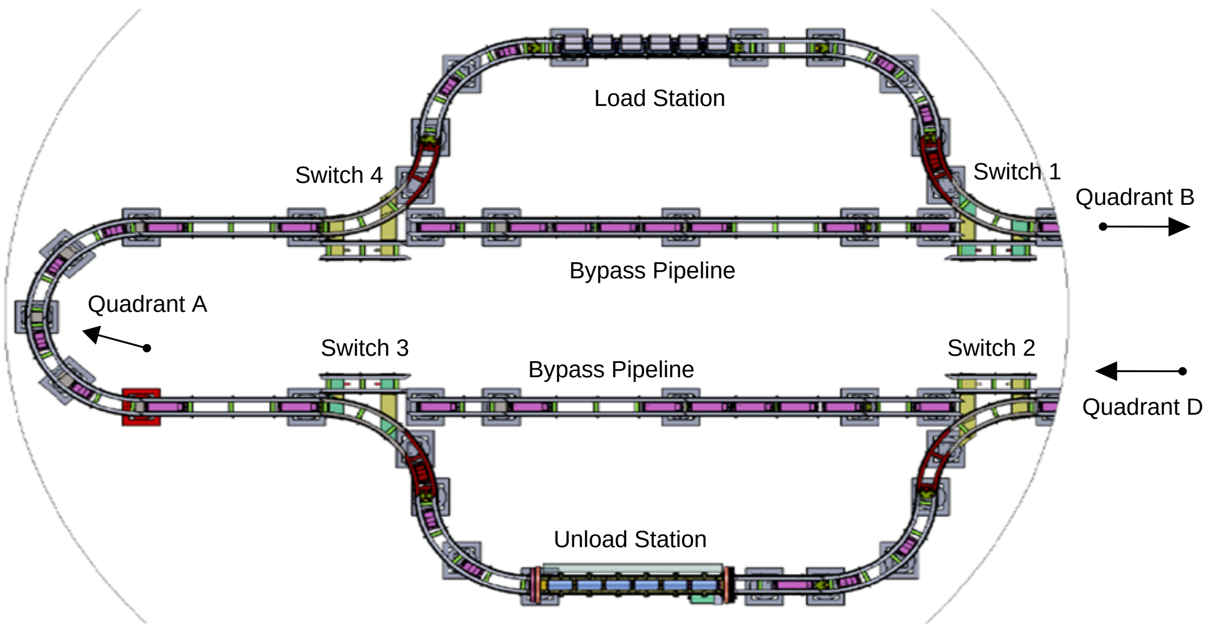

Fig. 5. Unload and load stations and bypass pipelines connected with four switches.

The new 3rd-generation 1km-long MagTrack Transportation System demonstrated in Zhangjiakou is shown in Figure 4. This 1km-long MagTrack demoline consists of an 500m outbound leg and a 500m return leg with two 180 degree U-turns at two ends to reverse the travel direction, and one load station and one unload station are set at the same end in order to return the unloaded materials back into the load station conveniently. Therefore, the 1 km long pipeline is divided into following four quadrants, load station (Quadrant A), outbound pipeline (Quadrant B), return pipeline (Quadrant C), and unload station (Quadrant D). As shown in Figure 5, four switches can let the capsule set run through load/unload station or bypass pipeline. Both load and unload stations can accommodate a six-capsule set, loading or unloading six capsules simultaneously.

The demonstration line is built as a combination of straight lengths and horizontal and vertical curves with an artificial hill to demonstrate full grade-climbing capability. The capsule design speed is 10 m/s, but the capsule sets will be driven at a much lower speed around 4 m/s in the U-turns with the bend radius of 7 meters, and the load/unload regions. The curves in the 10 m/s portion of the line have a minimal bend radius of 70 meters. At the beginning, the fully loaded capsule set will exit the load station, pass the switch to be accelerated to the operation speed of 10 m/s by the initial acceleration motor sections, go down to the flat ground, 10 degree upslope, hill top, 10 degree down slope, and then go back to the return line through a U-turn. The capsule sets will also travel through a 10 degree slope hill and decelerate to be stopped over the unload station. After the unloading, the capsule set exits the unload station, pass the switch and the U-turn, then return back to either load station through another switch or bypass a straight line to make another cycle running.

The Zhangjiakou Demonstration Line has the objectives of demonstrating all systems operations necessary for a commercial system, including the initial startup, a restart after an unplanned shutdown following a power failure and management of all fault conditions identified in commercial operation by simulated faults on the demonstration. It also contributes to a determination of demo system operating cost projected to a commercial system, including power consumption, scheduled maintenance, and necessary operating personnel. The projected operating cost needs to have a satisfactory return on investment and successful market penetration against both truck and rail transport.

3. MagTrack System Description

System Overview

A Magtrack Transportation System consists of tracks, capsules, one or more load and unload stations, and switches. The MagTrack consists of 12m-long standard modules which can contain one to four 3m-long standard non-continuous motor winding modules. The 1km demoline has totally 90 modules to simulate the straight section, horizontal and vertical curves, and an artificial hill to fully demonstrate slope-climbing capability.

Fig. 6. A 6-capsule train crossing two standard 12m-long modules

Figure 6 shows a 6-capsule train crossing two standard 12m-long modules. There are permanent magnets on the bottom of the capsules to interact with the linear motor windings mounted inside the tracks to provide the propulsion. The working gap between the permanent magnet arrays and the linear motor windings is 1.5 cm. The typical capsule parameters are listed in Table 1. Depending on the packing density of the coal or mined materials, the capacity of the capsule ranges from 750 kg to 1,250 kg, which is corresponding to the annual transportation capacity of 7.5-12.5 Mega-ton/year.

Empty weight	750kg
Payload	750kg
Weight of a 6-capsule train	9,000kg
Annual transportation capacity	10 Mega-ton/year

Table 1. Typical Capsule Parameters and Annual Transportation Capacity

Track

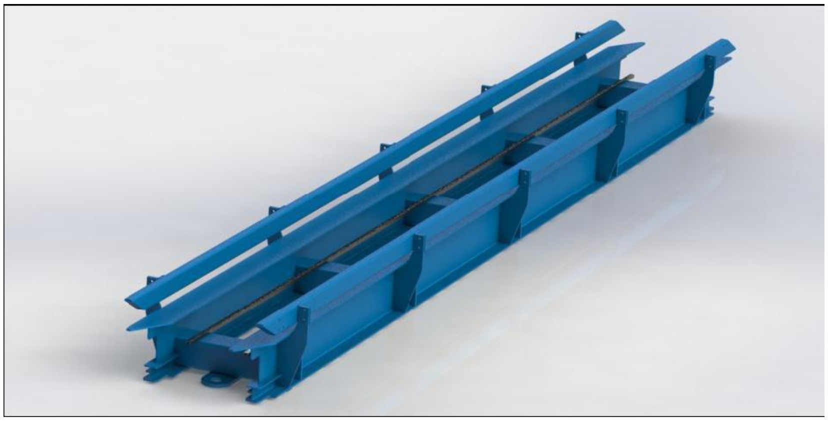

Fig. 7. A standard 12m-long track module

A standard 12m-long track module is shown in Figure 7. There are totally 90 modules along the 1km-long demoline in Zhangjiakou. MagTrack System track modules, supported by props above ground for less land, or laid at-grade, are convenient for installation. A variety of MagTrack System solutions can meet the different requirements of different sites and materials.

Capsule

The improved capsules have tight fitting covers that prevent the loss of the capsule content when traveling through the pipeline. This is particularly important in carrying coal where coal dust consists of fine powder, and accumulation in the pipe can represent a hazard. The cover is swung open during loading and unloading and closed prior to entering the pipe. The capacity of the capsule ranges from 750 kg to 1,250kg, depending on assumptions made on the packing density of the coal. The empty capsule and suspension weighs 750kg. There are 120 individual capsules per route km of double pipelines with the headway of 10s.

Fig. 8. A standard 1.92m-long Capsule

Linear Motor Windings

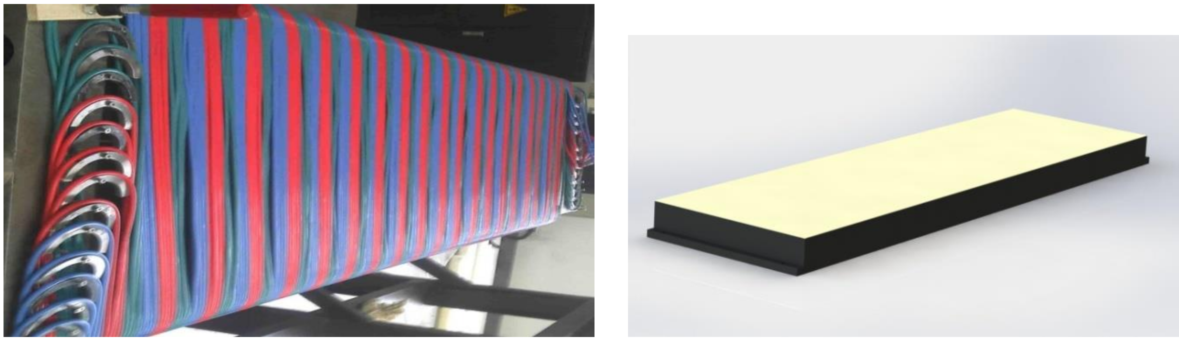

Fig. 9. Plan view of three-phase linear synchronous motor windings and a standard 3m-long stator box.

Figure 9 shows the plan view of three-phase linear synchronous motor windings and a standard 3m-long stator box. The motor windings are mounted inside the track and can be easily replaced by removing a winding module in the event of accident. As shown in Figure 9, each phase of the 3-phase winding is wound from a single cable length wound in five passes with turns around at the end of the module and therefore all five turns are in series. The windings are not continuous along the pipeline, and typically are inserted one pair in one standard 12m-long track module to reduce the motor cost significantly. There are totally 200 motor windings installed along the 1km MagTrack demoline in Zhangjiakou.

Cable	Copper AWG#6
Wavelength	0.24m
Motor width	0.75m
Cable layer thickness	0.01m
Air Gap between magnets and LSM windings	0.015m

Table 2. Dimension of 3-phase LSM windings

Table 2 lists some design parameters of linear motor coils. The motor winding is 0.75m wide with typical assembly length of 11 wavelengths as a standard 3m-long motor module. One 12m-long standard MagTrack module can mount one to four 3m-long standard motor winding modules. One vehicle carrying 1.68m-long magnet arrays can provide the 3,000N thrust at 150A which can accelerate one 1,500kg capsule to climb the slope with the continuous motor windings up to 10 degree angle.

Magnet Arrays

Fig. 10. Two wavelengths of Halbach-array permanent magnets

Magnet grade	N40 (NdFeB)
Basic block size	0.03×0.0125×0.05 m
Halbach array wavelength	0.24m
Block number for one Halbach wavelength	80
Block number for one capsule	560

Table 3. Parameters of permanent magnets for one capsule

One capsule is 1.92m long with the 7 wavelength (totally 1.68 m long) Halbach-arrayed magnets on the bottom. Each 0.24 m long wavelength Halbach-arrayed magnet consists of eight blocks of 0.03m wide N40 NdFeB magnet with the rotating 45 magnetization degree along the running direction as shown in Figure 10. The basic magnet block is 0.03m long in the running direction, 0.05m wide, and 0.0125m high. There are totally 10 pieces of N40 NdFeB magnets, so the Halbach array magnet is 0.5m wide. Table 3 summarizes the parameters of permanent magnets for one capsule.

Fig. 11. Magnets assembly attached to capsule bottom

During assembly the blocks are held in channels contact ~~cement is used~~ to hold the blocks in place. When mounted on the bottom of bogie, as shown in Figure 11, the magnet array is covered with a stainless steel sheet which secures the blocks in place and protects the surface.

Load/Unload Station

Fig. 12 Load Station (left) and Unload Station (Right)

Figure 12 shows the working load and unload stations at 1km MagTrack demoline. The pre-loaded weighting silo configuration can load the certain amount of coal materials into the six capsules simultaneously. The rotating auto-unloading mechanism enables simultaneous, reliable, efficient unloading of all six capsules in one train.

Switch

Fig. 13 Switches demonstrated at 1km Zhangjiakou MagTrack Demoline

Switches demonstrated at 1km Zhangjiakou MagTrack Demoline are shown in Figure 13. Four switches together with two bypass pipelines are used to simulate two load stations and two unload stations in parallel. In order to simulate the headway time of 10 seconds, the total switching time for each switch should be within 10 seconds, and every 10 seconds one 6-capsule train goes to either load/unload station or bypass pipeline. Therefore, the total working time for load/unload station is up to 20 seconds.

4. Motor Drives and Rectifier

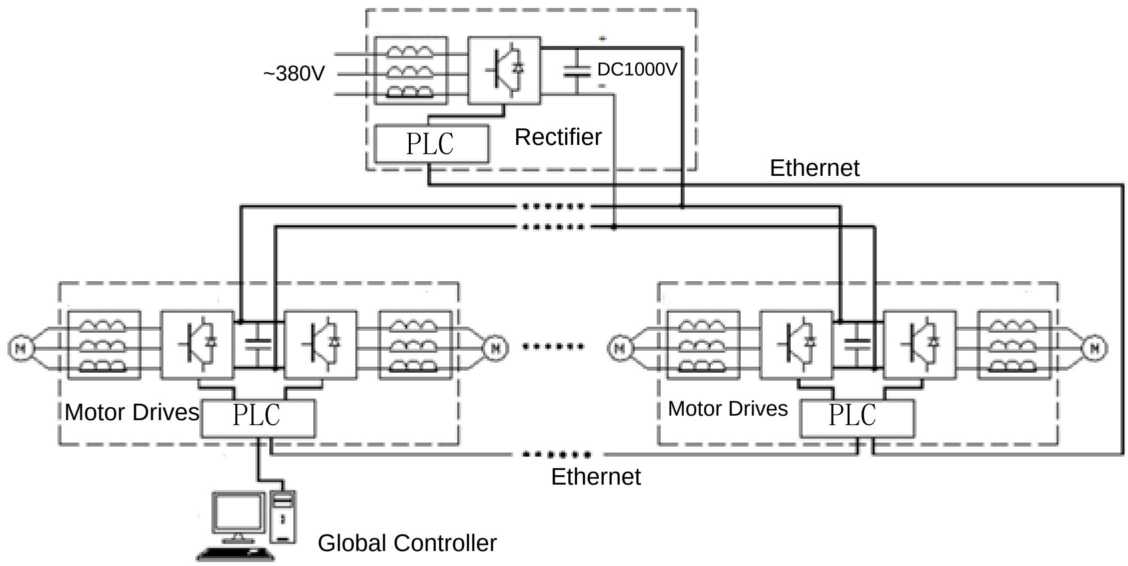

Fig. 14. Scheme of common DC Bus power for motor drives

Motor Drives	
Power	80kW/150kW
Power Supply	DC 1000V
Rectifiers with Regeneration	
Power	400kVA

Table 4. Parameters of Motor Drives and Rectifiers

As shown in Figure 14, the three-phase public utility power can be rectified by an active rectifier with braking regeneration into a common DC bus 1000V to power the motor drive cabinets along the track. There are totally 29 motor drive cabinets distributed along the track can verify the output voltage frequency to control the speed. One motor drive cabinet has two sets of motor drives 80kW/150kW to control typically two 12m-long connected linear motor windings. One six-capsule train needs to be driven by two motor drive units while crossing two motor drive sections. Therefore, two six-capsule trains running at the 1km demoline need four motor drive units. Some parameters of motor drives and rectifier are listed in Table 4. The common active four-quadrant rectifier can regenerate the braking power back to the grid in order to reduce the power consumption and operation cost.

5. Global Control System and Speed Profile for the Demonstration

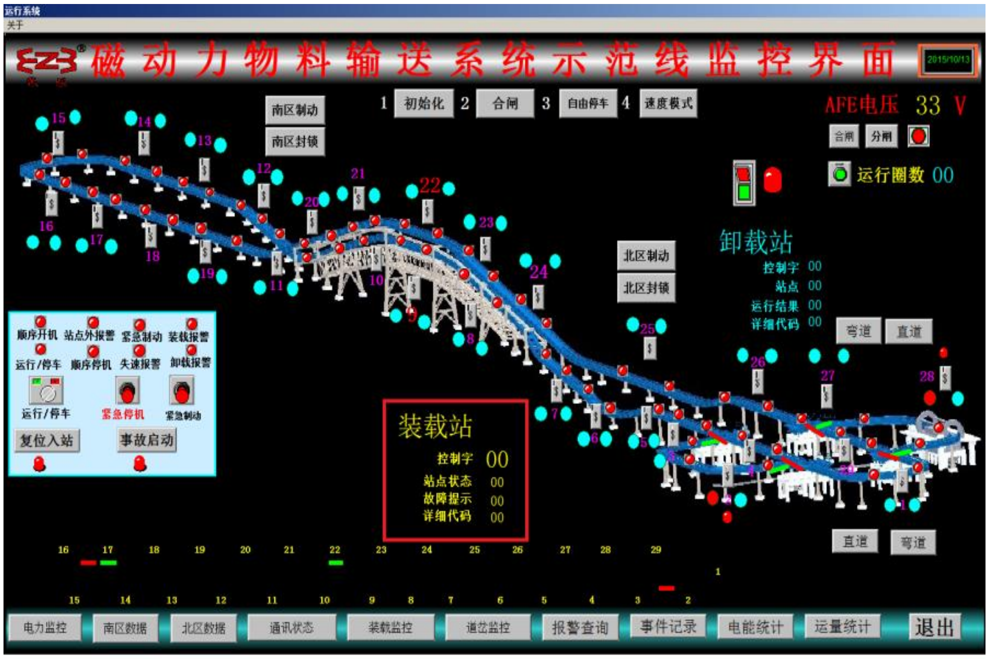

Fig.15. The monitoring interface of global controller

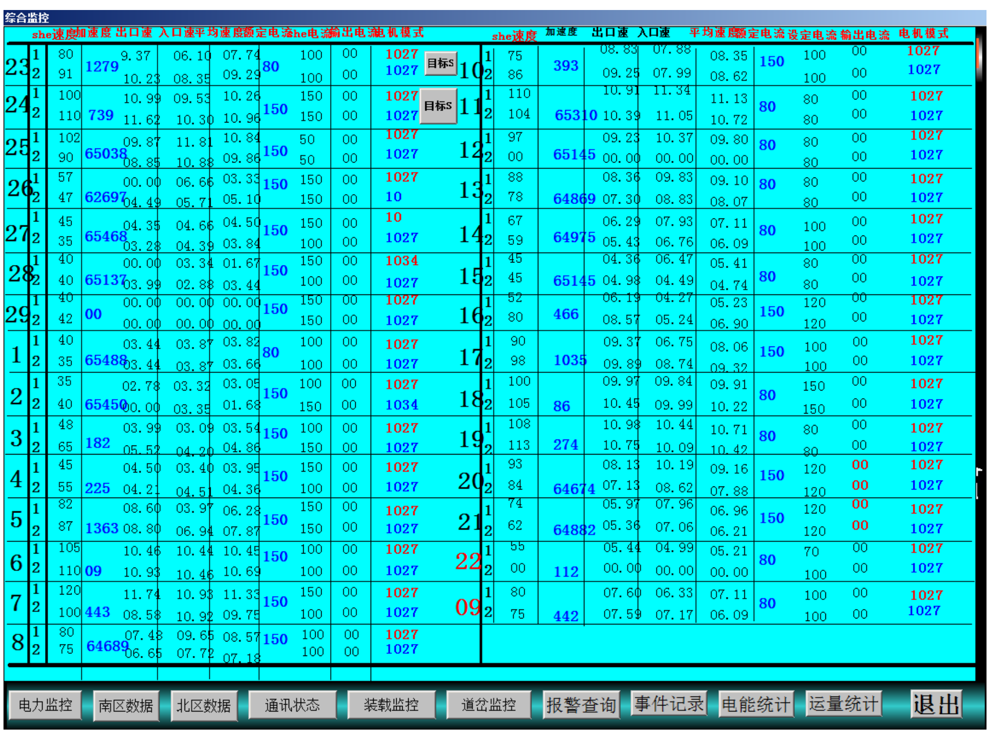

Fig.16. The global control interface

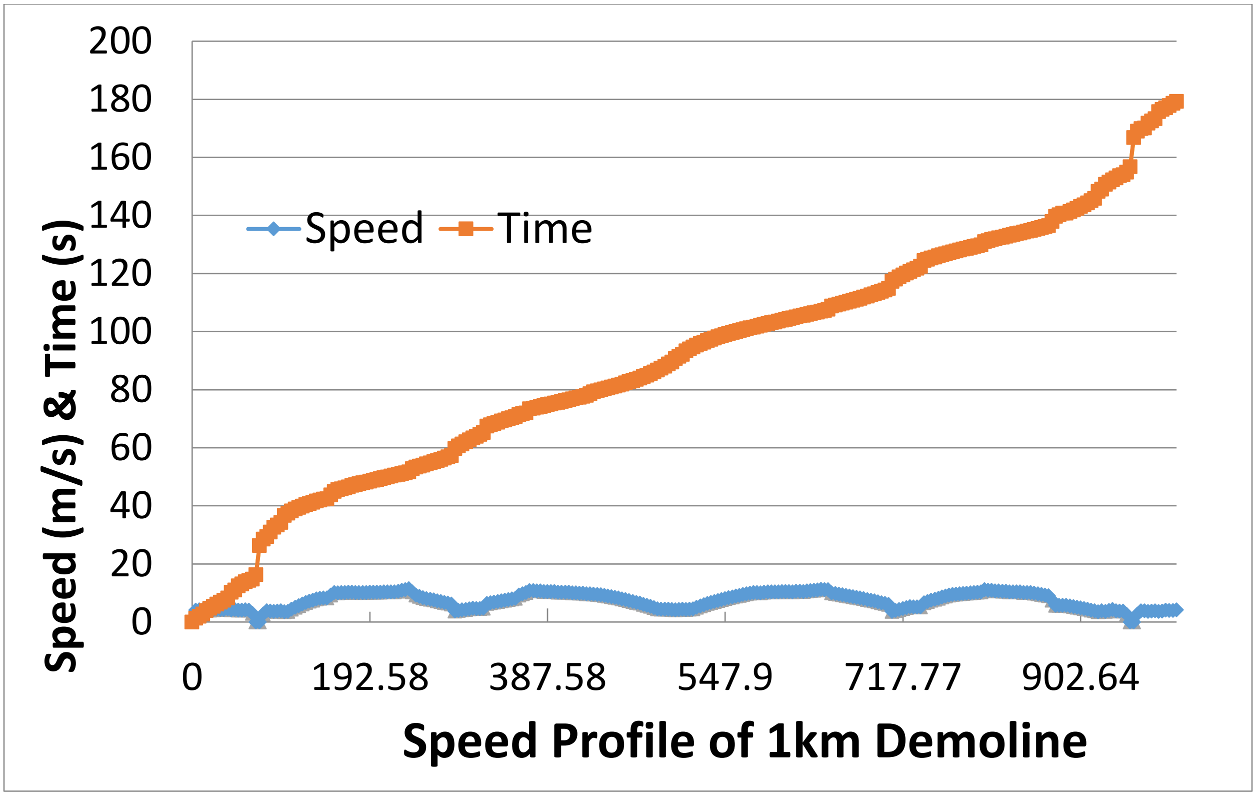

Fig. 17 Speed profile simulation on 1km MagTrack demoline

Figures 15 and 16 show the monitoring and operating interface of global controller, respectively. The global controller can control totally 29 motor drive cabinets along the 1km MagTrack, setting the speed target for each motor drive unit according to the simulated speed profile as shown in Figure 17. A six-capsule train takes totally 179.32 seconds to travel the full cycle length of 994.61m, and the average speed for one cycle is about 5.55 m/s, which is completely matched by the simulated speed profile.

After three years of manufacture, construction, and testing, two trains of coal-loaded six-capsules can be operated independently and fully demonstrated with all the functions of MagTrack systems as a pre-commercial demonstration line. The successful cycling running of 1km linear motor driven MagTrack system in Zhangjiakou was approved by China Machinery Industry Union and National Energy Administration as technical achievement in January 2016.

6. Xinjiang Project and Cost Estimation

Title	Unit Price (Million USD/km dual lines)	Percentage
Motor	1.24	28.5%
Control System	1.26	29.0%
Steel Guideway	1.25	28.7%
Mechanics	0.39	8.85%
Maintenance	0.007	0.16%
Others	0.21	4.79%
Total	4.357	100%

Table 5. Unit Price of MagPower Transport Systems (15MT/Year)

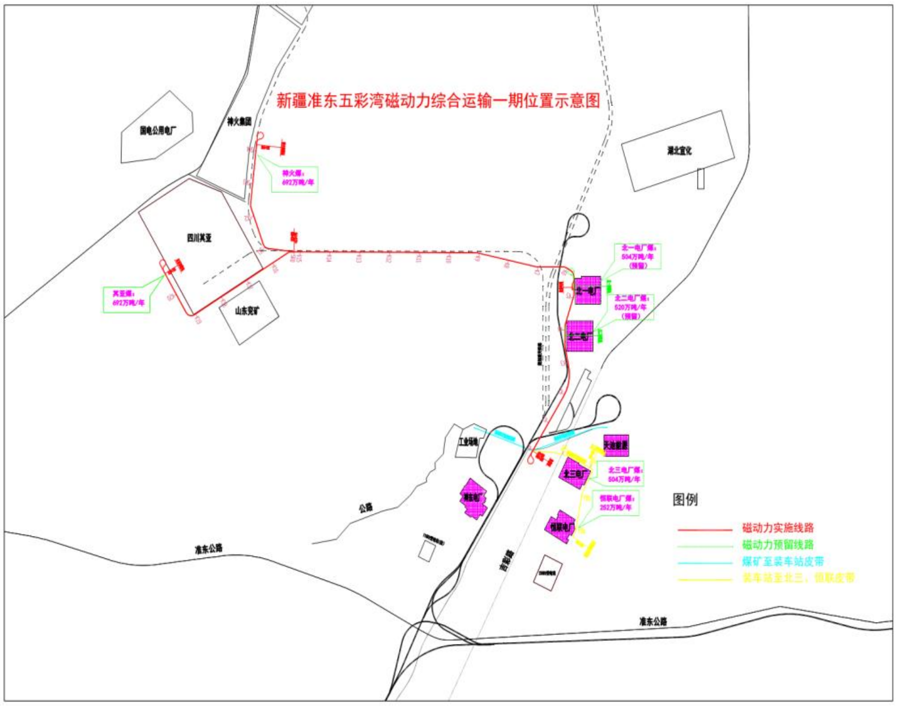

Fig. 18. Proposed Xinjiang Zhundong Transportation System with 15MT/year

Upon completion of the global control test at the 1km demoline, a feasibility study on Xinjiang Zhundong Transportation System has been conducted, and a 35km-long commercial MagTrack system is anticipated ~~expected~~ to be constructed as the phase one to carry coal ores from two mines to six power plants in Xinjiang as shown in Figure 18. The cost estimation for the transport capacity of 15MT/year is summarized in Table 5. The foundation cost is not included. Considering the 50% higher capacity with multiple destinations and severe weather in Xinjiang, the cost of Xinjiang commercial line per km dual-line is expected to be 40% higher than that for the regular MagTrack transportation line with 1MT/year.

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Jiarong Fang, Vice President for Engineering and Deputy Chief Technical Officer, Magplane Technology, Inc., received the Ph.D. degree from the Institute of Electrical Engineering, Chinese Academy of Sciences, China, in 2001. During the past two years, he was a project group director to lead all the three joint-venture partners for the whole project to make the successive running of 1km-long MagTrack Demoline in Zhangjiakou, China, in cooperation with China Coal and Rongxin Power Electric. Prior to joining Magplane Technology, Inc., in 2007, Dr. Fang was a Postdoctoral Fellow with the Francis Bitter Magnet Laboratory, Massachusetts Institute of Technology (MIT) in 2002 and then a Visiting Scientist with the MIT Plasma Science and Fusion Center. His main research contributions during the past 26 years have included maglev trains, linear drives, pipeline transportation, magnetic bearings, and superconducting magnets. Dr. Fang was an Administration Officer with the Maglev Office, Ministry of Science and Technology of China, in 1999-2001. He was a national maglev expert and a Review Committee Member for the maglev project of the National 863 High-Tech Plan.

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