

Energy Efficiency Analysis of Permanent Magnet Synchronous Motors in the Whole Life Cycle of Urban Rail Vehicles

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บทคัดย่อ บทความนี้วิเคราะห์ประสิทธิภาพการใช้พลังงานของมอเตอร์ซิงโครนัสแม่เหล็กถาวร (PMSM) ตลอดวงจรชีวิตของยานพาหนะที่ใช้งานในเมือง โดยช้ยานพาหนะ PMSM จากเส้นทางรถไฟเป็นตัวอย่าง โดยใช้ข้อมูลการทำงานของยานพาหนะจริงเพื่อสร้างแบบจำลองการใช้พลังงานของยานพาหนะ จากนั้นจะประเมินวงจรชีวิตเต็มของค่าการใช้พลังงานของยานพาหนะ PMSM ในทางสถิติ รวมถึงการใช้พลังงานระหว่างสี่ช่วงของการเร่งความเร็ว ความเร็วสม่ำเสมอ การเบรก และการหยุดรถ รวมถึงพิจารณาการใช้พลังงานและต้นทุนของยานพาหนะอย่างครอบคลุมและดำเนินการวิเคราะห์เปรียบเทียบระหว่างยานพาหนะที่ใช้มอเตอร์ซิงโครนัสแบบแม่เหล็กถาวร (PMSM) และมอเตอร์แบบอะซิงโครนัส (AM) ผลลัพธ์แสดงให้เห็นว่ายานพาหนะที่ใช้มอเตอร์ซิงโครนัสแบบแม่เหล็กถาวรสามารถประหยัดพลังงานและต้นทุนได้ 40% และ 36% ตลอดวงจรชีวิต ตามลำดับ ข้อมูลนี้แสดงให้เห็นว่ายานพาหนะที่ใช้มอเตอร์ซิงโครนัสแบบแม่เหล็กถาวรมีข้อได้เปรียบในการประหยัดพลังงานตลอดวงจรชีวิตเป็นอย่างมาก ดังนั้นยานพาหนะที่ใช้มอเตอร์ซิงโครนัสแบบแม่เหล็กถาวรจึงช่วยลดการใช้พลังงานในการใช้งาน ทำให้ประหยัดและเพิ่มความเป็นมิตรต่อสิ่งแวดล้อมของยานพาหนะ บทความนี้ให้ข้อมูลเพื่อสนับสนุนการเพิ่มประสิทธิภาพและการควบคุมการใช้พลังงานในยานพาหนะที่ใช้งานในเมือง

คำสำคัญ: PMSM, ยานพาหนะรางในเมือง, วงจรชีวิตทั้งหมด, ประสิทธิภาพการใช้พลังงาน, การขนส่งสาธารณะ, ความคล่องตัวในเมือง

Abstract This paper analyses the energy efficiency of Permanent Magnet Synchronous Motors (PMSM) throughout the entire life cycle of urban rail vehicles, using a vehicle with PMSM from a metro line as an example. The paper utilizes actual

vehicle operation data to establish a model for vehicle energy consumption. It then statistically estimates the full life cycle of the energy consumption value of the vehicle with PMSM, as well as the energy consumption during the four phases of individual acceleration, uniform speed, braking, and stopping. This paper comprehensively considers vehicles' energy consumption and cost and conducts a comparative analysis of the PMSM and asynchronous motors (AM) vehicles. The results show that the vehicle with PMSM saves 40% and 36% of energy consumption and cost throughout the life cycle. The data presented in this paper demonstrates that vehicle with PMSM offer significant energy-saving advantages throughout their life cycle. Therefore, the PMSM reduces operational energy consumption and improves the economy and environmental friendliness of the vehicles. The paper provides data to support the optimization and control of energy consumption in urban rail vehicles.

Keywords: PMSM, Urban rail vehicles, Whole life cycle, Energy efficiency, Mass public transport, Urban mobility

1. Introduction

Urban rail transport is becoming increasingly concerned with energy efficiency and operating costs. The majority of drive chain losses in urban rail vehicles are attributable to motor inefficiency. An attractive solution to reduce these losses and the associated energy consumption is the implementation of PMSM technology

[1]. PMSMs are preferred due to their high efficiency, high power factor, high power density, direct drive, fully enclosed structure, lighter weight, and excellent dynamic performance compared to AM [2-6]. PMSMs are suitable for high-speed trains, urban rail vehicles, and other similar applications. The structure of the PMSM is illustrated in Figure 1.

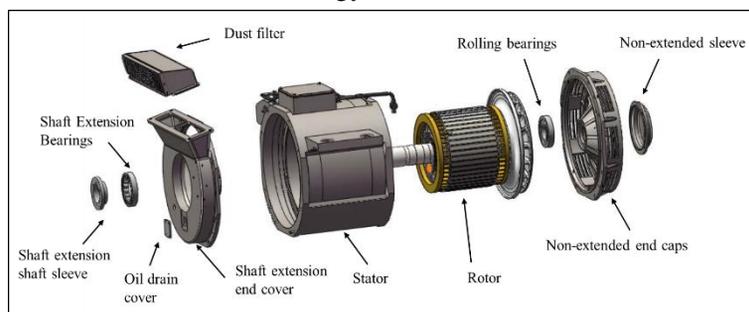


Fig. 1 Structure of the PMSM.

There is a growing trend among domestic and foreign scholars to research the application of PMSM in urban rail

vehicles. Khare and Shriwastava [7] investigated the weak magnetic control algorithm of the PMSM drive for light

vehicles. The importance of PMSM flux weakening for traction drives was discussed, along with the advantages and requirements of PMSMs in traction applications. They also analyzed the effects of different low/high speed modes on the network from an EMC point of view through simulation experiments. The research showed that PMSM have advantages in terms of low volume and direct drive of wheels. Liu et al. [8] conducted a line simulation to compare the energy consumption of the permanent magnet synchronous traction system with the asynchronous traction system. The comprehensive energy-saving rate of the permanent magnet traction system was found to be between 6.6% and 36.9%. Zhang et al. [9] analyzed the advantages and disadvantages of PMSM in the field of rail transportation. The study also covered the control strategy of high-power traction inverters and the weak magnetism control technology of traction motors. The basic theory, structure design, and control method of the permanent magnet traction system had been initially established. Kondo et al. [10] conducted a study on the energy consumption of PMSM for railway vehicle traction and showed that the total loss of PMSM is approximately 60% less than that of AM. This was achieved by establishing equivalent circuit and loss models. A comparative study on the efficiency of permanent magnet traction motors and AM was conducted by Qi et al. [11]. The results showed that the rated operating point

efficiency of PMSM is approximately 5% higher than that of AM. The advantage of the efficiency in the low-speed zone was even more pronounced, with an improvement of over 10% in the operating point efficiency. Franko et al. [12] conducted a study on the design and performance of AM and PMSM. They experimentally confirmed that improving the rotor of the PMSM could reduce loss, improve efficiency, and increase it by 2% compared to the AM. Recently, Yan and Wirogana [13] analyzed the energy transfer and dissipation in urban rail vehicles. Traction power consumption was found to account for approximately 50% of the system power consumption.

Table. 1 Line parameters.

Parameter	Value
Line length	22,700 m
Number of stations	18 seats
Average gradient	0.015
Average curvature	0.0025 m ⁻¹
Average traveling speed	32.2k m/h
Average stopping time	43.3 s
Average running time per day	0.78 h

Further exploring the potential energy-saving impact of PMSM is interesting. Since PMSM technology offers significant efficiency advantages, it is essential to consider its long-term benefits. This study presented a comprehensive analysis of the energy efficiency of PMSM throughout the entire life cycle of urban rail vehicles. The aim was to evaluate the energy savings, and operation and maintenance costs associated with the use of these motors, providing a

reference for the selection of energy-saving technologies for urban rail vehicles.

2. Research Methods

This study employed the Metro Line 5 in a city in central China as an example, providing information on its line conditions and vehicle parameters in Table 1 and Table 2.

The vehicle control unit integrates fault recorder and data logging functions to record status information on key control units and components of the vehicle. The Train Control and Management System (TCMS) then parses the required operational data. Figure 2 displays the TCMS data parsing interface.

Table. 2 Parameters of the study vehicles.

parametric	Vehicles with PMSM
Vehicle mass	189,000 kg
Average passenger capacity	63,000 kg
Maximum running speed	80 km/h
Acceleration (0-80km/h)	≥0.6 m/s ²
Coefficient of adhesion	0.158
Traction efficiency	0.98
Braking efficiency	0.98
Maximum Traction Force	360 kN
Maximum braking force	340 kN
Maximum power	3,040 kW
Maximum energy recovery	0.35
Battery capacity	437 Ah
Battery efficiency	0.9
Battery temperature (20°C) coefficient	0.86
Air Conditioning Power	22.8 kW
Lighting power	2.6k W
Design Life	30 years

MATLAB is then used to extract and analyze this data, calculating various parameters such as time, state, energy consumption, mileage, and other relevant factors for each stage of the vehicle's operation. Figure 3 shows the script editing interface for visual analysis of data in MATLAB. Such parameters were then used to construct a model of the vehicle's energy consumption, allowing for an estimation of the total energy consumption over the vehicle's entire life cycle.

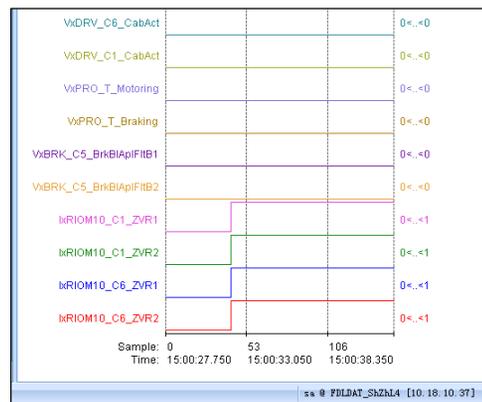


Fig. 2 Data parsing interface.



Fig. 3 MATLAB script editing interface.

Simultaneously, the economic perspective would consider the procurement, maintenance, and energy

costs of both motor types, as well as calculate the total cost in the whole life cycle of the vehicle with PMSM. The comparison of vehicle energy consumption and cost between the two motors would, then, reveal the energy-saving benefits of PMSM in the life cycle of urban rail vehicles, along with their advantages and limitations.

2.1 Calculation of vehicle energy consumption

Energy generation for vehicle operation was calculated in seconds. During traction mode, energy flows from the catenary to the wheels, resulting in positive power on the wheels. During regenerative

braking mode, energy flows from the wheels back to the power system, resulting in negative power on the wheels. The vehicle's auxiliary energy consumption mainly included battery chargers, passenger room air conditioning, and lighting. Following the vehicle energy consumption model proposed by Wang et al. and Jenks et al. [14, 15], this study first collected the real-time time, speed, mileage, and other data of a vehicle traveling through a large intersection (including both ends of the turnback) through the TCMS system. The vehicle operation curve is shown in Figure 4.

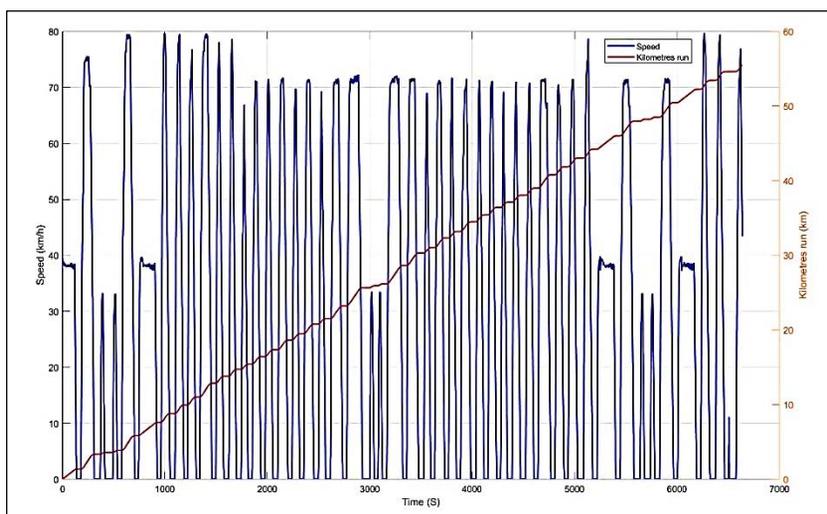


Fig 4 The typical vehicle running curve.

The vehicle operation process, due to its cyclical characteristics, included four phases: acceleration, uniform speed, braking, and stopping. To facilitate calculation, this study counted the time, energy consumption, and mileage data corresponding to acceleration, uniform speed, braking, and stopping in 20 cycles

(i.e., one major intersection). As a result, based on the traction energy consumption during acceleration and uniform speed, the regeneration energy consumption during braking, and the auxiliary energy consumption for the whole operation in the grand interchange, the unit traction energy consumption of 285 kWh, the unit auxiliary

energy consumption of 39kWh, the unit regeneration energy consumption of 162kWh, and the unit total energy consumption of 162kWh were calculated.

Based on a large intersection, the energy consumption of vehicles throughout their entire life cycle was calculated. With an average daily operating time of 15-18 hours, the crossing calculation took approximately 0.78 hours. The vehicle maintenance stops, and the operation of the crossroads were taken into consideration. Therefore, the energy model for the PMSM in urban rail vehicles throughout their life cycle would be defined in Equations (1) and (2).

$$N_c = \frac{T \times D}{0.78} \quad (1)$$

Where N_c is the number of operational intersections, T is the average daily operating time, and D is the number of operating days per month.

$$\begin{cases} E_y = E_u \times N_c \\ E_t = \sum_{n=1}^{30} E_y \end{cases} \quad (2)$$

Table. 3 Motors Cost Comparison.

Project	AM (RMB 10,000/unit)	PMSM (RMB 10,000/unit)
Procurement	9	10.1
Frame repair	0.9185	1.27
Overhaul	1.8	2.1

According to the “Management Measures for Operation and Maintenance of Urban Railway Transport Facilities and Equipment” [17], the frame repair interval should not exceed 5 years or 800,000 vehicle kilometers, while the overhaul interval should not exceed 10 years or 1.6

Where E_y type annual energy consumption, E_u is unit energy consumption, E_t is total energy consumption.

2.2 Calculation of traction motor cost

To enhance the economic performance of PMSM, AM was employed as a benchmark for analyzing the costs associated with the entire life cycle of urban rail vehicles. This comprehensive analysis encompassed procurement costs, as well as operation and maintenance costs.

The unit prices for procuring the two types of traction motors were derived from their respective procurement contracts. These prices were then utilized in the computation of the overall procurement costs. Additionally, drawing upon the actual outsourcing cost data from metro lines in select Chinese cities [16], the unit prices for vehicle frame repair and overhaul served as the primary input for the calculation of operation and maintenance costs associated with traction motors, as detailed in Table 3.

million vehicle kilometers. Additionally, the traction motor user manual should be consulted. The plan for estimating the vehicle design life cycle of traction motor procurement and maintenance costs based on a frame repair interval of 5 years and an overhaul interval of 10 years was outlined.

It was recommended that each train undergo 3 frame repairs and 3 overhauls.

3. Results and Discussion

3.1 Energy consumption

According to Section 2.1, the unit energy consumption value was brought into equation (1) to obtain the total energy consumption of the vehicle over its entire life cycle (as shown in Figure 4).

Figure 5 illustrates the energy consumption and train operation routes of the vehicle with PMSM throughout its entire life cycle. On the left side of the axis, the bar represents the total annual energy consumption, while the right side displays the number of train operation routes with the broken line indicating the annual train

operation routes. The vehicle completes 179,397 train operation routes over its entire life cycle, operating approximately 4,484,913 km, with a total energy consumption of 29,062.24 MWh.

Based on the research data from Deng and Zhong [18], the unit energy consumption of the asynchronous traction motor vehicle was 10.99 kWh/km. Assuming that it covered the same mileage as the vehicle with PMSM throughout its life cycle, its total energy consumption would be approximately 49,289.20 MWh, as presented in Table 4. The data showed that the vehicle with PMSM has a lower whole life cycle energy consumption compared to the asynchronous traction motor vehicle with 41% energy consumption saving (20,226.96 MWh).

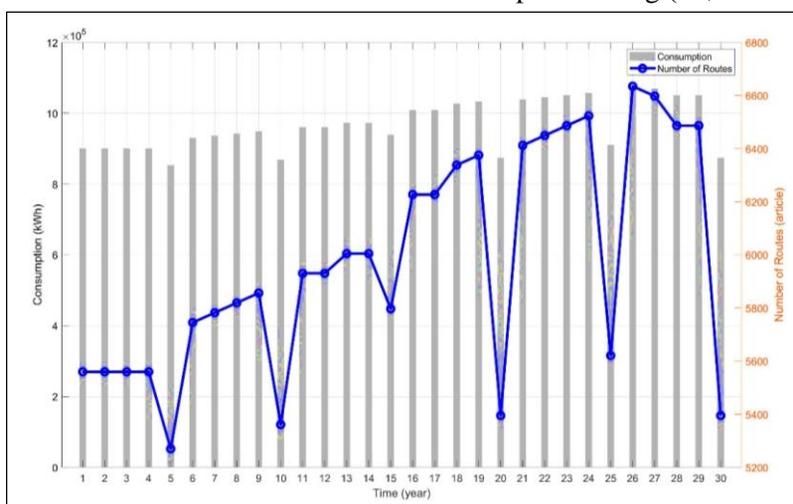


Fig. 5 Energy consumption and Train operation route.

Table. 4 Life cycle energy and electricity consumption values.

Vehicle type	Total energy consumption (MWh)	Total Electricity Consumption (10,000 RMB)
Vehicle with AM	49,289.20	2978.05
Vehicle with PMSM	29,062.24	1755.94

Figure 6 displayed the four stages of operation and energy consumption of a vehicle with PMSM at a large intersection; they were acceleration, uniform speed, braking, and stopping stages. The data indicated that the entire process had a total cumulative acceleration of 620 s, covering a distance of 8.35 km and consuming 224 kWh of traction energy. During the uniform speed operation, it took 557 s to cover 10.05 km, consuming 61 kWh of traction energy and 9 kWh of regeneration energy. Additionally, it took 755 s to operate 8 km during the braking, generating 153 kWh of

regeneration energy. The average traction energy consumption per kilometer and the total energy consumption are 15.49 kWh and 6.48 kWh. Compared to the asynchronous traction motor vehicle's energy consumption of 16.39 kWh and 10.99 kWh/km [18], the PMSM vehicle's energy consumption of 49 kWh and 6.48 kWh/km demonstrated a significant improvement in energy efficiency and regeneration rate. The less energy consumption revealed the advantages of using a PMSM.

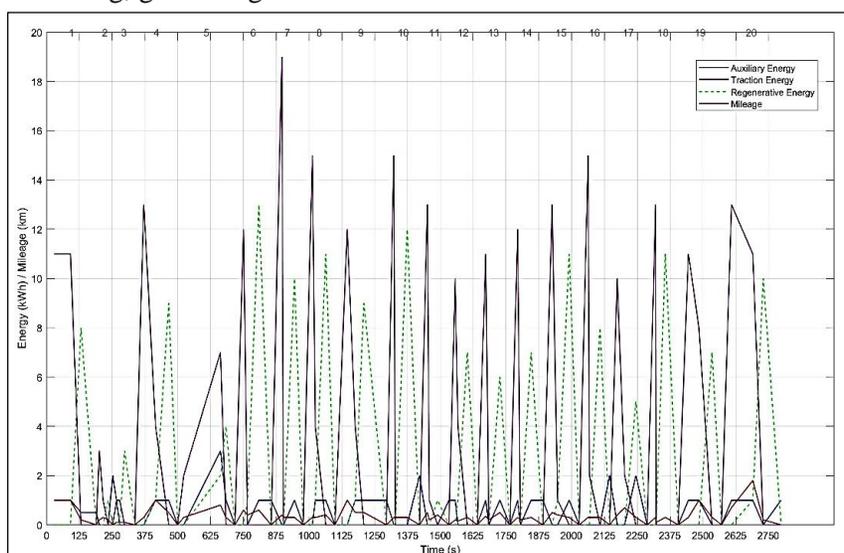


Fig. 6 Vehicle operating energy consumption/mileage.

3.2 Economic aspects

For the economic performance of the AM and PMSM, the electricity cost of the two different motors during the whole life cycle of the vehicle, as referred to China's urban railway electricity cost (with 0.6042 RMB/kWh), was shown in Table 4. The total cost of electricity in the entire life cycle of vehicle with PMSM is approximately 17,559,400 RMB, which is a saving of about 12,221,100 RMB compared to asynchronous traction motors. From section 2.2, the expenses for procurement and maintenance throughout the entire lifespan of vehicles with two different types of motors are presented in Figure 7. The cost analysis showed that the PMSM had a procurement cost of 1,616,000 RMB (which was 176,000 RMB higher than that of the asynchronous traction motor). Likewise, the maintenance cost of PMSM was 1,617,600 RMB, which was 312,700 RMB higher than the asynchronous traction motor. As a result, the total cost of the PMSM was also 488,700 RMB higher than the

asynchronous traction motor, representing an increase in cost of approximately 17.8%. Such total cost was attributed to the current scarcity of permanent magnet materials for PMSM, making the production and manufacturing costs more expensive compared to AM [19]. At the same time, the frame repair and overhaul such as maintenance place cleanliness, and other environmental requirements contributed to the overall higher costs [20, 21].

In summary, the energy-saving of PMSM was about 40% over the whole life cycle of the vehicle from the point of view of comprehensive energy consumption and economic analysis. Even though the total cost of procurement and maintenance of PMSM was 17.8% higher than that of asynchronous traction motors, it was still possible to save around 11,732,400 RMB, which is 36% of the cost. Therefore, PMSM offers clear energy efficiency advantages in urban rail vehicles, reducing operating costs.

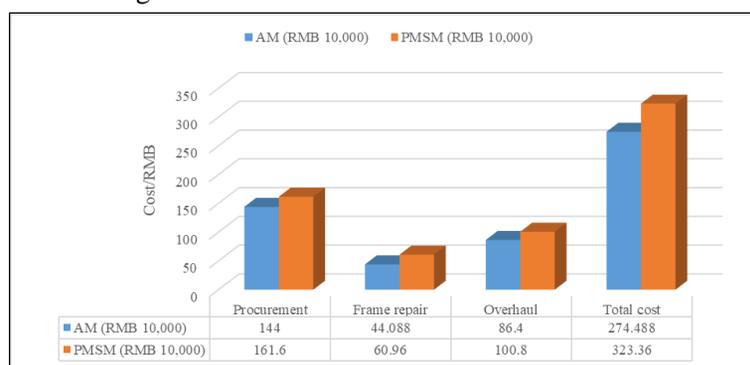


Fig. 7 Expenditure on two types of motors.

4. Conclusion

This study explored the energy efficiency analysis of PMSM compared to asynchronous traction motors over the whole life cycle of urban rail vehicles, using a permanent magnet vehicle on a ground line as an example. The study concluded with the following main findings and contributions:

1. Based on the actual vehicle operation data, we established a reliable model for vehicle energy consumption that applies to this line. The full life cycle energy consumption of the permanent magnet vehicle of approximately 29,062.24 MWh was calculated. Additionally, the energy consumption characteristics and energy-saving mechanisms of the PM vehicle during the four phases of individual acceleration, uniform speed, braking, and stopping were analyzed.

2. A comparative analysis of PMSM and AM vehicles, taking into account energy consumption and economic costs, indicated that although the procurement operation and maintenance costs of PMSM are higher than those of AM throughout the vehicles' life cycle, vehicle with PMSM have higher energy efficiency and lower economic costs. The energy consumption and costs of PM vehicles are saved by 40% and 36%, respectively. Such values indicated that vehicles with PMSM are more energy-efficient and cost-effective.

3. Finally, this study provided a reference and basis for improving energy efficiency, saving energy, and reducing emissions of

urban rail vehicles. It also offered data support for optimizing and controlling vehicle energy.

5. Limitations and Future Research

This study only considers the permanent magnet vehicles of one metro line as an example. It does not take into account the differences of other lines or the effects of seasonal changes and other factors on the vehicles with PMSM. It is important to note that this approach may have some limitations.

In the future, the collection and analysis of vehicle operation data from different lines and environments to establish a more general and perfect energy consumption model should be studied. Such activities would enable the carrying out of comprehensive and in-depth energy efficiency analysis and comparison, providing more effective solutions for the energy-saving technology of urban rail vehicles.

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Author's Biography



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Assoc. Prof. Boonruk Chipipop has held the position since 2000. He received his master degree in electrical engineering from King Mongkut's Institute of Technology Ladkrabang in 1997. His current research interests are fractional-order electrical network application and fractional-order control application applied to engineering management