Green Energy, Environment and Sustainable Development
C. Wang et al. (Eds.)

doi:10.3233/ATDE230287

Design of an Automatic Battery Swapping Station for Electric Vehicles

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Abstract. This article proposes a design scheme for an automatic battery swapping station for electric vehicles. The automatic battery swapping station mainly includes a cyclic battery pack storage device, a battery pack storage compartment, a swapping platform and so on. The cyclic battery pack storage device has a battery life processor, and the battery pack storage compartment reads the usage curve data of each battery through an interface. The battery life processor collects data on the temperature and current of the battery during electric vehicle driving and establishes a capacity degradation model for non-linear Wiener processes. It calculates the lifespan of the battery pack, sorts the batteries, sets the priority of each battery, and ultimately places the battery with the highest priority at the top of the battery swap queue. The swapping platform can automatically disassemble and assemble the battery pack when it reaches the designated position. The automatic battery-swapping station can lift and stack the battery packs without complex lifting mechanisms, making the swapping process simple, the battery pack exchange time short, and the swapping efficiency high.

Keywords. Automatic electric vehicle swapping station, battery pack storage, sort

1. Technical Background

The birth of automobiles has brought great convenience to human life and transportation, accelerating the pace of life and greatly improving human efficiency, while also changing human lifestyles. Today, as the global automobile industry continues to grow, environmental pollution and the shortage of petroleum resources are the bottlenecks of current automotive development. With the improvement of living standards around the world, energy-saving and emission-reducing automobiles have become a new development trend. In this context, new energy pure electric vehicles have emerged [1-2]. However, due to the limitations of current battery technology, the range of pure electric vehicles is limited, thus requiring timely charging or battery replacement.

Currently, electric vehicles have a promising development prospect in China, and various Chinese automobile companies are producing various new types of electric vehicles [3]. However, due to issues such as inconvenient charging and insufficient range of electric vehicles, their development in China and worldwide has been limited [4]. At present, the main power supply solutions for electric vehicles include charging schemes and battery swapping schemes. For the charging solution, the charging gun connected to the power source can be connected to the vehicle's charging port to charge

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the power battery on the vehicle. This process takes a long time, but there is currently fast charging technology that can fully charge the battery in a short time. However, this type of charging technology seriously damages the battery life [5]. Another method is to use a charging station, but the charging station technology is not well developed, requiring dedicated charging stations for specific vehicles, greatly reducing their utilization rate. For the battery swapping solution, it is to directly replace the discharged power battery on the vehicle with a fully charged power battery. This process takes less time and can solve the problem of insufficient energy in a shorter time, making it more popular among users and manufacturers. Therefore, a car swapping station similar to a gas station has emerged [6-7]. Establishing battery swapping stations in cities and on important roads satisfies the requirements of electric vehicle range and meets a range of social demands [8].

2. Design Scheme of Automatic Battery Swapping

This article describes a design for an automatic battery swapping station for electric vehicles. During the battery swapping process, there is no need to lift the vehicle, which saves the high-power motor that would be necessary to do so. The design also controls the overall height of the swapping platform and station. The battery pack can be easily lifted and stacked without the need for complex lifting mechanisms. The swapping process is straightforward and the battery swapping time is reduced, resulting in high efficiency. Additionally, the station includes a feature to detect the lifespan of electric vehicle batteries in real-time, which improves driving safety and enhances the user experience.

The main components of the automatic battery swapping station include a cyclic battery pack storage device, a battery pack storage compartment, a swapping platform, and an electric vehicle traction device, as shown in Figure 1.

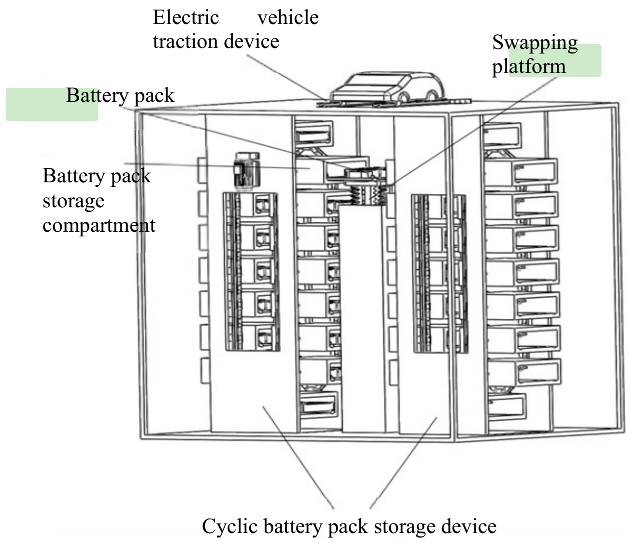


Figure 1. The main components of the automatic battery swapping station.

The positional relationship of each main component is as follows: the electric vehicle traction device is located on the ground, while the cyclic battery pack storage device, battery pack storage compartment, and swapping platform are located underground. The cyclic battery pack storage device has two sets and is located on both sides of the swapping platform. The cyclic battery pack storage device can change the storage position of the battery pack and the location of the vacant battery pack storage compartment, while the swapping platform can lift fully charged battery packs from the battery storage position to the battery swapping position, and lower partially charged battery packs from the battery swapping position back to the storage position. The electric vehicle traction device is located above and used to tow the electric vehicle to a position where battery swapping can take place.

The cyclic battery pack storage device has a total of 16 battery pack storage compartments, and during operation, there is always one battery pack storage compartment available to accommodate batteries swapped from electric vehicles. Additionally, if space allows, another cyclic battery pack storage device can be installed on each side of the lifting platform to increase the storage capacity.

2.1. The Cyclic Battery Pack Storage Device

The cyclic battery pack storage device is used for storing battery packs. The device is equipped with a battery life processor and a battery usage information recording device on each battery, which records battery life information. The battery pack storage compartment reads the usage data of each battery through an interface. The battery life processor can collect temperature and current information of the battery during the operation of the electric vehicle. As the capacity of the electric vehicle battery pack deteriorates with changes in external conditions and internal chemical reactions, which usually have nonlinear characteristics, the battery life processor establishes a non-linear Wiener process capacity degradation model for battery life data based on the usage curve data of the battery by using equation (1) and calculates the battery pack life. The cyclic battery pack storage device sorts the batteries according to their life and assigns priority to each battery. The battery with the highest priority is placed at the top of the list of batteries to be swapped.

Let $X(t)$ be the capacity degradation amount of the electric vehicle battery pack at time t:

$$X(t) = x_0 + a\int_0^t \mu(b,v)dv + \sigma_B B(t) + G\left[A(I,T)e^{E/kT} \times n_c^{B(I,T)-1}\right] \times e^{-E/kT} \times n_c$$

Here, $\mu(b,v)$ and $B(t)$ are independent; x_0 represents the initial degradation amount of the lithium battery at time zero; a is the drift coefficient and follows a normal distribution, that is, $a \sim N(\mu_a, \sigma_a^2)$, representing heterogeneity among individuals of similar equipment types; σ_B is the diffusion coefficient; $\int_0^t \mu(b,v)dv$ is a nonlinear function of b, representing the nonlinear characteristics of battery capacity degradation, with G representing battery capacity; n_c is the charge-discharge cycle life; T is the absolute temperature; I is the discharge current; $A(I,T)$ is the function that represents the influence of current and temperature on coefficients; $B(I,T)$ is the function that represents the influence of current and temperature on the exponent of the power function; E represents the activation energy of failure; k is the Boltzmann constant.

2.2. The Swapping Platform

The battery swapping platform consists of a first working position and a second working position. The first working position is used for retrieving and storing battery packs from the storage compartment, while the second working position is used for removing and installing battery packs from the electric vehicle. The first working position is located below the second working position.

The cyclic battery pack storage device in each group has a battery pack access position. The battery pack storage compartment can move cyclically in a forward or reverse direction within the cyclic battery pack storage device. Only when the battery pack storage compartment moves to the battery pack access position, the battery pack can be accessed. The battery pack access position corresponds to the first working position of the battery swapping platform.

2.3. The Electric Vehicle Traction Device

The structure of the electric vehicle traction device is shown in Figure 2. It has rails on the ground, with auxiliary rollers installed at the front end of the rails. The vehicle traction device is mounted on the rails, and uses a traction clamp to secure the front wheels of the vehicle to be swapped. The vehicle traction device then pulls the electric vehicle along the rails to a designated location and secures it in place before initiating the battery swapping process.

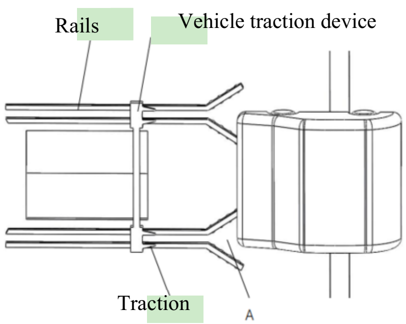


Figure 2. The electric vehicle traction device.

2.4. The Battery Pack Storage Compartment

When the battery pack storage compartment is being transported, it moves clockwise from top to bottom and the compartments do not interfere with each other. The compartments are sequentially located at different positions, and only the storage compartment at the first position has the ability to store and install the battery pack, as shown in Figure 3.

The battery pack storage compartment includes a battery pack holder for positioning and transferring the battery pack, as well as a communication interface for reading battery storage data and simultaneously completing the battery charging process. The communication interface is in contact with the battery pack through two PINs.

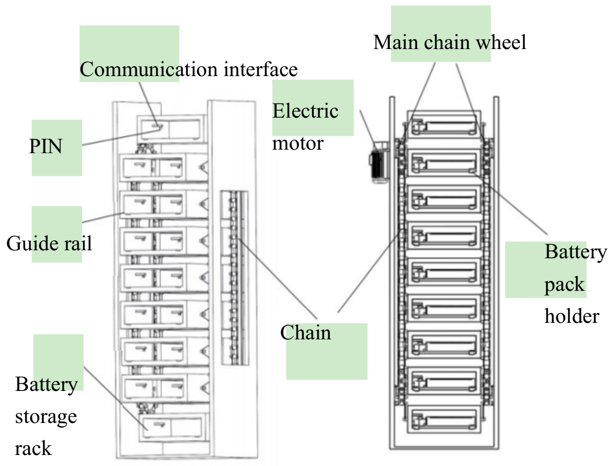
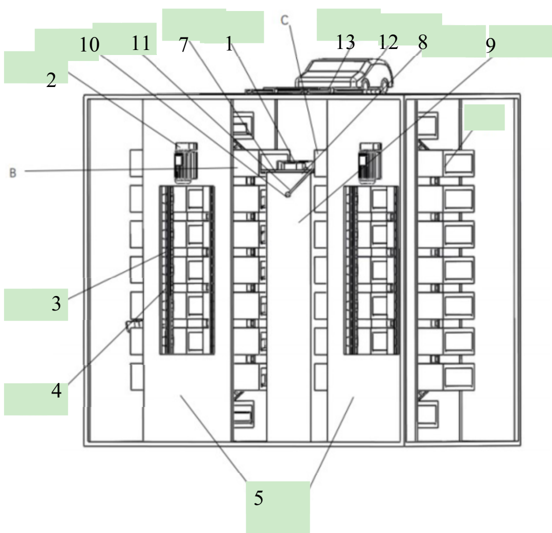


Figure 3. The battery pack storage compartment.

2.5. Specific Implementation Methods of the Automatic Battery Swapping Station

In order to further clarify the technical methods adopted in this article, the following will provide a detailed explanation of the specific implementation and benefits of an automatic swapping station for electric vehicles based on the proposal of this article, in conjunction with Figure 4.



1-battery pack 2-electric motor 3-chain 4-loop track 5-frame 6-battery storage rack 7-battery pack holder 8-battery swapping pallet 9-elevator 10-wheel 11-pendulum 12-rails13-vehicle traction device

Figure 4. The detailed composition of the automatic battery swapping station.

The workflow of the automatic electric vehicle swapping station described in this article consists of four steps.

- In the first step, when an electric vehicle drives into the designated position A on the traction rail as shown in Figure 2, the electric vehicle puller drives the traction clamp to fix the front wheel of the electric vehicle. After fixing the front wheel, the electric vehicle is adjusted along the rail, and under the traction of the electric vehicle puller, the electric vehicle stops and is fixed directly above the battery swapping platform. Due to the constraints of the rail on the width direction of the electric vehicle, the electric vehicle puller only needs to complete the positioning constraint of the electric vehicle along the direction of the rail to achieve the entire replacement constraint of the electric vehicle.
- In the second step, the elevator drives the battery swapping pallet to the second working position on the battery swapping platform. Then, the positioning pin captures the position of the depleted battery pack on the electric vehicle. The fastening gun fixed on the battery swapping pallet removes the depleted battery pack from the electric vehicle. Due to the presence of the positioning pin, the removed depleted battery pack is securely fixed on the battery swapping pallet. The battery swapping pallet then descends vertically until it reaches the first working position.
- In the third step, before the elevator with the swapping tray descends to the first working position, the battery pack holder traction slider grabs the front circular buckle of the battery pack holder at position B in the storage compartment of the battery pack, and then the turning wheel drives the swinging rod to swing. The battery holder traction slider pulls the empty battery pack holder in the storage compartment of the empty battery pack along the battery holder guide rail, until it slides to the sliding rail on the elevator and reaches the first working position on the battery swapping platform. At this time, the depleted battery pack that was removed by the swapping tray will fall onto the battery pack holder on the elevator. During this process, the battery holder traction slider also grabs the battery pack holder and the fully charged battery pack at position C in one side of the battery pack storage device, then the swinging rod swings in reverse to send the battery pack holder with the fully charged battery pack back to the B position in the battery pack storage compartment, while pulling the fully charged battery pack in the C position battery pack storage compartment onto the swapping tray. When the battery pack holder with the depleted battery pack moves back into the battery pack storage compartment, the communication interface in the compartment connects with the battery pack through PIN needles to complete the reading of battery usage information and to charge the battery. Then, the cycle type battery storage device rotates, and the next storage compartment with the fully charged battery pack moves to the first swapping position (position B).
- In the fourth step, the battery pack holder with the fully charged battery pack in the storage compartment is lifted up to the area above the swapping tray. At this time, the lifting platform is at the first working position, and the elevator drives the swapping tray to rise to the second working position. After that, the tightening gun installs the fully charged battery pack onto the electric vehicle above it, and the automatic swapping process ends. The traction clamp in the electric vehicle traction device releases the grip on the electric vehicle, and the electric vehicle drives out of the battery swapping station.

2.6. Battery Management Methods for Battery Swapping Stations

Battery management methods for electric vehicle battery swapping stations described in this article include the following steps:

- Step A: A battery data storage device is installed on the battery pack to record the battery usage curve during electric vehicle operation.
- Step B: A battery life processor is able to read the usage curve recorded in the battery data storage device of the battery pack. The battery life processor calculates the battery life data based on the data in the battery usage curve.
- Step C: The cyclic battery storage device reads the life data of each fully charged battery pack. The battery life processor sorts the battery packs based on their life data according to a certain priority, and moves the battery pack storage compartment containing the battery pack with the highest priority to the battery access position.
- Step D: As the electric vehicle is secured to the designated position by the vehicle hauler, one set of cyclic battery storage devices moves the battery pack with the highest priority to the battery access position, while another set of cyclic battery storage devices moves the empty battery pack storage compartment to the battery access position.

3. Results

The electric vehicle battery swapping station described in this article mainly accomplishes the following functions:

- A battery usage information recording device is installed on the battery to record battery life information. The battery pack storage compartment reads the usage data of each battery through an interface, and then calculates the battery life using the formula provided in this article. The batteries are sorted according to their lifespan and their usage priority is set accordingly.
- The battery pack can be transported without the need for additional battery transmission mechanisms or complex lifting mechanisms through a circular battery pack storage device.
- The circular storage device for the battery pack is designed with multiple layers to store multiple battery packs, with multiple battery exchange ports, and a simple and efficient battery exchange process. This increases the storage capacity of the battery packs and enhances the efficiency of the battery exchange process.
- The main components of the battery exchange station are installed underground, occupying a small amount of surface space. The elevated battery exchange platform ensures high stability of the battery pack structure.

4. Discussions

The electric vehicle battery swapping station designed in this article has significant advantages and beneficial effects compared to existing technologies. They are as follows:

- The prioritization of battery swap operations based on battery life data can help extend the life of batteries, improve resource utilization, and reduce operational costs.
- By prepping the battery pack with the highest priority and making sure that empty battery pack compartments are readily available, the wait time for the next customer's battery swap can be minimized. This contributes to a smooth and uninterrupted flow of customers, enhancing the swapping station's reputation and customer satisfaction.

- There is no need for additional battery transfer mechanisms or complex lifting mechanisms, simplifying the structure and reducing the construction cost of the swapping station.

There are also the following drawbacks to the electric vehicle automatic swapping station described in this article:

- High investment cost: Constructing an electric vehicle automatic swapping station requires purchasing a large number of swapping equipment and related facilities, resulting in relatively high investment costs.
- Inconvenient site layout: Electric vehicle automatic swapping stations need to be distributed in various areas of the city to provide convenient swapping services for users. Suitable sites need to be found within the city.

In the future, we can consider the following aspects to solve the problems we encounter:

- Intelligent management system: Develop an intelligent electric vehicle automatic swapping station management system, including functions such as remote monitoring, fault diagnosis, and optimization of the swapping station. By connecting the automatic swapping station to the internet and smartphones, users can remotely inquire and control, providing personalized swapping services [9-11].
- Supporting infrastructure construction: Fully consider the layout of electric vehicle automatic swapping stations in urban planning and construction, and provide supporting construction of swapping stations and parking spaces to provide more convenient swapping conditions [12]. At the same time, cooperation with other infrastructure such as malls, hotels, and gas stations can provide more swapping locations to meet the diverse charging needs of users.

5. Conclusions

The battery swapping process of the designed electric vehicle swapping station in this article is simple and efficient, improving user experience and offering practicality and wide industrial utility value. It provides a preliminary and effective solution for the design and construction of electric vehicle swapping stations.

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