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Review on Electric Vehicles Battery Swapping Technology

Dr. G. Sree Lakshmi
Professor, CVR College of Engineering/EEE Department, Hyderabad, India
Email: g.sreelakshmi@cvr.ac.in

***Abstract:* The goal of research and development organizations is to intelligently design the architecture of battery swapping stations (BSSs), with the hope of offering a reliable platform for the successful installation of a large fleet of electric vehicles (EVs) and hybrid electric vehicles (HEVs). The BSS can calibrate its subsystem for the deployment of electric vehicles (EVs) by implementing a similar concept to those found in current gas stations, which involve exchanging or swapping out discharged batteries for partially or fully charged ones after a short while. Because it gives the relevant stakeholders a more comprehensive understanding of the business prospects, the BSS approach has emerged as a promising technological alternative to the conventional EV recharging station approach. This paper addresses the introduction to BSS, covering its methods, infrastructure, advantages over charging stations, and main obstacles.**

***Index Terms:* Battery Swapping Station (BSS), Battery Charging Stations (BCS), Electric Vehicles (EVs), Hybrid Electric Vehicles (EHVs).**

I. Introduction

Traditionally, EVs are bought with "fixed" batteries, which can only be charged with the power source inside the vehicle. Mass adoption of EVs depends on the availability of sufficient, reasonably priced, easily accessible, and dependable charging networks like ICE vehicles need fueling stations [1]-[2]. In India, initiatives are in place to increase the accessibility of infrastructure for charging. Even so, charging still takes a lot longer than ICE refueling. An alternative is battery swapping, which allows you to charge the batteries independently and entails swapping out discharged batteries for charged ones [3]. As a result, there is very little downtime while the car is in operating mode and charging and battery consumption are disconnected. Battery swapping is more common for smaller vehicles, like 2Ws and 3Ws, because their batteries are smaller and easier to change, as opposed to 4 wheelers and e-buses, though there are also solutions being developed for these other vehicle segments. As long as each swappable battery is actively used, battery swapping has three main benefits over charging: it saves time, space, and money [4]- [5].

The goal of battery swapping policy is to protect the ecosystem's potential for innovation in EV batteries while establishing a framework for increased interoperability.

• Regular charging of e-2W and e-3W devices requires at least three to four hours with current technologies, which is inconvenient and increases range anxiety. This results in a significant amount of vehicle downtime, especially for shared mobility and freight vehicles. On the other hand, because swapping stations have pre-charged batteries, switching out batteries only takes a few minutes [6].

• Charging stations take up more space due to the need for vehicles to park nearby during charging. Battery swapping stations can stack multiple batteries and require minimal parking, making them ideal for urban areas with limited space [7].

• Battery swapping requires more batteries than traditional batteries, but each swappable battery can have a smaller capacity (kWh) due to lower range anxiety [8].

One of the most crucial components for battery leasing and swapping companies is the ability to track the location and performance of batteries. From the swapping stations, it is simple to track and observe the battery swapping process. IoT can be very helpful in tracking and monitoring batteries, as well as preventing theft and loss. The Internet of Things has a particularly noticeable impact on industries like grid-scale energy storage and electric vehicles (EVs). IoT-enabled EV batteries can interact with charging stations to ensure the best possible charging while simultaneously sending vital information for upkeep of the vehicle [9].

The communication protocol is an essential part of a Battery Management System (BMS) that ensures prompt and efficient communication with other systems or components in a particular application. In its most basic form, a communication protocol is a set of rules that define how two or more entities. In this case, electronic devices interact with one another. These rules may regulate data rate, error-checking protocols, data structure and order, and mutual device identification between transmitting and receiving devices [10].

Adoption of communication infrastructure standards (protocols and technology) is crucial for maintaining data stability and security. BIS will define and approve communication standards between batteries and vehicle controllers, chargers, and energy operator servers. To promote "back-end" interoperability in the battery swapping ecosystem, an open standard communication protocol like OCPP can be used. This protocol should allow network switching. The BMS constantly monitors and regulates a number of battery-related parameters, including temperature, voltage, current, and state of health (SoH) and state of charge (SOC). However, in the event of a serious issue, the BMS may receive instructions from the car's central control unit to limit current output, initiate a cooling cycle, or even isolate the battery. This unprocessed data must be sent to this unit. This sharing of information is made possible by the communication protocol [11]-[12].

This paper provides an overview of the most advanced battery swapping technologies and implementations currently on the market. This paper highlights the technical challenges facing this newly proposed model and the potential for

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technological advancements in the near future. It also presents a redesigned model of battery swapping methodologies that addresses some of the issues that current battery swapping technologies face. The advantage of this battery swapping technology over the state-of-the-art is also emphasized, including mechanical, electrical, and financial ones. In order to commercialize this proposed model, significant differences, advantages, and technological advancements are highlighted. Finally, research opportunities and technical challenges related to this novel model are presented.

II. Methods of Battery Swapping

A. Manual Battery Swapping Station

At a battery-swapping station, batteries are manually inserted and extracted. This process involves manual labor, usually done by hand. These stations are modular and require very little space. These have smaller battery packs and are manageable for one or two people to handle, so they can be used with 2W or 3W batteries [13].

B. Autonomous Battery Swapping Station

At the Autonomous Battery-Swapping Station, the process can be automated entirely or in part. 4W makes use of the robotic arm. More space is necessary before setting up an autonomous battery swapping station, though. This is typically more expensive than doing it by hand. Furthermore, due to their increased weight and size, battery packs require mechanical support. The Ministry of Road Transport and Highways (MoRTH) has approved the sale and registration of electric vehicles (EVs) without batteries. This is a good step that will help battery swapping solutions a lot, even though it seems to take forever. Commercial electric vehicle fleets, especially those in the electric two- and three-wheeler segments, can find it feasible because batteries can currently be changed [14]-[16].

For the first time on a commercial scale, China used the battery swapping technique for electric buses in 2008—that is, during the Summer Olympics. The batteries on about fifty buses that ran various routes were switched. Since then, the bus swapping method has also been widely adopted by China, Japan, South Korea, and other countries. The different swapping techniques are as follows, with distinctions made based on where the robotic arm is being used and where the battery is located within the vehicle:

Sideways Swapping: This is mostly applied to vans and other vehicles where having the sideways position is the most sensible.

Rear Swapping: This is used in cars where the battery is installed backwards. Usually, in the case of cars with a large boot.

Bottom Swapping: This is applicable to vehicles that have their batteries installed at the bottom. At the swapping station, the car is positioned on an elevated platform, and a robotic arm is used to swap the batteries from the bottom using other accessories that are usually found below ground level.

Top Swapping: The most common application of this is in electric bus technology, where the batteries are kept at the top and the rooftop opens upon the bus's arrival to enable the robotic arm to complete the battery swap.

TABLE I
ELECTRIC VEHICLES WITH AND WITHOUT BST

S.No	Manufacturer	Model	Country	Battery Swapping
1.	NIO	NIO ES8	China	Manual
2.	Geely	Geely Geometry EX3	China	Manual
3.	Tesla	Tesla Model S	United States	NO
4.	Nissan	Nissan Leaf	Japan	NO
5.	BMW	BMW i3	Germany	NO

III. Mathematical Model for BSS

The battery swapping station's total charged power and total discharged power are represented by equations 1 and 2:

$$P_{cbss}^{t} = \sum_{b=1}^{B}(P_{cbs}^{t,b}) \quad \forall\, t \in T \tag{1}$$

$$P_{dbss}^{t} = \sum_{b=1}^{B}(P_{dbs}^{t,b}) \quad \forall\, t \in T \tag{2}$$

By adding the power of each battery in the battery swapping station, the total powers are determined. Each battery in the battery swapping station is charged or discharged in the same way as a conventional battery, as demonstrated by:

$$U_{cbs}^{t,b} + U_{dbs}^{t,b} \leq 1\ \forall\, t \in T; \forall\, b \in B \tag{3}$$

$$P_{cbs}^{t,b} \leq P_{bs}^{r,b} * U_{cbs}^{t,b}\ \forall\, t \in T; \forall\, b \in B \tag{4}$$

$$P_{dbs}^{t,b} \leq P_{bs}^{r,b} * U_{dbs}^{t,b}\ \forall\, t \in T; \forall\, b \in B \tag{5}$$

Each battery's stored energy within the battery swapping station is determined by

$$E_{bs}^{t,b} = E_{bs}^{t-1,b} + \left\{P_{cbs}^{t,b} - \frac{P_{dbs}^{t,b}}{\eta_{bs}}\right\} X\, I_{dur}^{t}$$

$$\forall\, t \in T; \forall\, b \in B \tag{6}$$

Each battery's rated capacity and efficiency are indicated by

$$\eta_{bs} \frac{\sum_{t=1}^{T}\left(P_{dbs}^{t,b}\, X\, I_{dur}^{t}\right)}{\sum_{t=1}^{T}\left(P_{cbs}^{t,b}\, X\, I_{dur}^{t}\right)} \tag{7}$$

$$E_{bs}^{t,b} \leq E_{bs}^{r} \forall\, t \in T; \forall\, b \in B \tag{8}$$

Modeling the process of switching batteries is done by

$$\begin{cases} E_{bs}^{t,b} = 0 \\ P_{cbs}^{t,b} = 0\ \ \forall\, t \in t_{swap}; \forall\, b \in B \\ P_{dbs}^{t,b} = 0 \end{cases} \tag{9}$$

$$E_{bs}^{t,b} = E_{bs}^{r}\ \forall\, t = (t_{swap} - 1)\ \forall\, b \in B \tag{10}$$

During the battery swapping procedure, the fully charged battery in the station is replaced with a depleted battery from an electric vehicle that pulls up to the station. When a battery needs to be changed, an empty battery is replaced with one that is fully charged. Furthermore, it is not feasible to charge or discharge the battery at this time due to the ongoing swapping process [17]. As such, during the swapping time, the battery's power and energy are set to zero, as shown by Eq. 9. The battery needs to be fully charged during the time period before swapping it out at the next time interval. In order to replace the batteries at the next time interval, the energy management system must ensure that there are sufficient fully charged batteries available at each time interval. This point is expressed in Eq. 10.

IV. Electric Vehicle Charging Ecosystem

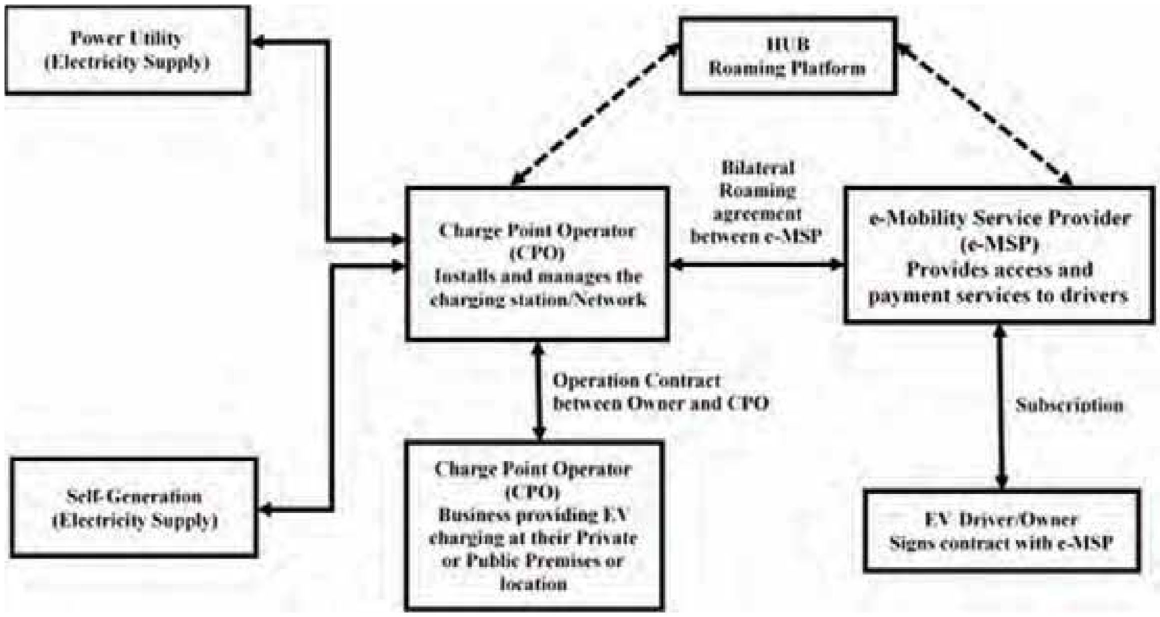

Figure.1. Electric Vehicle Charging Ecosystem

To ensure smooth operation of EVs certain guidelines are needed for EVs charging and Battery Swapping systems which are given as:

- To provide universal access to the infrastructure needed for charging electric vehicles.
- To promote a quicker uptake of electric vehicles by making sure that the environment and infrastructure for charging are secure, dependable, accessible, and reasonably priced.
- To encourage charging rates that are reasonable for both owners of electric vehicles (EVs) and operators of charging stations.
- To create chances for small business owners to get work and income.
- To actively encourage the development of EV charging infrastructure in the first stages and ultimately establish a market for the EV charging industry.
- To promote the adoption of EV Charging Infrastructure by Electrical Distribution Systems.
- To establish consistency and assurance in the direction of the nation's accelerated adoption of EVs.

The electric vehicle charging ecosystem consists of Power Utility, Self-Generation, Roaming Platform (HUB), Charge Point Operator (CPO), e-Mobility Service Provider (e-MSP), Charging Station Owner, EV Driver/Owner [18]-[19].

For effective battery monitoring, data analysis, and safety, the batteries must be BMS-enabled. In order to safeguard the battery against situations like thermal runaway, the battery swapping provider must make sure the proper BMS is in place. In order to guarantee asset security and battery safety, swappable batteries will be outfitted with sophisticated features such as remote monitoring and immobilization capabilities, Internet of Things-based battery monitoring systems, and other necessary control features.

V. BSS Modes

State-of-the-art EV charging studies include models of battery swapping and charging stations to give EVs additional energy. Electric car drivers link their vehicles to a charging station and allow their batteries to run for several hours while in BCS mode. When an electric vehicle is in BSS mode, it just takes a few minutes to replace its depleted battery with a fully charged one. To comprehend the BSS operation models, this investigation will first concentrate on two key areas: the two types of stations (BSS/BCS) and the number of BSSs and BCSs in the business models. Based on various combinations of BSS and BCS, these can be divided into four categories: a single BSS, multiple BSSs, an integrated BSS and BCS, and multiple BSSs and BCSs [20].

Single BSS: The fundamental mode of operation for a single BSS is the most common business mode among commercial BSSs that are currently in use. The workflow is explained in the following. When the battery's state-of-charge (SOC) drops, the EV driver first notifies the BSS; if the request is granted, the driver then visits the BSS. Second, after being exchanged, the battery is mixed with the batch of swapped batteries at the BSS. Third, if there are charging piles at the recharging center, the switched battery is placed on a charger to be charged. Fourth, when the battery reaches its full charge or the termination criterion is satisfied, it is moved to the batch of fully recharged batteries to wait for future swapping. Lastly, the battery of an arriving EV is installed in place of the fully charged battery that was previously installed in the BSS [21]-[22].

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Multiple BSS: There are three ways that the drivers can start a swapping order: by calling one hour ahead of time, by making a reservation (based on a daily schedule), or by just showing up without an appointment. Second, following the EV driver's swapping orders and ongoing battery condition monitoring at each BSS, the control center chooses a potential BSS for the EV based on predefined objective values and constraints. Once assigned, the EV driver can either accept it and visit the BSS to replace it, or they can reject the suggested BSS. In conclusion, updating each BSS's battery queuing and dynamic availability requires real-time communication between the control center and BSSs [23].

Integrated BSS and BCS: This BSS mode is different from the previous two in that it features ten parking ports in the charging section, eight EVs in the recharging mode, and nine EVs in the queuing mode. Here, two distinct types of chargers are displayed: Four 25 kW maximum power slow chargers and six 50 kW maximum power fast chargers are available. The control center is responsible for handling requests from EV drivers, monitoring the BSS and BCS's current status in real time, determining the most efficient way to replace and recharge EVs, and developing the best charging schedule for both BSSs and BCSs. An integrated BSS and BCS station's decision-making process is defined by the combination of centralized and decentralized models: While decentralized models manage swapping or charging requests independently, centralized models take into account drivers' preferences when deciding whether to swap or charge an incoming EV. This helps to minimize station load.

TABLE II
BENEFITS AND BARRIERS OF BATTERY SWAPPING TECHNOLOGY

Aspects	Benefits of Battery Swapping Technology	Barriers of Battery Swapping Technology
Charging Time	When compared to conventional charging, rapid battery replacement minimizes waiting time.	Requires the development of infrastructure, which can be costly and time-consuming.
Battery Life & Health	Batteries can be maintained and charged to achieve ideal conditions and a longer lifespan by switching them out on a regular basis.	Quality control must be strictly adhered to in order to guarantee that all replaced batteries are in good condition.
Vehicle Cost	Possibility of lowering the initial cost of EVs if batteries are leased as opposed to purchased.	Difficulties with standardization could limit compatibility between different car models, which could raise costs.
Environmental Impact	The production of clean energy is ultimately facilitated by centralized charging, which is essential for optimizing the potential of renewable energy sources.	Batteries should be recycled or disposed of properly because improper handling can pose risks to human health and the environment.
Grid Load	Can centralize charging to lessen the burden on the electrical grid during peak hours.	Needs a steady power supply to guarantee that replaced batteries are constantly charged.

VI. BSS CHALLENGES

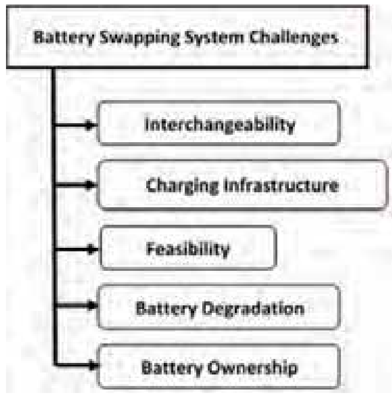

Figure 2. Battery Swapping System Challenges

A. Interchangeability

Cross-platform capability and brand compatibility are prerequisites for technology's success and ascent to prominence in the market. The availability of similar interchangeable battery packs from multiple manufacturers is the only way a battery swapping system has any chance of continuing to be a viable primary option. Consent from the manufacturer is required for this easy fix. But this could also limit the creativity, individuality, and adaptability of goods created solely by a single manufacturer. Furthermore, it will restrict the development of new products because cell manufacturers at the top of the supply chain will be forced to create standardized cells that are comparable to those produced by the next level of manufacturing, which will be the only way to achieve further standardization. It is possible to argue that the battery pack has different power segments, but this would lead to issues with supply and demand as well as potential incompatibilities with cars not built for higher or lower powered battery packs [24]-[25].

B. Feasibility

Currently, the biggest obstacle to battery swapping technology is the battery design. Robustness in removing and reinstalling the battery from the car should be incorporated into its design. There are currently very few cars in India with these kinds of battery pack designs. Hero Maxi, for instance, enables the simple replacement of a discharged battery with a charged one and the independent charging of the discharged battery [26].

C. Infrastructure

The infrastructure required to power the battery packs is much larger, more complex, and expensive than that required for charging. BSSs and charging stations both place equal demands on battery packs in terms of their primary need for charging. The only distinction is that since the former's demand can be managed, the battery packs should always be available for incoming customers and should, therefore, offer charging times that are suitable. Furthermore, for any station to meet its requirements, the stacked quantity of charged battery packs must always exceed the daily demand by a predetermined percentage. It is therefore a feasible plan to have two battery packs for each car, one inside the vehicle and one at the swap station. A national vehicle charging system makes more financial sense than a national battery swapping system, so even if everything works out, it still seems like a far-off future [27].

D. Battery Degradation

The degradation of battery performance over time has an adverse effect on the maximum battery charge range. Customers will therefore prefer the new battery packs over the alternative of other, comparatively older battery packs because the latter will provide less energy storage owing to deterioration with time, which will be reflected in the EVs' mileage. Customers will therefore only be satisfied with brand-new battery packs, which will significantly shorten each battery pack's operational cycle [28]-[29].

E. Ownership

The battery belongs to the owner of the vehicle; in this scenario, the owner will need to buy a spare battery pack to use as a replacement when the vehicle's battery runs out, which is extremely unlikely to happen. An owner of a vehicle will never have any ownership over a battery pack. This has numerous benefits. EVs are less expensive because the owner of the car does not have to pay for it because he does not own it. Instead, he must pay an extra lease payment in addition to the cost of energy and will never receive his replaced battery back. This can be charged every time a swap is made or at any other frequency that is mutually agreed upon, like once a month. The latter method of calculating the lease amount is more expensive because it includes the service charge for the swapping station and a minimum of two battery packs (instead of just one battery being purchased if the car is charged and already owns one battery). The lease-on-each-swap option is more expensive because there will be greater investment risk associated with swapping stations. Additionally, customers may be persuaded to use fewer swap stations in order to avoid paying these exorbitant fees, particularly if there is a charging option [30]-[31].

VII. Conclusions

BSS strategies are a promising alternative to traditional battery charging stations, offering more business opportunities to dedicated stakeholders. Battery swapping technology for electric vehicles appears to be technically feasible, as evidenced by a number of prototypes and pilot projects. Advances in robotics, automation, and battery design have helped to make the process more efficient and practical. Automation, and battery design have helped to make the process more efficient and practical. In this paper, different types of BSS, mathematical model, BSS modes and the BSS's key challenges, including interchangeability, feasibility, infrastructure, battery degradation, and ownership are discussed briefly. Finally, it is concluded that battery swapping has advantages in terms of convenience and possibly quicker charging times, but its long-term sustainability depends on a number of factors, such as cost-effectiveness, the development of EV ownership models, and technological advancements.

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