Existing and Future Investigation of Charging Technology for Electric Bus

Ziling Zeng, Danni Cao, and Xiaobo Qu

Abstract Bus fleet electrification achieves momentum and inspiration within public transport aiming at further improving the mobility sustainability. In many countries, such as Sweden, China, and the USA, there are several ongoing demonstration projects of electric buses and many research projects. The charging technology development and implication is key for the expansion of electric buses and to foster it. An investigation of characteristics and benefits of various existing and future charging technologies has been created in this paper. The main types of charging infrastructure are depot charging, station charging, and inductive charging. The choice of different types is highly related to infrastructure construction, investment, and daily operation. The detailed illustration and analysis of them can provide a solid foundation to the near-future large-scale electric buses' operation.

Keywords Electric bus · Charging technology · Depot charging · Station charging · Inductive charging

1 Introduction

Recently, researches proposed an estimation of the benefit of bus fleet electrification showing that a larger number of electric vehicles can synergistically deliver greater air quality, climate, and health benefits. For example, when electric bus accounts for 27% of the total bus fleet, it can largely reduce the annual concentrations of NOx, O_3, and PM2.5 (in China). Furthermore, the number of annual premature deaths

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caused by air pollution can be reduced by 17,456 [1]. Meanwhile, some projects with electrified buses are carried out. In Gothenburg, Sweden, 300 electric buses are newly bought and will be implemented in the near future. In Europe, Zero Emission Urban Bus System (ZeEUS) project studies different electrical systems for urban buses including depot charging, station charging, and inductive charging. The construction and maintenance fee are important when deciding which system to apply. These costs vary from different type of batteries, chargers, and the detailed system design. In this case, the main challenge is to figure out the advantages and disadvantages of different charging strategies, in order to provide a cost-effective system.

The main barrier in the rapid development of electric bus services in Europe is the infrastructure-related problem. First, the cost of constructing on-board large capacity batteries for depot charging is extremely high. Second, for station charging, it lacks dedicated infrastructure and robust charging station deployment plan, and it requires high infrastructure and bus acquisition costs [2]. Balancing the operation cost and charging requirements is crucial to provide a more efficient and cost-effective bus operation system.

There are mainly two concepts for the charging of batteries, standard and fast charging. Standard charging is adapted mainly in the bus depot overnight and during longer brakes with a moderate charging power. This causes a high battery capacity and a high weight of the system, since electric buses serve routes during the entire day. Fast charging on the track during operation can reduce the battery capacity and more importantly reduce the weight significantly. However, the bus schedule should provide enough buffer time for charging at certain locations. Especially inductive solutions offer the possibility to charge during driving, but this has not yet been implemented for a public electric bus due to the lack of an integrated charging and serving plan.

Terminal stop charging and along-route charging can be combined as station charging. Compared to depot charging, it provides more charging opportunities. However, the idea of inductive charging provides the easiest access and the most effective way for maintaining the battery in an optimal range of electricity usage along the route. When deciding which strategy to take, the consideration of energy consumption, charging times and possibilities, operation safety, and battery lifetime should be inevitable.

2 Depot Charging

Depot charging is the most time-consuming charging strategy for electric buses. When buses finish their scheduled routes or stay in the depot during the shift, this strategy is adopted as shown in Fig. 1. This charging is usually overnight or sometimes within the dwell time period with slow chargers (typically 40–120 kW). The full charge process for depot charging takes around 4 h. Fast chargers can also be adopted

Fig. 1 Depot charging process [3]

in overnight charging, sharing the same infrastructures as station charging technology. But currently, depots prefer to be equipped with lower charger considering the construction fee and unlimited charging time.

Centralized and decentralized depot charging scheduling researches raised recently for small-, medium-, or large-scale electric buses considering different constraints, such as battery aging cost, grid distribution, and battery electro-thermal [4–9]. A centralized charging process is managed by a central controller (Fig. 2), while decentralized charging process is operated by individual providers considering personal charging profiles. Figure 2 illustrates a centralized charging system, where AC/DC module converts input AC power into adjustable output DC power and DC/DC module converts a source of direct current (DC) from high voltage level to a low level which is suitable for electric bus. These two modules are monitored by the center controller maintaining the conversion infrastructure and communicating with the electric buses to perform the charging plan according to standardized communication protocol [10].

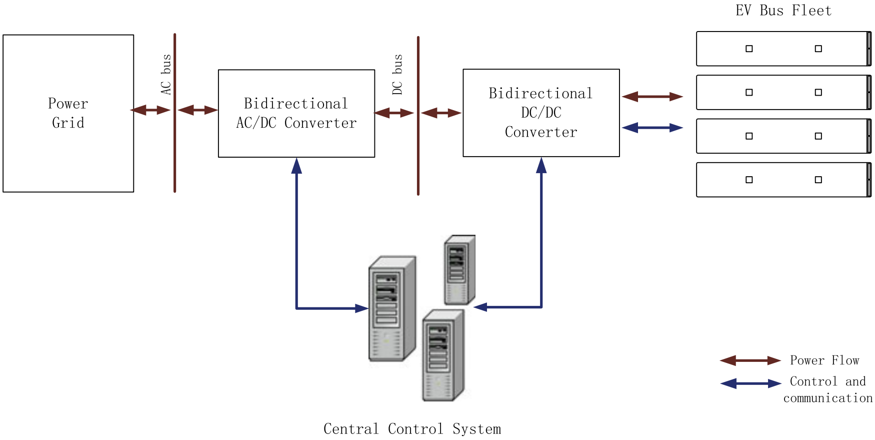


Fig. 2 Centralized depot charging system

From the cost-effective aspect, charging at depot is the one that requires the least amount of infrastructure, as no other equipment is needed except the depot charger. But a large battery capacity is highly concerned, since electric buses need to serve a scheduled route during the daytime without being recharged. However, in some daily operational cases, it is difficult to complete the entire trip without charging. In order to increase the battery capacity, turning bigger and heavier is inevitable, which accordingly increases the overall consumption and reduces the maximum payload of the bus. Although the cost for infrastructure is the least, a large expenditure is required for large-capacity batteries.

From operational optimization aspect, depot charging strategies will not improve current electric bus route plan, since buses are supposed to arrive at depot after serving the whole assigned trips. During the scheduling process, there is no delay caused by charging. If operators aim at improving the scheduled trips, some methodologies can be proposed to manage overnight charging of an electric bus fleet by identifying optimal charging strategy that minimizes the battery aging, charging cost, or maintenance cost [11].

From the grid network aspect, this strategy avoids peak hour charging, where the subscribed power and the maximum charging power delivered by the charger are rather stable. Some optimization algorithms [11] can attribute an optimal charging power for each bus.

3 Station Charging

Station charging refers to bus charging at a certain station within its operational time. Based on the charging location, station charging can be classified as termical stop charging and along-the-route charging.

3.1 Terminal Stop Charging

Terminal stop chargers are placed in the initial or end stops of a bus trip; this placement can be illustrated as shown in Fig. 3, using mainly the regular dwell time at the certain stops to charge their batteries [12]. This charging plan is in a strong linkage between the electric bus scheduling [13] and the charging infrastructure planning. The battery capacity of the bus should be big enough to allow several missed charges, to avoid the bus running out of energy due to external factors such as congestion or emergency. Lower battery capacity requirement reduced the cost of battery, while fast chargers will increase the expenses on station infrastructure.

Terminal stop charging has a rather long dwelling time, so that delays can be compensated, and practical bus running can be adjusted to scheduled time during the charging process [12]. One of the main aspects that need to be considered in this strategy is the impact that charges may have on the schedule. The charging time should

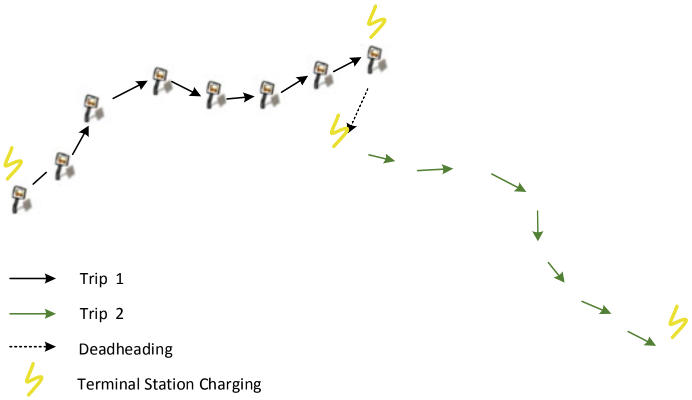


Fig. 3 Terminal stop charging strategy

not exceed the next trip's departure time to avoid trip delay. For scheduling of electric bus terminal stop charging, some solving algorithms such as genetic algorithm [14], dynamic programming [15], exponential smoothing model [16], and locally optimal scheduling [17] techniques have been used in literature.

3.2 *Along-the-Route Charging*

Along-the-route charging strategy charges electric buses at several intermediate stations along the route as shown in Fig. 4. Two main problems in this system are the deployment of chargers and the charging plan for electric buses.

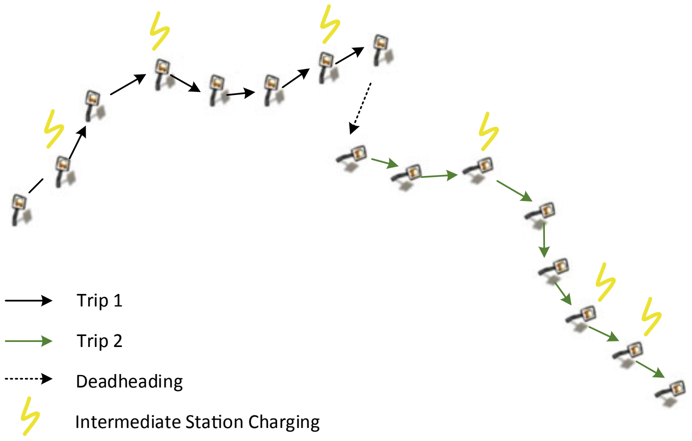


Fig. 4 Along-the-rout charging strategy

For charging infrastructure deployment, the major question is how to plan the deployment and operations of charging facilities along the routes to meet the ever-growing electric bus demand in a systematic and integrated way, and how to couple the traffic and power grid networks. The methodologies will include developing an equilibrium framework, which can be user equilibrium [18] or system equilibrium, capturing the balance between estimated traffic flow and grid power distribution [19, 20]. Based on this framework, a number of chargers along the routes can be allocated, and locations of allocated charging stations and their corresponding capacities can be determined relatively. A trade-off between the capacity of the battery and the amount of charging locations (number of chargers) is also required.

When designing charging plan, the charging cost, energy density, power density, and battery lifetime should be considered [21]. The lifetime of the battery mainly depends on the cycle between charging and discharging. State of charge (SOC) is a measurement of the level of charge of the battery. A fully loaded battery has SOC of 100%, while a fully discharged battery has 0%. To generate an efficient charging plan, the difference between the allowed maximal and the minimal SOC should be kept in a certain optimal level as shown in Fig. 5.

In this strategy, electric bus will be charged according to the current SOC. A frequent charging plan allows smaller batteries, while higher power is needed along the route. The trade-off between battery size, charging power, and different charging strategies can be shown in Fig. 6.

As shown in Fig. 6, the battery capacity for along-the-route charging is the lowest with the lowest battery cost. However, the cost of charging infrastructures and daily operation is the highest among all mentioned strategies.

Fig. 5 Battery state of charge (SOC)

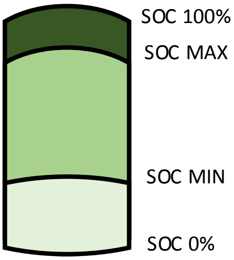
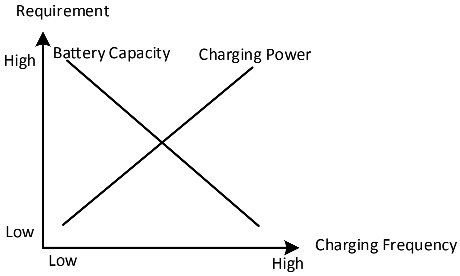


Fig. 6 Requirement for different charging frequency



The main benefit of along-the-route charging is the possibility to fully charge electric buses without any interruption during the daily operation. An optimal charging plan will maintain the battery in a certain SOC without letting the batteries deplete completely. Therefore, with this charging strategy, electric bus operation resembles the current diesel buses' operation, and some existing operational strategies can be easily adapted to manage the electric bus fleet [22].

4 Inductive Charging

Using a technology of inductive charging, electricity is transmitted through an air gap from one magnetic coil in the charger to a second magnetic coil fitted to the car as shown in Fig. 7. Accordingly, this wireless system includes two parts—the charger which sits on the floor at the redefined place and a power receiver which attaches to the bus. The charging process can be divided into two classes—charging while parking (static way) or charging while driving (dynamic way). For the dynamic way, the estimation of boarding congestion [23] and bus dwell time [24] at each station should be considered to further avoid delay.

The cost of inductive charging infrastructure is much higher than conductive chargers. A reasonable cost for an inductive charger with capacity to transfer up to 200 kW can be estimated to be 3 MSEK, including on-board pick-up system and power electronics [25]. The corresponding cost for a 300-kW conductive charger, according to the same reference, is estimated to be 1.5 MSEK.

However, inductive wireless charging systems require ferrite cores for magnetic flux guidance and shielding, which are bulky and costly. Also, to control the minimum loss in the ferrites, the charging system is kept under 100 kHz. In this situation, larger coils are needed, and lower power transfer densities occur. The high cost and low power transfer density are particularly problematic for implementing dynamic

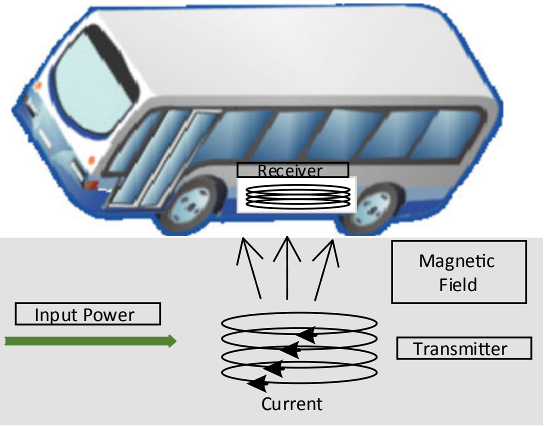


Fig. 7 Illustration of inductive charging for buses

wireless charging, especially for dynamic charging, as the charger should be equipped with a high power capability to deliver enough energy to the electric bus during its very brief time passing over a charging coil [26, 27]. Therefore, this charging strategy has not yet been implemented.

5 Conclusion

Depot chargers are equipped with slow chargers (typically 40 to 120 kW), while station charging is for bus stops (up to 600 KW) or terminals (usually between 150KW to 500 KW) using conductive or inductive chargers. Station charging requires less energy to be stored in the bus, which could significantly reduce the capital costs. However, the construction expenses are much higher compared to depot charging. Wireless charging requires the costliest infrastructure and has the lowest power transfer density, while it enjoys the least requirement of battery capacity and the highest guarantee of battery health. Recently, wireless charging is yet to become commercially viable, although a few experimental systems have been demonstrated.

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