Analysis of Various Charging Strategies for Electrified Public Bus Transport Utilizing a Lightweight Simulation Model

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***Abstract*—In order to deal with fine particulate air pollution as well as promoting an ecofriendly image, many cities all over the world are striving to integrate electric vehicle (EV) buses in their public transportation systems. But the introduction of electromobility raises the question how to sufficiently energize the vehicles during daily operation. In this work, we present a lightweight yet potent simulation model developed in Matlab/Simulink, which derives energy consumption profiles of electric buses from driving data of conventional diesel vehicles considering route and vehicle characteristics as well as temperature conditions. With it, several charging strategies are analyzed regarding their practicability for an existing bus route of a major German city. Subsequently, we display how the tool can be applied to examine the simultaneity of the buses power consumption and power generation by fluctuating renewables. Furthermore, the paper provides an overview of existing charging technologies to reenergize EVs and depicts in a rough calculation of profitability in which manner increased investment in a dense charging infrastructure can be a self-amortizing or even profitable measure.**

***Index Terms*—public transportation; electrification; urban bus traffic; charging technology, charging strategies; simulation; renewable energy**

I. Introduction

More and more cities worldwide as well as in Germany are considering the deployment of electric instead of conventional diesel buses [1]. Since these battery electric vehicles (BEV) shall not only tackle the problem of fine particulate air pollution in inner cities by relocating the combustion process of fossil fuels out of the vehicle towards power plants, but shall also reduce the overall carbon dioxide emissions, the usage of power generated by renewables, i.e. CO_2-neutral sources, is inevitable [2]. Central issue utilizing renewables like PV or wind power is their naturally fluctuating generation characteristic over the seasons as well as over the day, which makes it difficult to ensure synchronicity between generation and demand without enormous application of storage systems. Another issue to address is the question which strategy works best to recharge the EVs. Several different charging technologies as well as policies arose in the last decade, which had to be limited by guidelines like [3] to preserve clarity and workability. A public transportation company has to ask itself which method they want to bank on considering for one thing the practicability, reliability and profitability of the system and for another thing safety concerns and the high requirements in the quality of service of their customers. Having optimized schedules and infrastructure with the focus on combustion technology for decades, the motivation of the operators to develop a completely new operational management strategy is naturally rather low. Hence, a major need for a gentle migration roadmap towards electrical propulsion exists.

To ease decisioning, we examine in this paper different equipment as well as strategies to charge electric buses in line operation. Furthermore, we briefly outline for one particular case how synchronicity between power consumption of the buses and generation of fluctuating renewables can be analyzed. To do so we developed a model in Matlab/Simulink based on the framework of [4] able to simulate consumption profiles of electric buses deduced from driving data of conventional diesel buses with respect to the altitude profile of the route, properties of the deployed BEVs as well as charging equipment and the impact of temperature fluctuations. Considered strategies were sole recharging overnight and cases with various density of charging infrastructure reenergizing the BEVs during operational breaks on their respective routes with either conductive or inductive charging devices in variable dimensioning. Results help to compare variable system design and sizing of electrified public bus transportation systems in a time- and cost-efficient manner.

The remainder of this paper is structured as follows: In Section II an overview is provided on established as well as innovative charging technologies relevant to public bus transport and how recharging can be scheduled. Section III outlines briefly the modelling approach of the Simulink tool and the simulated scenarios while in Section IV results are presented and in addition some economic considerations are discussed. Section V summarizes the findings, concludes the paper and provides an outlook on possible future work.

II. State of the Art

A. Charging Technologies

Beginning in the first decade of 20th century, for example with the introduction of the Tesla Roadster in 2006, electromobility experiences a renaissance away from a niche towards a serious future competitor of combustion propulsion technology [5]. The product lineup of EVs grew and so did the options regarding the charging. Two major technologies of charging interfaces can be distinguished. On the one hand conductive charging via physical connection and on the other hand inductive charging – a wireless method. Then again for conductive charging two general approaches can be differentiated, which are charging via cable or via current collector often in the form of a pantograph.

Although lately politics and standardization organizations recognized the need to maintain a tolerable amount of plugs and systems trying to regulate them, for instance in [6], several standards for cable charging coexist based on distinct modes of operation: A Type 1 plug is a single-phase vehicle coupler following the SAE J1772/2009 specification charging with alternating current (AC) and being mostly utilized in North-American and Japanese EV-markets. Type 2 plugs are the preferred type on the European market and are able to charge with single-phase AC, three-phase AC as well as medium voltage direct current (DC). A third coupler type exists, which is in derogation from Type 2 equipped with touch protection shutters to prevent direct contact with live pins. [7]

However, relevant to electric bus recharging are particularly fast charging couplers like the so called ”combined charging system” (CCS) plug or the ”charge de move” (CHAdeMO) plug visualized in Figure 1. Both support high voltage DC charging exceeding the maximum possible power output of Type 2 plugs and are sometimes referred to as Type 4 plugs. CCS is based on a Type 2 coupler extended by two high-power DC pins, whereas the CHAdeMO was developed on the basis of approaches of Tokyo Electric Power Company (TEPCO) and is mainly utilized by Japanese EV manufacturers. Usually charging stations with these kind of couplers have an output power of 50 kW [8], since 2017 though stations deploying both Type 4 plugs offering output power up to 400 kW [9] are commercially available. [7]

Fig. 1. CCS 2-plug (left) [10] and CHAdeMO-plug (right) [11]

Nonetheless, conductive charging via cable is not feasible for reenergizing BEV buses in line operation during the day due to the fact that it would be too time-consuming and inconvenient for the driver to get out of the bus to manually plug in the couplers at each recharging spot. Hence, systems utilizing a pantograph as current collector are deployed guaranteeing a practicable workflow. Figure 2 depicts two common designs. These fast charging systems, adopted from railroad industry technology, are available in various power classes reaching up to 650 kW [12], [13].

A technology gaining more and more popularity recently is wireless inductive charging. This method utilizes inductive coupling to transmit current: a magnetic field originates from a transmitter installed under the road in form of an AC-carrying coil and induces an alternating voltage in

Fig. 2. Pantograph designs: off-board top-down (left) [14] and on-board bottom-up (right) [15]

the receiving coil. This results in an AC in the receiver, which is placed in the EV that can be used to charge the vehicle’s battery. Advantages of this charging method are that a mechanical docking process is not required saving time and since there is no physical connection between charging station and bus the technology ensures a higher durability of the system components thanks to less mechanical stress. This partly also applies because the transmitting coil is embedded in the street and therefore sheltered against corrosion, which in addition is an aesthetical benefit. Commercially available realizations achieve maximum power outputs of 200 kW [16] – thus enabling considerably slower charging than some conductive equivalents. Another drawback is the slightly reduced efficiency of inductive charging hardly reaching 90 % compared to 95 % and more of conductive systems [17].

B. Charging Strategies

Generally, two prime charging policies for BEV buses can be distinguished – charging overnight in the bus depot with or without intermediate charging during daily operation on the route. Choosing the most suitable strategy is a complicated endeavor considering the following facts: For sole charging overnight the buses require huge amounts of battery packs – the most expensive part of a BEV – in order to manage daily scheduled distances up to 250 km or more autarchical. Furthermore, higher storage capacities lead to a higher power consumption of the buses due to the additional weight of the batteries carried along (see Section IV). Alternatively does fewer battery equipment raise the need for recharging devices along the route, which can be also cost intensive depending on the utilized technology and density of charging infrastructure. Besides, transportation companies strive to minimize changes to their often already time-, route- and cost-wise optimized operational management, like e.g. longer layovers at bus stops to recharge. This partly also applies because customers might be irritated with major changes to the known operating principles and quality of service. Moreover, one has to consider that charging overnight allows for intelligent recharging [18], i.e. utilizing optimization algorithms which control the procedure under consideration of e.g. the electrical net workload or economic factors to minimize overloading or charging as cost effective as possible. Since PV power plants naturally generate electricity during daylight though while buses are deployed, sole charging overnight collides with the endeavor to guarantee simultaneity between power generation and consumption. In contrast charging on the route stresses grid stability through its characteristically short and high power withdrawal rates and is very limited to have considerations for profitable electricity rates. However, charging by day and during line operation grants better matching of generation profiles of renewable power and consumption profiles of the EVs.

III. Modelling Concept

Simulations are a common way to provide a time- and cost-efficient overview of different system designs and dimensionings in a – since realized only digitally – fail-safe environment. This motivated the here presented model created in Matlab/Simulink. It takes the following time series of parameters into account: speed and acceleration of the vehicle, topography data – i.e. altitude profiles – of the regarded routes and temperature profiles in the considered period. The simulation was fed with real driving data of diesel buses of a transportation company in a major German city and ambient data of the region provided by the German Meteorological Service (DWD) [19]. It was parametrized with vehicle data of several electric bus models as well as technical data of charging systems, which are acquirable on the market. This allows for a discrete evaluation of the demand and charging characteristics of electric buses in line operation over a full year with a high resolution. The model concept is depicted in Figure 3 as a flow chart illustration.

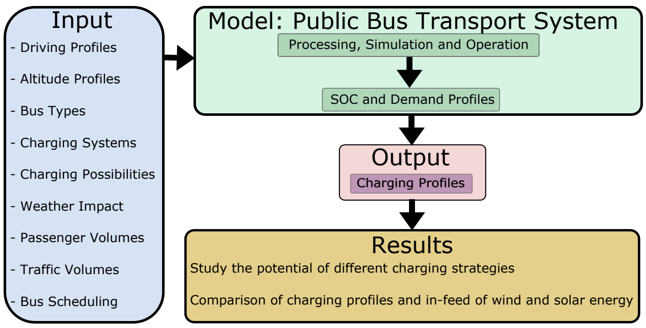

Fig. 3. Flow chart of the model structure and working routine

A. Underlying Framework

The mathematical framework of the model builds upon the work of Kurczveil et al. [4], which we enhanced in [20] by a straightforward temperature model extension to accurately capture the significant influence of energy needed to climatize the vehicle on the BEV's consumption profile. The model determines the vehicle's energy gain for each point in time considering its energy of the previous time step, the change in kinetic and potential energy as well as the sum of energetic loss mechanisms, like air drag, rolling friction, demand of the heating, ventilation and air conditioning (HVAC) and other auxiliary systems of the regarded time step. A negative energy gain expresses that energy is drawn from the internal battery, a positive gain that energy can be retrieved through recuperative breaking, both with regarding efficiencies. That way it is possible to calculate the state of charge (SOC) of the battery at each time step of the vehicle's operation generating profiles of power consumption and SOC. For a more in-depth view on the underlying formulas, the model configuration and validation process we would like to refer the interested reader to [20].

B. Examined Scenarios

Here presented cases (see Section IV) shall outline the possibilities the model is capable to simulate in excerpts. By way of illustration, a bus route of a major German city with a common urban velocity profile is selected to analyze regarding different charging strategies. The route represents an 11 km long main line with 25 bus stops through urbanized areas and heavy downtown traffic on which solely articulated buses are deployed. According to the plan of the bus company, which provided the driving data for this route, we completely retained the operational management for the BEV buses as usual with diesel buses – i.e. durations of the stops on the given route especially at the terminal station (TS), deployed bus size, service frequency and passenger volume stayed the same. In other words, the migration of deploying BEV instead of diesel buses was implemented in the simulations from a customer's perspective with no change in the quality of service. Hence, the charging cycles or more specifically the time given to recharge was defined by the operational schedule.

Contemplated charging strategies were sole overnight charging and two differing scenarios regarding density of charging infrastructure for reenergizing the vehicles on the route with an output power of 200 kW: recharging the vehicle at both TSs of the route and at only one of the TSs. For the latter case, we also depict how installation of charging equipment with higher output power of 450 kW, for example through utilization of pantographs instead of inductive technology, enables otherwise not possible charging strategies. In addition, we briefly outline for this scenario how simultaneity values of power consumption through BEV bus charging and power generated by renewables can be determined in order to gain insight how different charging system configurations affect the need for storage capacity.

IV. Results

A. Simulation Outcome

Simulations of the initially described scenario (Section III-B) are visualized in Figure 4, which depicts the SOC-profile of one bus on the route during its daily operation under three different charging policies. As stated above solely articulated buses are deployed on this route, which they are considered not to switch during daily operation. One of the buses, selected here as a representative for this route, leaves the depot at 5:45 a.m., returns around 8:15 p.m. and is recharged at the depot with a low output power of 50 kW. Simulated was a regular daily tour of about 220 km with an average amount of passengers, but under harsh climatic conditions to demonstrate a worst-case scenario with – due to highly increased demand for heating – maximum energy consumption. Parameters characterizing the bus were set according to the commercially available BEV bus model "Sileo S18" [21] of the manufacturer Sileo, which has a vast battery capacity of 300 kWh. The orange curve in Figure 4 displays the SOC-level of the bus being inductively recharged with an output power of 200 kW at both TSs, thus represents a relatively dense charging infrastructure. As the chart shows, the SOC drops only to just about 70 % at its minimum – thus the risk of running out of energy is inexistent. An entirely different picture is drawn if the

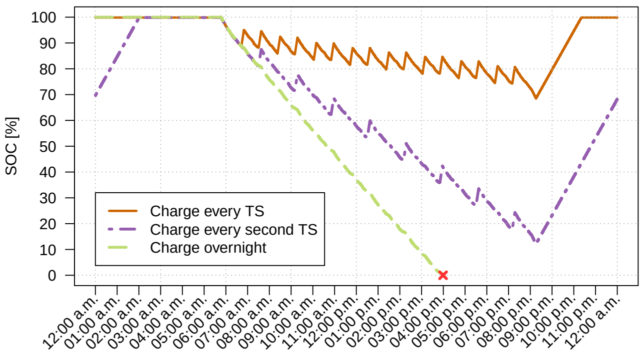

Fig. 4. Intraday SOC-profile of one bus under various charging strategies

bus is recharged only at every second TS – purple curve in Figure 4 – which exemplifies the case of a sparse recharging infrastructure: The bus returns at 8:15 p.m. with only 12 % of its battery capacity left, which is admittedly sufficient for this case, but would be hardly enough for a slightly longer tour or higher energy consumption caused by e.g. a higher passenger volume. As visualized by the green curve sole overnight charging is not capable to energize the bus adequately over the whole day in this scenario, since at 4:00 p.m. the battery would run out of stored energy, marked by the red cross – the bus could not continue its journey. Accordingly, pursuing this charging strategy would raise the demand for extra buses, which have to replace the BEVs once they are running low on energy. Apart from the fact that this would lead to huge additional investments for the buses to spare, a tremendously higher amount has to be spend for additive staff, i.e. drivers. Considering that circa 70 % [22] of the operational costs for buses arise due to payroll costs, one can imagine that this strategy clearly disqualifies as practicable.

The importance of achievable output power and therefore also of the installed technology regarding the feasibility and practicability of a certain charging strategy is highlighted in Figure 5. Depicted is a simulation of the same bus under

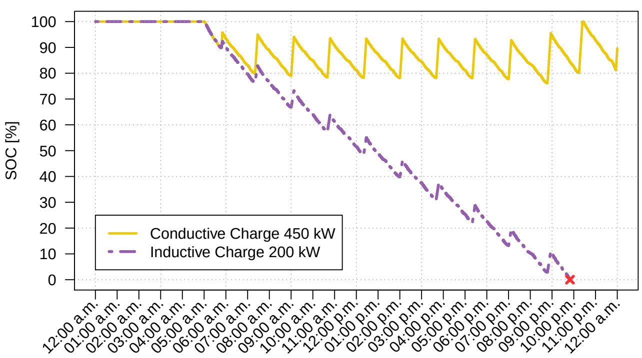

Fig. 5. Intraday SOC-profile of one bus charged with differing charging performances

identical conditions as before except it is servicing a slightly longer tour of 290 km, which is not an unusual distance to run for buses in line operation [17]. Indicated by the purple curve one can see, that reenergizing the bus with 200 kW inductively at just every second TS would lead to a break down near the end of its daily service, marked again by a red cross, since the battery is completely rundown. Replenishing the battery with 450 kW conductively instead, for instance with a pantograph system, would be enough and to spare as the yellow curve indicates. This example is of course a hyperbolic one, but serves to show quite plainly how changes in system design broadens the range of practice significantly. In reality, it might for instance sometimes just be enough investing in conductive instead of inductive charging while retaining the same output power, due to better efficiency of first-mentioned method.

As stated in Section III-A the model is also capable to provide power consumption characteristics or in other words the profile of current drained from the grid caused by recharging the buses. Correlated to generation profiles of PV or wind turbine power plants one can identify values for the average coverage of the power demand of the electrified bus fleet by renewables. In [20] we compared simulated demand profiles of a bus route (similar characteristics as examined route) to measured generation profiles of renewables and evaluated simultaneity values for a full year of operation. The assumed generation capacity of renewables was scaled to a magnitude that on average could provide the daily amount of energy needed by the buses on the route. Under the assumption of a dense charging infrastructure, e.g. frequent recharging at every TS, results showed that on average circa 37 % of the produced electricity by PV power plants or 41 % produced by wind turbines respectively could be utilized directly, thus without bridging in buffer storage applications. Furthermore, over a full year the consumption drain of the buses would be covered completely (without additional application of electricity acquired from non-renewable sources) by renewable power generation approximately 20 % of the time.

B. Economical Considerations

Regarding the density of recharging infrastructure installed, the following consideration is worthwhile to reflect upon: As a byproduct of the model simulations a value of $7.0 \cdot 10^{-5}$ kWh per loaded kilogram and kilometer for the weight dependency of the specific energy demand was identified – a value highly similar to $7.2 \cdot 10^{-5} \frac{\text{kWh}}{\text{kg}\cdot\text{km}}$ determined by simulations of [23]. In addition, a higher battery storage volume leads to a higher consumption due to the additional weight that has to be carried along. Specifically quantified a value of circa 10 kg per installed kilowatt hour battery capacity (kWh_{inst}) can be calculated from the reciprocal of an achievable energy density of lithium iron phosphate accumulators of 100 $\frac{\text{Wh}}{\text{kg}}$ [24], which is the build-in battery type of "Sileo S18" [21]. Comparing the orange and the purple curve in Figure 4 it is obvious, that the buses' battery capacity could safely be reduced by half deploying a dense charging infrastructure, i.e. charging at every TS instead of just at every second TS. Given the fact that up to ten buses are servicing the examined route simultaneously and that a bus has an average mileage of at least 50,000 kilometers per year [25], one can determine how much energy could be saved simply because not as much (battery) weight has to be carried along as in Equation (1). Taking specific energy costs for industrial companies of 0.1702 $\frac{€}{\text{kWh}}$ [26] as a basis,

$$\Delta E = 150\ kWh_{inst} \cdot 10\ \frac{kg}{kWh_{inst}} \cdot 7.0 \cdot 10^{-5} \frac{kWh}{km \cdot kg} \cdot 50,000\ \frac{km}{a} \cdot 10 = 52.5\ \frac{MWh}{a} \tag{1}$$

$$Savings = 52.5\ \frac{MWh}{a} \cdot 20\ a \cdot 0.1702\ \frac{€}{kWh} = 178,710\ € \tag{2}$$

the total savings can be approximated over a 20-years lifecycle of a charging station like shown in Equation (2) to roughly 180,000 €. This amount equals quite accurately the acquisition costs of a charging station [17], which leads to the conclusion that in the outlined scenario increased investment in a dense charging infrastructure can be a self-amortizing measure. In case the operational management of bus routes is well conceived, a close-meshed net of charging points could therefore even be economically profitable. For the examined scenario this would for instance apply, if the selection of the charging station's location is carried out strategically in order to be utilized by a second route and therefore to increase the savings.

V. Conclusion

Migrating from an optimized, fossil-fueled public bus transportation system to a fully electrified one in an operationally as well as economically feasible and grid beneficial way is a complex endeavor. As we depicted in this paper there are many options to consider technology-wise regarding the realization of EV charging. Furthermore, we outlined how our simulation tool can help to analyze the practicability of different charging strategies and how it can be applied to determine which impact the chosen policy has regarding the simultaneity of power generation of renewables and power consumption by the buses. Finally, we briefly indicated through some profitability considerations how a denser charging infrastructure could not only be reasonable operationally but also economical-wise. This can aid transportation companies to ease the process of decisioning to find a suitable design and dimensioning to operate an electrified bus system. In future work we strive to enhance our modelling framework, examine the impact of charging strategies and deployed equipment on the grid in greater detail including regression as well as sensitivity analyses for characteristic variables and automatize data preparation for the model infeed in order to simplify its application.

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