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Numerical analysis of electric bus fast charging strategies for demand charge reduction

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ABSTRACT

Electric transit buses have been recognized as an important alternative to diesel buses with many environmental benefits. Electric buses employing lithium titanate batteries can provide uninterrupted transit service thanks to their ability of fast charging. However, fast charging may result in high demand charges which will increase the fuel costs thereby limiting the electric bus market penetration. In this paper, we simulated daily charging patterns and demand charges of a fleet of electric buses in Tallahassee, Florida and identified an optimal charging strategy to minimize demand charges. It was found that by using a charging threshold of 60–64%, a $160,848 total saving in electricity cost can be achieved for a five electric bus fleet, comparing to a charging threshold of 0–28%. In addition, the impact of fleet sizes on the fuel cost was investigated. Fleets of 4 and 12 buses will achieve the lowest cost per mile driven when one fast charger is installed.

1. Introduction

Due to increasing environmental pressure and unstable diesel fuel prices, the public transit agencies have been gradually replacing legacy diesel buses with alternative fuel buses. There are over 70,000 transit buses operated by 800 transit agencies in the United States (Dickens and Neff, 2014). The percentage of alternative fuel buses including compressed natural gas (CNG), biodiesel, and hybrid electric buses rose from 8% in 2000 to 41% in 2012 (Bradley and Associates). The plug-in electric bus (EB) is the newest player in the alternative bus arena and attracting increasing attention as it emits zero tail pipe greenhouse gases and produces less noise. The price of electricity is not directly tied to the price of crude oil as it can be generated from multiple domestic sources including solar, hydropower, coal, and natural gas, thus results in less price variation than diesel (U.S. Energy Information Adminstration).

One of the major obstacles for EB market penetration is their high capital costs. Multiple studies conducted cost-benefit analysis of EB by considering both capital costs and operational costs. For instance, Lajunen et al. analyzed the life cycle cost of EB by taking into account of capital costs, electricity consumption, maintenance costs, battery system replacement costs, and possible carbon emission costs (Lajunen, 2014; Lajunen and Lipman, 2016). Zhou et al. investigated the emission and lifetime cost of several models of commercially available EBs in China and placed focus on traffic condition, passenger load, AC operation and system charging efficiency (Zhou et al., 2016). Most research concluded that low fuel cost of EBs made them competitive to diesel buses despite the high capital cost. However, a significant component of the electricity cost,

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demand charges, was overlooked by these studies. Demand charge is a fee determined based on the peak power during a given electricity billing cycle, usually a month. It is calculated as the peak demand (measured in kW) multiplied by a demand charge rate ($/kW). Peak power is determined as the highest power (averaged over a 15 or 30 min window) for the billing cycle. The demand charge rate ranges from $6 to $25/kW in the US (U.S. Utility Rate Database). Demand charges represent as much as 30% of a typical electricity bill for commercial and industrial buildings, but may constitute a much higher percentage in an EB charging station.

There are currently two general types of all electric transit buses in the U.S. market. One type uses 200–300 kWh lithium iron phosphate batteries and has a range of up to 155 miles. After the battery is depleted, the EB must be taken off the route to recharge, usually with a 40–50 kW charger and taking up to 5 h to complete. The second type of EB employs lithium titanate batteries with a much smaller energy capacity (55–72 kWh) and has a range of up to 30 miles. Due to the unique chemistry and relatively compact battery design, these EBs can tolerate repeated charging at high power, which in turn will facilitate in-route charging. The typical recharge time for a lithium titanate EB is 10 min or less, which can be easily accommodated into the bus schedule. Although the total range of a lithium titanate EB is lower than the lithium iron phosphate, the use of high speed, in-route charging can enable continuous operation of the lithium titanate EBs without the need to remove them from service for recharging purposes.

High speed charging is accomplished through the use of a 500 kW DC fast charger that must be installed somewhere along the bus route, enabling the bus to recharge during a typical layover (Proterra, Charging technologies). While this approach facilitates continuous operation, the operational costs are significantly increased by electricity demand charges. These demand charges are associated with the high power requirement of the in-route charging station, and can represent a large portion of the total electricity costs. In the case of StarMetro, a City of Tallahassee transit agency which operates a fleet of five lithium titanate EBs, it was reported that the demand charges consist of 75.2 ± 8.6% of the total electricity bill at their fast charger (StarMetro). Since the electricity cost of EBs plays a significant role in their economic viability, the demand charge-induced fuel cost is a major road block in lithium titanate electric bus adoption.

Some strategies are proposed to mitigate the demand charges, including increasing electric bus efficiency, employing energy transfer technology, using time-of-use (TOU) pricing, or temporarily suspending demand charges (Gallo et al., 2014). You et al. propose a method based on EB battery switching strategy where depleted batteries are replaced with charged ones at battery switching stations and the battery charging is scheduled so that the electricity cost and battery degradation is minimized (You et al., 2015). Ding et al. consider an energy storage system which has the potential to reduce the network integration cost for fast chargers and to reduce the charging cost of EBs via electricity price arbitrage (Ding et al., 2015). They formulate and solve the problem of optimal charging/discharging of the energy storage system and the coordinated charging of EBs with a goal of minimizing the total cost of investment and total charging cost. However, these strategies may not be economically viable due to the added cost of the stand-by batteries or energy storage systems. In this paper, we investigate a strategy to mitigate the demand charge by optimizing the charging schedules. Current research on electric vehicle charging scheduling is mostly focused on consumer electric vehicles, with goals ranging from filling the overnight electricity demand valley, minimizing power losses and improving voltage profile, to maximizing the total amount of energy that can be delivered to the EVs over a period while satisfying the power network constraints (Gan et al., 2013; Deilami et al., 2011; Iversen et al., 2014; Richardson et al., 2012; Karbasioun et al., 2014). In comparison to the consumer electric vehicles, the charging scheduling of EBs is a unique problem due to its strict driving schedule and fixed routes. Paul et al. propose a method to determine the optimal charging schedule of EBs operated in a city bus route in Japan (Paul and Yamada, 2014). The proposed algorithm reduces the fuel cost by maximizing the travel distance of the EBs between charging events. However, this simulation is based on a Japanese electricity rate structure and does not take demand charges into consideration. To the best of our knowledge, there is no study that systematically investigates methods to mitigate EB demand charges through charging scheduling. In this paper we conduct a case study on the Tallahhassee EB Fleet containing five EBs and one fast charger. We propose a realistic strategy to minimize demand charge while maintaining the current route and scheduling requirements. Specifically, we perform numerical analyses to explore charging decision making strategies based on the battery state of charge thresholds. The approach does not require any EB technology breakthrough or policy change, and can be adopted at no additional costs to the transit agencies. This paper also describes the EB fleet size impact on the fuel cost.

The rest of the paper is organized as follows: Section 2 describes the electric buses, the fast charging station, and operation route and schedule; Section 3 is the method section which describes an electric bus energy consumption model and explains the electric bus charging strategy and demand charge modeling; Section 4 discusses the optimization results; and Section 5 compares the economics of different fleet sizes.

2. Case description

2.1. Electric bus and fast charging station

The StarMetro bus fleet in Tallahassee includes five all-battery electric EcoRide BE-35 electric buses (EBs), manufactured by Proterra. The EB employs a 72 kWh lithium titanate battery energy storage system and a 150 kW electric motor. The battery uses lithium titanate spinel oxide instead of graphite as anode materials. It has a lower energy density of 60–70 Wh/kg