Co-optimizing the Smart Grid and Electric Public Transit System

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1. Introduction

We formulate a mathematical optimization model for the joint operation of public transit and electric grid systems, to optimize the charging of electric transit buses while the transit fleet is "off-schedule". Specifically, we seek to schedule transit buses that inject power to the electric grid when they are not serving public transit demand. This work is motivated by a practical project planned to incorporate electric transit buses into the operation via our partner Santa Clara Valley Transportation Authority (VTA, `https://www.vta.org`).

Our work is related to the literature on both power systems and interdependent power–transit systems. From a power systems perspective, the work presented in this paper is related to the multi-period optimal power flow problem introduced by Zhongwei Wang et al. (2013), but extends that model by considering the additional loads placed on the batteries (transit buses) and additional operational constraints related to the transportation system. From a interdependent systems perspective, Zakariazadeh, Jadid, and Siano (2014) address the problem of privately owned electric-vehicle charging coupled with the power network. Our work differs from the existing works in that we consider (i) a fleet of electric vehicles operated by a single authority, (ii) operational constraints related to the transit fleet while injecting power to the power grid, (iii) schedules for the battery (transit bus) connection, and (iv) relocation of the batteries within the power grid.

We consider a single social planner who optimizes both the power and public transit systems. This includes charging/discharging of the transit bus batteries when buses are off-schedule, over

a horizon of one day. The only operational requirement on the transit buses is that they have to be fully charged before starting their schedules on the following day. The following decisions are addressed in the formulation: (i) where to locate transit buses to charge/discharge, (ii) how much electricity to charge/discharge while satisfying operational constraints, and (iii) power dispatch. We cast the model as deterministic, assuming that there are enough connection points to the power grid for all of the transit fleet.

2. Mathematical Formulation

Our model is a mixed-integer quadratic program (MIQP). We omit the mathematical formulation due to space considerations but provide a brief description in words. The objective function minimizes a weighted sum of the total power generation cost and the charging/discharging cost of the transit buses over the planner's time horizon. There is no setup cost associated with the generators. The constraints include standard DC optimal power flow constraints, with additional terms to incorporate charging and discharging decisions. Other constraints ensure that generation quantities satisfy ramping limits; that battery states-of-charge stay within bounds; that a battery can only charge/discharge if the transit bus is connected to a node in the power network; that in each period, a transit bus must either be connected to a node in the power network or relocating within the network; that bus relocations are feasible with respect to travel times. Additional transversality conditions include initial and final state-of-charge levels, initial locations of the transit buses; and integrality constraints. The time periods in the formulation are inherently cyclic in their nature, i.e., period 24 today equals period 0 tomorrow.

3. Numerical Results of a Case Study

We consider a synthetic case study consisting of realistic data meant to reflect the actual transit network in San Jose, CA. We overlay the 9-bus power network from MATPOWER (Zimmerman, Murillo-Sánchez, and Thomas 2011) atop the geographical area. Figure 1 provides a visualization of the layout, indicating the locations of charging stations for electric bus connection in both the power and transit networks.

Line limits and demands from the 9-bus system are scaled down to the order of ≈1MWh so that we can clearly analyze the impact of the electric buses on the power network, since battery energy capacities considered in this work are 0.66 MWh. Since the standard case file in MATPOWER provides a snapshot of the system in one time period, we scaled the demands over the time horizon using the California independent system operator (CAISO, `https://www.caiso.com`) data for the San Jose region. Moreover, the charging/discharging costs in the objective function are the electricity prices obtained from CAISO for the San Jose region. The total demand and electricity price data are given in Figure 2.

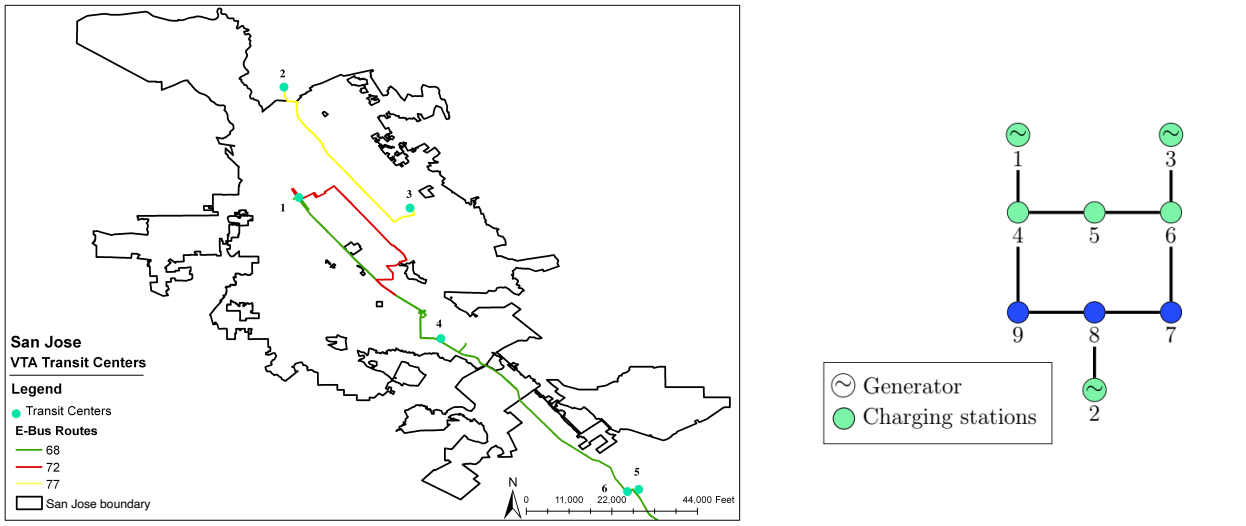


Figure 1: Transit layout (left) and power network schematic (right); charging stations are assumed to be located at Transit Centers

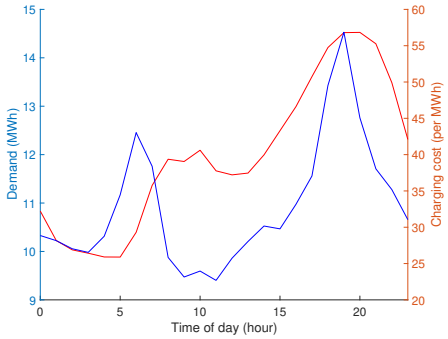


Figure 2: CAISO data for 09/09/19 in San Jose

We assume that the four transit buses are 40-foot Proterra Catalyst E2Max models; the data on battery consumption, battery capacity and charge/discharge limits are obtained from Proterra (`https://www.proterra.com`). The battery efficiency is set to 0.9. The schedules of the buses and charging station locations are obtained from VTA. Travel times between charging stations are calculated using Google Maps. Moreover, we consider hourly time steps and a 24-hour horizon. The optimization is done using Gurobi (`http://www.gurobi.com`).

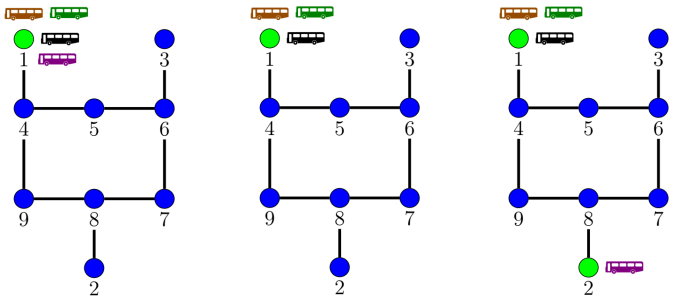
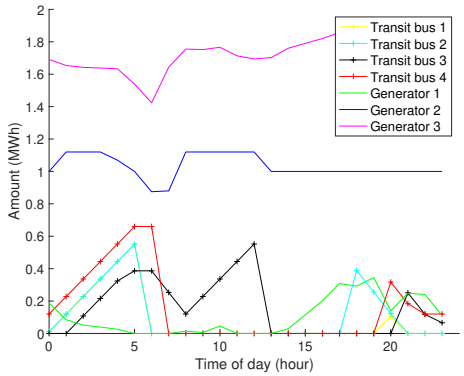


Figure 3: Transit bus locations for $t = 22$, $t = 23$ and $t = 24 = 0$ in optimal solution

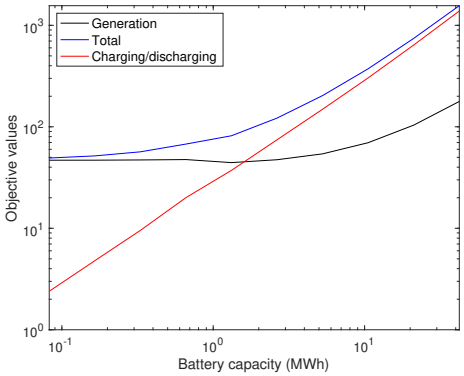
Figure 3 displays the optimal locations of the transit buses for 3 consecutive time periods. At time $t = 22$, all four vehicles are located at node 1, the transit depot. In the next time period, three of the buses remain at node 1, while the fourth is in transit. At $t = 24 = 0$, this bus will arrive at its new location, node 2, in order to help decrease total generation cost. Figure 4a shows the generation and battery level profiles. The battery levels in the first periods increase due to the operational constraints, and decrease in the last periods since the price of

electricity and the demand are high. Note that battery levels are set to zero during the periods in which the transit buses are on their schedule.

Figure 4b shows that the total cost and charging/discharging cost increase when we increase the battery capacity on the transit buses. This is due to the requirement that the buses must be fully charged before their operation on the next day. However, the total generation cost first decreases, then increases. This suggests that the presence of the batteries can alleviate some strain on the system even though the total generation amount increases.



(a) Generation and battery level profile



(b) Objective values with varying battery capacity

Figure 4: Optimization results

4. Conclusion

We propose a model to co-optimize the operation of the public transit system and the power grid when electric transit buses are in their off-schedule. The results demonstrate that charging can be done at no detriment to the power system. The formulation we propose is general in the sense that it can incorporate different schedules, renewable generation, and different transportation and power networks.

Acknowledgments

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