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Optimal contracts for providing load-side frequency regulation service using fleets of electric vehicles

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HIGHLIGHTS

- We study using a fleet of electric vehicles to provide frequency regulation service.
- The optimization objective is the product of the regulation duration and regulation range.
- We compare the effects of stochastic and deterministic (worst-case) regulation signals.
- We model and compare dynamic and one-shot optimization settings.
- We evaluate the effect of number of update points on system performance.

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ABSTRACT

We focus on the charging process of a fleet of electric vehicles overnight for providing load-side regulation service. At the heart of this complex problem, the goal is to transfer a certain amount of energy to the fleet by a given deadline; however, when and how fast the energy is sent is flexible. We examine a unidirectional setting in the cases where regulation signals are deterministic (worst case) and stochastic. We study both a single-shot optimization scenario carried at the start of the charging period, and a dynamic optimization scenario, where the optimal control strategy is re-evaluated several times over the duration of the charging interval. We show that most of the gains from dynamic optimization can be obtained by re-evaluating the optimization problem at the midpoint of the charging interval. Moreover, the optimal value of the regulation service in the worst-case deterministic setting nearly matches the stochastic setting with dynamic optimization. We validate our results using both simulation and real-world data.

1. Introduction and state of the art

1.1. Introduction

The *frequency regulation service*, one of the key ancillary services in the power grid, balances generation and load, taking control action as frequently as once every 30 s. Without this balance, alternating current frequency deviates from its standard value (for example, 60 Hz in North America), which can hurt grid-connected equipment, and, in the worst case, permanently damage generators. Currently, frequency regulation service is provided by a set of generators contracted to respond rapidly to control signals to increase or decrease their power. If the amount of generated power is increased to compensate for the excess grid load, the service is called *regulation up*. On the other hand, if the amount of generated power is decreased to match the reduced load in the grid, the service is called *regulation down*.

The balance between generation and load can be equivalently achieved by changing the aggregated load, provided these loads have some level of flexibility in their consumption profile. This approach has several benefits:

- Generators that provide frequency regulation service are typically natural gas or hydroelectric generators. That is because, unlike coal and nuclear generators, the output of these generators can be easily adjusted by changing the level of the input gas or water. The problem with gas generators is that they burn fossil fuels, thus causing economical and environmental problems. Hydroelectric generators do not burn fossil

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Nomenclature

m	mean of regulation signals [kW]
r	maximum deviation of regulation signals from mean [kW]
T	total time available for charging the fleet [h]
T_0	time instant up to which regulation service is provided [h]
T_1	maximum possible duration of regulation service given the capacity constraint of storage units [h]
T_2	maximum possible duration of regulation service given the time constraint to fill all storage units by a given deadline [h]
Δt	time interval between incoming regulation signals [h]
v_i's	baseline (normalized) regulation signals [kW]
x_i's	regulation signals sent from grid [kW]
p	peak power of individual storage units [kW]
P_L	peak power of the main line connecting fleet to the grid [kW]
n	number of vehicles in the fleet
C_s	maximum capacity by which each individual storage unit can be charged [kWh]
C	maximum capacity by which the whole set of storage units can be charged, $C = nC_s$ [kWh]
S_i	initial residual capacity of the ith storage unit (i.e., at the beginning of the charging period) [kWh]
S_0	sum of initial residual capacities of the storage units, residua $S_0 = \sum_{i=1}^{n} S_i$ [kWh]
$S(t)$	residual capacity of the whole system at time t [kWh]
R_i	remaining capacity of the ith storage unit at the beginning of the charging period [kWh], $R_i = C_s - S_i$
P_e	probability of error
α	standard interval multiplier: given P_e, α is determined such that $(\mu - \alpha\sigma, \mu + \alpha\sigma)$ is a $(1 - P_e)$-confidence interval for the normal random variable $\mathscr{N}(\mu, \sigma^2)$
$\mu_S(t)$	mean of total residual capacity at time t [kWh]
$\sigma_S(t)$	standard deviation of total residual capacity at time t [kWh]
$\sigma_0(t)$	normalized standard deviation of total residual capacity at time t [kWh]
$R_v(i)$	autocorrelation function of the stationary baseline signal v [(kW)^2], $R_v(i) = \mathbb{E}[v_j v_{j-i}]$
σ_v	standard deviation of the stationary baseline signal v [(kW)^2], $\sigma_v^2 = R_v(0)$
μ_v	mean of the stationary baseline signal v [kW]
T_C	correlation time of the regulation signal x [h]
$f_{m,r}^{\text{up}}(t)$	upper bound on the system residual capacity at time t [kWh]
$f_{m,r}^{\text{down}}(t)$	lower bound on the system residual capacity at time t [kWh]
P_C	average power necessary for charging the fleet [kW], $P_C = (C - S_0)/T$
Q	Q is called power ratio and defined as $Q = P_C/(P_L/2)$ (unitless)
κ	a constant defined as product of α and σ_v squared [(kW)^2], $\kappa = (\alpha\sigma_v)^2$
T_u	time interval between update points in the dynamic charging [h]
d	number of update points in the dynamic charging
m^i	value of mean charge rate decided at time $t_i = iT_u$ [kW]
r^i	value of maximum deviation from mean m^i decided at time $t_i = iT_u$ [kW]
T_0^i	optimal duration of frequency regulation service starting from $t_i = iT_u$ [h]
T_{reg}^i	realized duration of frequency regulation service starting from $t_i = iT_u$ [h]
m^{opt}	optimal value of the mean charge rate [kW]
r^{opt}	optimal value of the maximum deviation from mean [kW]
T_0^{opt}	optimal duration of regulation service [h]

fuels. However, a generator that is planned to provide regulation service has to work below its maximum capacity to create room for manoeuvring its output. As a result, if a hydroelectric generator is used for providing regulation, some capacity for generating clean energy will be lost.

- Generators typically achieve maximum efficiency when working at maximum capacity. However, a generator providing balancing service necessarily works, on average, below its maximum capacity, and thus does not achieve its maximum efficiency.
- Generating variable-rate power leads to higher wear and tear of generators. In contrast, some loads may be insensitive or less sensitive to the variations in the input power, and are therefore better candidates for providing regulation service.
- With the advent of new sources of renewable generation and variable load in the future grid, the need for regulation will increase. Being equipped with control units, some loads in the future smart grid can actively participate in the regulation service market.

For a load to be able to participate in the frequency regulation market, three conditions must be met: First, it must have some level of flexibility in its consumption profile and therefore be relatively insensitive to variations in input power. Second, the load must be significant with respect to the power fluctuations in the grid, because the utility does not want to deal with minor players. Third, the load should be controllable, so that it can respond to regulation control signals. Examples of such loads include industrial cold storage units, industrial boilers, large-scale pumps and ventilators, and storage units of fleets of electric vehicles [9,11]. Over the past years, pilot programs have demonstrated successful application of load-side regulation service providers [8]. This has even motivated commercial entities to monetize the aggregation of loads to provide regulation service [9].

In this paper, we focus on the charging process of a fleet of electric vehicles overnight as a representative system for providing load-side regulation service [7,12]. This system provides a simple setting to study this complex problem. At its heart, the goal is to transfer a certain amount of energy to the fleet by a given deadline; however, when and how fast the energy is sent is flexible [9]. Studying fleets also allows us to analyze a simple multi-component system (each vehicle in the fleet is one component of the overall system). Studying multi-component loads is important in the context of load-side frequency regulation service because, as mentioned earlier, for a load to take part in the frequency regulation market, it needs to have a consumption rate that is significant with respect to the power fluctuations in the grid. A coalition of multiple loads may be required to achieve this minimum required input power.

The integration of electric vehicles with the power grid to achieve a mutual benefit is termed vehicle-to-grid (V2G) [2–4,6]. This integration may take two forms: *bidirectional* and *unidirectional*. In bidirectional integration, electric vehicles can both receive energy from the grid and send energy to it depending on the consumption