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Dynamic programming-based optimisation of charging an electric vehicle fleet system represented by an aggregate battery model

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ABSTRACT

This paper proposes a DP(dynamic programming)-based optimisation method of charging an EV (electric vehicle) fleet modelled as a single, so-called aggregate battery. The main advantage of the approach is that it provides a globally optimal solution, with a relatively non-excessive computational load owing to a low order of the aggregate battery model. The method is illustrated through a case study of an isolated, hypothetically electrified delivery truck transport system charged from both grid and RES (renewable energy sources). Two scenarios of energy production from RES (with and without excess in RES production), along with several electricity price models are studied. The DP optimisation results are compared with the results obtained by an existing heuristic charging algorithm used in EnergyPLAN software to illustrate the DP algorithm advantages in minimising the charging energy cost and satisfying the aggregate battery charge sustaining conditions. The proposed DP optimisation method can be used in various energy planning studies, as well as a core of the supervisory/aggregator level of hierarchical EV fleet charging strategies.

1. Introduction

Due to the intermittent nature of RES (renewable energy sources), the related energy systems need to include significant backup in terms of traditional energy sources or a large capacity of electric storage elements. This increases the cost of electrical energy and the overall energy system, and hinders the RES proliferation. The growing presence of EV (electric vehicles), such as PHEV (plug-in hybrid electric vehicles) and BEV (battery electric vehicles), brings a substantial distributed battery storage that can be connected to the grid during long vehicle-parking intervals, thereby opening new opportunities for the RES integration. Also, EV fleets as spatially-distributed energy storage systems become convenient for providing various ancillary services to the grid (e.g. voltage/frequency regulation and spinning reserves). For the purpose of various techno-economic analyses related to electric vehicle-to-grid integration, energy system optimisations are deemed to have a crucial impact since they reveal optimal structure, parameters, and guidance/control of an analysed, integrated energy system.

There are several approaches in literature related to modelling and charging optimisation of individual EVs or EV fleets. The related studies are mostly focused on assessment of: (i) techno-economic potential of integrated EV-grid systems [1–6], (ii) benefits related to ancillary services that EVs can provide to the grid [4,7,8], and (iii) boost of RES penetration based on EV proliferation [5,9,10]. All these studies involve the aspect of EV charging management, for which the EV battery should be modelled as an energy or charge storage [1,9]. Regardless of whether a charging management study is related to the single EV level or the EV fleet level, battery of each EV can be modelled individually [1,4,7,11]. However, in order to provide numerically efficient optimisations of integrated transport-energy systems, including EV fleet charging management, batteries of a large number of individual EVs within the fleet are usually lumped into a single so-called aggregate battery with a single state-of-charge state variable [2,3,9,12]. The optimal charging management problem is then to find a time sequence of the aggregate battery charging power as a single control variable which minimise some predefined cost function (e.g. the charging energy cost).

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Nomenclature

$A_{eff,PV}$	effective solar panel area installed
C	electricity price (EUR/kWh)
C_{bat}	cost of aggregate battery charging energy
$E_{ch,RES}$	amount of energy charged to aggregate battery and produced from RES
$E_{ch,total}$	overall amount of energy charged to aggregate battery
$E_{max,agg}$	maximum energy capacity of aggregate battery
K_{g1}	cost function weighting factor related to soft constraints
K_f	cost function weighting factor related to (SoC) final condition
k	discrete time step
$N_{control}$	number of aggregate battery charging power discrete values
N_{soc}	number of aggregate battery SoC discrete values
N_t	number of discrete time steps
N_v	total number of vehicles in EV fleet
n_{dc}	number of vehicles parked in distribution centre and connected to grid
P_{EL}	electrical power consumption of other (not EV) electrical consumers
P_{RES}	electrical power produced from RES
$P_{c,agg}$	aggregate battery charging power
$P_{c,agg,RES}$	aggregate battery charging power supplied from RES
$P_{cmax,ind}$	maximum charging power of an individual battery (here, 10 kW)
$P_{dem,agg}$	aggregate transport demand
P_{grid}	electrical power taken from a grid
$P_{reg,agg}$	regenerative braking charging power of transport at aggregate level
SoC_{agg}	state-of-charge (SoC) of aggregate battery
t_f	end time
ΔT	discretisation time (here, 1 h = 3600 s)

Abbreviations

DP	dynamic programming
EV	electric vehicle
EREV	extended range electric vehicle
HEV	hybrid electric vehicle
RES	renewable energy sources
SoC	state-of-charge

The charging optimisation problem can be solved by using the DP (dynamic programming) algorithm [1,2,4,7], or other linear or nonlinear, stochastic or heuristic optimisation algorithms [3,5,6,8–10]. An aggregate battery heuristic charging method proposed in Ref. [9] is focused on minimizing the energy excess production from RES. This charging method is justified in the case when a relatively large RES installation potential is considered, but in general it cannot provide optimal results in terms of minimum charging cost. Among other cited algorithms, only the DP algorithm can guarantee the global optimality of obtained results for the general nonlinear optimisation problem. On the other hand, computational load of the DP algorithm increases exponentially with the number of state and control variables [13], and it is generally found highly inefficient for systems of medium and large size [11].

In this paper, a DP optimisation method of an EV fleet aggregate battery charging is proposed. The main motivation for using the DP method is that it results in globally optimal results (see e.g. similar HEV (hybrid electric vehicle) optimisation applications [14,15] and references therein). At the same time, the aggregate battery modelling approach is employed to reduce the number of state and control variables, in order to overcome the problem of computational inefficiency of DP algorithm. The optimal charging results can be used for various energy and transport planning purposes, e.g. for estimating benefits of replacing conventional vehicles with electric ones and introducing power production from RES, as well as for assessment of computationally efficient heuristic charging strategies against the optimisation benchmark. The presented optimisation study relates to an isolated transport and energy system of a retail company, which includes a hypothetical electric delivery vehicle fleet and photovoltaic RES power production. The main objective of DP optimisation is to minimise the cost of (charging) energy taken from the grid. The transport and energy system model is parameterised based on realistic/recorded set of data.

The aggregate battery model of EV fleet is adopted from Ref. [9], while a novel, more accurate and more complex aggregate battery model is proposed and validated in the accompanying authors' paper [16], including its use in a similar DP optimisation study. Two realistic scenarios of RES energy production are considered: with and without excess in RES production. The DP optimisation results are compared to those obtained by using the heuristic aggregate battery charging method from Ref. [9].

The main contributions of the paper are twofold: (i) proposing a DP-based charging optimisation method on the aggregate battery level for various energy planning and hierarchical charging management applications, and (ii) quantification of charging energy cost reduction and RES potential exploitation when compared to the heuristic charging approach from EnergyPLAN software for the case study of EV fleet and RES production of a local retail company. The paper contributes to the existing literature [1,4,7,11] where charging optimisations of EV fleets or individual EVs are based on individual EV model. In Ref. [2], modelling of EV fleet is again based on individual EV model (agent based modelling), but the DP-based optimisation is enabled by reducing highly dimensional state and control space, which is considered as an approximate dynamic programming method. On the other hand, the references [3,6,12] consider the aggregate battery modelling approach, but the corresponding optimisations are performed by using sequential quadratic programming, mixed integer linear programming, and genetic algorithm, respectively, which cannot guarantee the globally optimal solution.

The paper is organized as follows. Section 2 describes the EV fleet model based on the aggregate battery modelling approach, and proposes the DP method for optimisation of aggregate battery charging. The considered transport and energy system is depicted in Section 3, and associated time distributions of the aggregate model inputs are presented and discussed. The DP optimisation results are given in Section 4, including a detailed comparison with the results obtained by using the heuristic charging approach. Concluding remarks are given in Section 5.

2. EV (Electric vehicle) fleet charging optimisation

2.1. EV fleet model

For the purpose of energy planning and optimal charging studies, an EV fleet is modelled as a single, so-called aggregate battery with the single state-of-charge (SoC_{agg}) as a state variable [9]. The aggregate battery model is described by the following discrete-time state equation