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Research
Smart Grid—Article

Combining Market-Based Control with Distribution Grid Constraints when Coordinating Electric Vehicle Charging

Geert Deconinck[1*], Klaas De Craemer[2], Bert Claessens[2]

ABSTRACT The charging of electric vehicles (EVs) impacts the distribution grid, and its cost depends on the price of electricity when charging. An aggregator that is responsible for a large fleet of EVs can use a market-based control algorithm to coordinate the charging of these vehicles, in order to minimize the costs. In such an optimization, the operational parameters of the distribution grid, to which the EVs are connected, are not considered. This can lead to violations of the technical constraints of the grid (e.g., undervoltage, phase unbalances); for example, because many vehicles start charging simultaneously when the price is low. An optimization that simultaneously takes the economic and technical aspects into account is complex, because it has to combine time-driven control at the market level with event-driven control at the operational level. Different case studies investigate under which circumstances the market-based control, which coordinates EV charging, conflicts with the operational constraints of the distribution grid. Especially in weak grids, phase unbalance and voltage issues arise with a high share of EVs. A low-level voltage droop controller at the charging point of the EV can be used to avoid many grid constraint violations, by reducing the charge power if the local voltage is too low. While this action implies a deviation from the cost-optimal operating point, it is shown that this has a very limited impact on the business case of an aggregator, and is able to comply with the technical distribution grid constraints, even in weak distribution grids with many EVs.

KEYWORDS electric vehicle charging, distribution grid, combining technical and economic objectives, distributed control

1 Introduction

In a smart grid, the contribution of the demand side is key to balancing the grid. Demand response (DR) allows adapting the electricity demand to a varying electricity supply from, for example, renewables. Energy service companies emerge that aggregate the demand of small appliances into volumes that can play a role in an electricity market. This study focuses on aggregators that utilize the flexibility of electric vehicles (EVs), which are charged from the distribution grid. To control its EVs, an aggregator typically determines a collective charging schedule for the fleet, based on the electricity energy prices (economic objective). However, when charging, the EVs are physically connected to a low-voltage distribution grid, which is inherently constrained by its infrastructure. To assure correct operation of the distribution grid, the distribution system operator (DSO) can enforce technical constraints by using grid congestion management mechanisms.

To integrate the objectives of both aggregator (economic objectives) and DSO (technical objectives) in the coordination of EV charging, two operation levels are identified [1, 2].

- The market operation level entails actions with the objective of following previously traded volumes on the wholesale electricity markets, where trading takes place on a relatively long-term scale (months, seasons) and amounts are expressed as energy quantities—usually MW·h—in time slots of typically 15 min or 1 h. A time-driven approach is well suited here.
- The real-time operation level entails actions to comply with instantaneous consumer preferences and to respect local grid constraints (such as voltage constraints). Because changes and control are relatively more instantaneous and dynamic at this level, real-time operation (or technical operation) is usually expressed in quantities of electrical power, such as kW. Granularity is in the range of minutes to seconds. At this level, fast response is important and the amount of communication needs to be limited. An event-driven approach is well suited here.

A large part of research on the integration of EVs is aimed at optimally coordinating the charging at the market op-

[1] KU Leuven-EnergyVille, Leuven 3001, Belgium; [2] VITO-EnergyVille, Mol 2400, Belgium
* Correspondence author. E-mail: geert.deconinck@kuleuven.be
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eration level, facilitating larger shares of renewable energy sources or providing system-wide ancillary services, or minimizing electricity costs for charging [3–5]. At the same time, a considerable amount of the work in literature has been carried out toward the use of EVs to avoid grid overloads or reduce grid losses [6–10], objectives that are situated in the technical operation level.

The interaction between the economic market operation and the technical real-time operation, when coordinating the charging of EVs, has not often been considered [2], except when considered in the same context as vehicle-to-grid energy transfer [11, 12]. However, the economic and technical levels can come into conflict, which typically occurs when the distribution grid reaches its constraints (i.e., voltage, current, unbalance, etc.), at which point the technical objectives will intervene in the economic market objective(s). As market operation is overruled, consumption can deviate from what is intended by the aggregator, impacting the aggregator's business case.

In this paper, the influence of the technical, real-time operation level on the economic market operation level is analyzed by simulating both levels in a set of varying distribution grid scenarios. For the market operation level, an existing event-driven market-based control (MBC) for coordinated EV charging is used. When there is a constraint from the real-time operation level, it will take precedence. In addition, a voltage droop controller can be used to mitigate local voltage limitations. The quantitative effects of using droop control on the aggregator's objective at the market level will be analyzed.

Section 2 discusses existing algorithms and models for both market and real-time operation levels. Section 3 details and motivates the choice of the algorithm for the market operation level. Section 4 describes a set of relevant distribution grid scenarios, together with an explanation of the models and assumptions for the simulations. In Section 5, the chosen algorithms are simulated in these predefined scenarios, and the influence of real-time operation on market-level objectives is thoroughly analyzed.

2 Background

2.1 Market-level operation

Research regarding the optimization and coordination of clusters of DR participants at the economic market level can roughly be divided according to the way in which the optimization is performed, using centralized, distributed, and aggregate & dispatch algorithms (Figure 1).

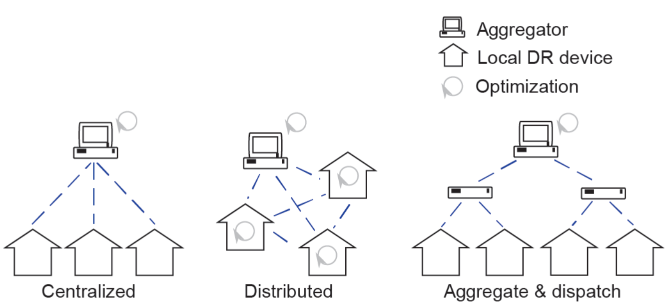

Figure 1. An illustration of the three classes of algorithms and coordination for demand response (DR) at the market level.

For centralized algorithms, a central actor collects information from the DR devices. This information can consist of individual constraints and deadlines or comfort settings. Using the collected knowledge, and possibly including additional information such as predictions, the central coordinator performs a single optimization that returns an optimal schedule satisfying all the constraints at once. This process inherently makes centralized algorithms less scalable, as the optimization process becomes very computation-intensive with an increasing number of participating devices. Furthermore, the communication to the central actor poses a potential bottleneck. Several solutions are proposed that help to overcome the tractability issue [11, 13].

Distributed algorithms, on the other hand, perform a significant part of the optimization process at the participating devices themselves. This way, the computational complexity of finding a suitable solution is spread out over the cluster, typically using an iterative process in which information is communicated between the participants. This distributed aspect does not exclude the existence of an entity responsible for initiating or coordinating the convergence of the iterations. A share of distributed algorithms in literature is based around distributed optimization techniques, in which a large optimization problem is divided into smaller parts that can be iteratively and independently solved [14–17]. In particular, the use of gradient ascent methods and their derivatives, such as dual decomposition, are common.

Aggregate & dispatch algorithms combine both approaches to some extent. They decouple the optimization of the objective from the dispatch of its outcome. An aggregate & dispatch mechanism allows information (such as constraints) from and to the central entity to be aggregated, reducing the complexity of the optimization and improving scalability, but carrying certain compromises or constraints regarding the optimality of the results. The work of Refs. [18–20] follows this idea.

While distributed and centralized algorithms can determine an optimal DR schedule given the appliances' constraints or market data, they carry some disadvantages regarding computation times, complexity, or communication. Aggregate & dispatch mechanisms are a compromise allowing for a scalable and low-cost implementation with a limited loss of optimality [3]. In this study, MBC is chosen as a particular instantiation of an aggregate & dispatch algorithm (see Section 3).

2.2 Real-time level and grid congestion

As the electricity grid cannot get physically congested, the term "grid congestion" refers to a situation in which the demand for active power exceeds the nominal power transfer capabilities of the grid [21]. Grid congestion can be mapped to the violation of one or more constraints at its connection points. In this paper, these violations will mainly be in the form of power quality problems in distribution grids, and can be attributed to the resistive and unbalanced nature of distribution grids.

2.2.1 Grid congestion metrics

The EN 50160 standard on *Voltage characteristics of electricity supplied by public distribution systems* describes, among others,