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Integrating electric vehicles as flexible load in unit commitment modeling

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ABSTRACT

Fully EVs (electric vehicles) and PHEVs (plug-in hybrid electric vehicles) have attracted much attention in recent years. Towards an increasing share of EVs, their economic feasibility and impact on the electricity distribution have been studied in detail. However, little has been achieved in investigating the impact on the electricity generation systems. This paper presents a MILP (mixed-integer linear programming) unit commitment model with focus on the effect of EVs on the generation side. The most important advantage of the proposed method is the ability to solve systems with a very large number of EVs. The algorithm is demonstrated on a benchmark system, which has been widely used in the literature and has been used here for all scenarios. It is demonstrated that optimized charging (centrally controlled) is cheaper and allows for higher EV penetration, compared to random charging. Simulations were also run for two scenarios based on the advancement in the charging infrastructure: (1) perfect infrastructure, with opportunity for charging everywhere and (2) moderate infrastructure, where charging is possible only at the owners' homes. In both cases the generation cost increases by 1% for every 10% of additional EV penetration, the modest infrastructure case being slightly more expensive.

1. Introduction

The need to reduce greenhouse gas emissions, the local air pollution problems in big agglomerations and the growing demand for oil are important reasons for the hoped-for transition in the transportation sector. The current status of EV (electric vehicle) developments is encouraging. Several countries worldwide have ambitions to electrify their car fleet (see, e.g. Ref. [1], or Ref. [2] for an overview). In Europe, this is typically within the context the 20-20-20 energy and climate package and within Europe's longer term ambition towards drastic decarbonization by 2050. In regions like China, where it is important that the shift to EVs is made quickly, because of all the new first-time purchases of vehicles, by 2015 there should be more than 100 000 PHEV (plug-in hybrid electric vehicles) just in Beijing and 150 000 000 all over China according to the "Twelfth Five Year Plan" [3]. The main purpose of vehicles is for transportation; however, they are used on the road only 4% of the time, making them potentially available for other purposes in the remaining 96% of the time [4].

The increasing share of EVs on the road is a reason for the initiation of detailed analyses of their economic feasibility and effects on the electricity distribution side. However, as it will be discussed later in the paper, little has been accomplished in studying the impact on the generation side. There are important questions to be answered regarding the possibility of an electricity generation system to serve the additional load caused by EV charging. What type of power plants will cover the additional generation? What will happen if every owner uncontrollably decides to plug-in and charge his/her EV during the peak hours? Moreover, it is important to trace how the introduction of EVs will affect the total generation cost and CO_2 emissions.

Answering these questions is not a trivial task due to the complexity caused by the large number of EVs, which actively alter the load throughout a day. The power plants available in the system need to be scheduled to meet this demand pattern at lowest cost. This scheduling optimization is typically referred to as the UC (unit commitment) problem, and has to be solved (for a given system) specifying the on/off states of all available generating units. One option to include EVs in the unit commitment model is to represent the battery of every single EV as a "movable" storage unit of electric energy, which is discharged and charged over time. However, the individual behavior of every EV requires that every EV be represented with a separate variable. In the cases of large systems with

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thousands or millions of EVs, the complexity increases dramatically and finding an optimal solution is virtually impossible.

The current paper presents a new model for solving the unit commitment problem including the (sometimes erratic) behavior of EVs. The method is based on MILP (mixed-integer linear programming), which has been extensively used for optimization of power plant scheduling [5,6]. As the focus of the analysis is on the impact on the electricity generation and the additional electric energy that has to be produced, the individual charging pattern of every EV is of less relevance here. What really matters is the amount of electric energy that has to be transferred to all EVs in the system at every hour throughout the day (i.e., the average electric power in a 1-h time step) so that their batteries are full in the morning before the first trips. The proposed algorithm is a fast and efficient method for solving unit commitment problems with a large number of EVs for special analysis of the electricity generation side. The aim of this paper is to describe the algorithm and demonstrate its capabilities on a benchmark system, with a methodological focus. Future work includes studying (with high technical detail) the integration of intermittent renewables in systems with EVs, also including the option of discharging batteries of EVs back into the grid.

The paper starts with a literature survey. Section 3 describes the data of both the electricity generation system and the EVs. The algorithm of aggregating different individual vehicles (with specific driving patterns) in specific groups is also presented. Section 4 provides the model formulation. Section 5 presents the simulation results while Section 6 concludes.

2. Literature survey

Research regarding electric vehicles has been mostly concentrated on the economic feasibility of the technology, on policies, on interconnection of EVs to the distribution grid, on battery limits and on the potential [4,7–15]. Some studies have also analyzed the impact of EVs on the electricity generation side, where especially the interaction with intermittent renewables is studied (see, e.g. [1,16,17],). Most of these studies find that the benefits (reduced CO_2 emissions, cheaper transportation) of EVs strongly depend on the method of electricity generation, i.e., the types of power plants. The advantage of PHEVs is large in areas where electricity is generated with low carbon fuels, but is modest or nonexistent in regions with coal-based electricity generation [18,19]. However, most of the studies are based on strong assumptions and do not take into account the properties of the power plants in the system. Therefore, solving the unit commitment problem for the investigated system is crucial for understanding the underlying impact on the generation side and the changes in the electricity generation fleet that have to be introduced.

A bibliographical review of UC models with EVs reveals that research efforts in this field are only recently being made. Zhang et al. investigate the interaction of EVs with the electricity generation side, with a self-developed simulation tool [20]. Saber and Venayagamoorthy claim that they have developed the first UC model to consider also so-called gridable vehicles with V2G (vehicle-to-grid) technology [21]. The authors propose a solution using a PSO (particle swarm optimization) algorithm and demonstrate it for 50 000 gridable vehicles on the same benchmark system as used in the current paper. The results show that 50 000 gridable vehicles with V2G technology reduce the total electricity generation cost by approximately 0.83% in comparison to a scenario without V2G (whereby vehicles can only be charged, i.e., solely grid-to-vehicle – G2V) [21]. Sioshansi et al. have used a unit commitment model of the power system and a vehicle driving model based on linear programming to analyze the effect of a PHEV fleet in the state of Ohio [22]. The authors conclude that a PHEV penetration level of 30% could potentially necessitate the installation of more generating capacity in the system. The model assumes 227 groups of PHEVs according to different daily driving patterns, where it is assumed that all vehicles within each group are charged identically. Hadley and Tsvetkova make use of the ORCED (Oak Ridge Competitive Electric Dispatch) model to forecast the effects of PHEVs' market penetration on electricity demand, supply, price and emissions [18]. The authors concentrate on a limited scope, i.e., on the changes that will follow if charging is possible only during the evening hours. Estimations for different limits of the charging circuits (1.4 kW, 2 kW and 6 kW) are made and it is predicted that with an EV penetration level of 25% and all vehicles being able to charge with 6 kW power lines, the peak electric power demand could increase by approximately 12% in 2030. The analysis, though, is based on some strong simplifications in modeling supply and demand in the system. An economic and environmental evaluation model, based on MILP, has been developed by the G4V (Grid for Vehicles) project [23]. The authors' results are a clear indication that EV charging has a profound impact on electricity generation scheduling and system operation costs. Unfortunately, the exact model formulation is not presented in the report [23].

In the present paper, an optimization methodology is developed for analyzing the complex system of electricity generation units and a multitude of potentially flexible loads, with a high accuracy and limited calculation time. If the number of vehicles is high, it is not possible to model all these vehicles as individual units, as the complexity of the system would become very high and virtually impossible to solve. Hence, this algorithm proposes a solution without keeping track of the charging pattern of every individual vehicle, while it still efficiently traces the effect on the electricity generation system. The algorithm does not enforce fixed driving patterns, which avoids approximations applied in other studies. Furthermore, the technical detail on the generation side (power plant level) goes beyond what is presented in the current literature.

3. Data description and processing

3.1. Electricity generation system

The electricity generation system used throughout this paper was adapted from the work of Kazarlis et al. [24]. This can be considered a benchmark system, as it has been used for a wide range of various comparative studies in the scientific literature. The system consists of 10 dispatchable power plants with parameters as shown in Table 1. The total electricity generation capacity is 1.66 GW. Throughout the rest of the present paper, this system will be used.

3.2. Electric vehicles

In most Western European countries (for example Austria, Belgium, France, Germany, Spain, Switzerland) the yearly electricity production per capita ranges between about 7000 and 9000 kWh/cap [25]. When assuming a level of 8500 kWh/cap, this is equivalent to an average annual power level of roughly 1 kW/cap. Consequently, following this reference number, the benchmark system used in the present paper can serve approximately 1.66 million people. We have assumed a moderate vehicles-per-capita factor of 0.45 vehicles/cap. Just for comparison the vehicles per capita factor in Belgium in 2008 was 0.55, in Germany 0.53, in Greece 0.45 [26]. Using 0.45 vehicles/cap for our system leads to EV penetration levels as summarized in Table 2.

Typical PHEV battery sizes range from 5 kWh to 20 kWh [27]. Other studies have assumed battery sizes of 9.4 kWh [22], 11 kWh [8], 25 kWh [21]. The company Coda recently released a fully electric vehicle model with a battery of 31 kWh. Tesla Motors delivers its