Simulation-based Approach for Investigating the Impact of Electric Vehicles on Power Grids

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***Abstract*—The large-scale introduction of plug-in electric vehicles (PEV) may pose challenges to power system operators by causing grid congestion or voltage fluctuations. This work presents a simulation-based approach for investigating the impact of transport electrification on power grids. The framework consists of an agent-based traffic simulation which is coupled with a power system simulation through the IEEE Standard High Level Architecture. As detailed power grid information is often unavailable, the framework further contains a method for synthesizing power networks from tempo-spatially resolved demand data. Using a high-performance computing infrastructure, the approach allows simulating the traffic and power system on the scale of a megacity faster than real-time. An application to the example of Singapore shows that grid congestion and voltage drops are observed on the low voltage level while the high and medium voltage grid remain unaffected. The presented framework may facilitate infrastructure decisions and support the development of smart charging strategies minimizing power grid impact.**

***Index Terms*—Power grid synthesis, power flow simulation, plug-in electric vehicle, grid congestion, power grid impact**

I. Introduction

The electrification of road transport has the potential to mitigate local traffic emissions, reduce dependency on fossil fuels and support the grid integration of renewable energies. With large market penetrations of *plug-in electric vehicles* (PEVs), however, additional demand for electricity arises which may have detrimental effects on power grid stability [1]–[3]. These could either be avoided by expanding the infrastructure or by implementing smarter charging strategies [4]–[7]. A number of previous studies has investigated the effects of PEV charging on load profiles [8]–[10]. A common conclusion is that moderate numbers of PEVs only have an insignificant impact on load curves while uncoordinated charging of a great amount of PEVs may lead to undesirably high load peaks [8]–[10]. A drawback of these studies is that the focus on peak demand may not reveal localized bottlenecks within the power system. These issues are addressed by studies investigating the impact on system components such as transformers [11] and power lines [12]. From this work it is concluded that the impact of PEV charging on system components is network specific so that in certain cases decreased transformer lifespan, transformer failure or cable overloading can occur.

Due to the dependency of power grid impact on a great variety of infrastructure characteristics, it is essential to provide planners with tools to investigate the system as a whole. A holistic investigation of the impact of electric mobility on the power grid requires the ability to consider a large variety of different scenarios in different environments. The tempo-spatial distribution of charging demand depends on manifold human and technical aspects. Human factors comprise individual travel patterns, driving behavior, range anxiety and charging cost sensitivity. Technical factors include vehicle specifications such as battery capacity, energy consumption and charging rate limitations. From a system perspective, charging infrastructure availability and traffic congestion pose additional boundary conditions influencing spatial energy demand. The impact of a certain tempo-spatial power demand distribution finally depends on the state of the power infrastructure itself so that system capacity and robustness need to be taken into consideration.

This paper therefore proposes a simulation-based framework for the holistic investigation of the entire system. This is achieved by means of an agent-based, discrete-event traffic simulation coupled to a time-stepped power system simulation which are both described in further detail in Section II. The traffic simulation allows modeling the transportation infrastructure of an entire city at the level of individual vehicles. At the same time, the power

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system simulation models the power flow on a similar scale. As accurate information on the power grid topology is often unavailable, the approach also comprises a method for synthesizing the power grid from tempo-spatial power demand data. In order to demonstrate the capabilities of the presented approach and to provide an insight into the potential impact of PEV charging on the power system as a whole, in Section III the method is applied to the example of Singapore. A conclusion and an outlook on future work are given in Section IV.

II. Simulation Framework

The simulation framework is based on the *Scalable Electro-Mobility Simulation* (SEMSim) platform. This simulation environment consists of the agent-based traffic simulation *SEMSim Traffic* [13]–[15] and the power system simulation *SEMSim Power* [16]. Both simulations are coupled through the IEEE Standard *High Level Architecture* [17] (HLA) which enables bi-directional communication. The simulation components are described in further detail in Sections II-A and II-B.

A. Traffic Simulation

SEMSim Traffic is an agent-based traffic simulation designed to run on *high performance computing* (HPC) infrastructures. An agent in the simulation consists of a driver-vehicle unit which contains both driver behavior and vehicle models. The driver component determines acceleration, speed and lane changing behavior through car-following and lane-changing models [18], [19]. At the same time, the energy consumption of the vehicle is determined by vehicle models which allow simulating components such as drivetrain, engine and battery. Traffic is generated by creating origin-destination tuples defining start location and time of individual agents as well as their destination. The agents' routes are then calculated using a bi-directional *Dijkstra* algorithm [20].

B. Power Simulation

Simulating the effect of PEV charging on the power system on a large scale requires a power grid model and a power flow simulation. The methodology for generating a *reference network model* (RNM) through network synthesis is briefly outlined in Section II-B1 followed by the description of the actual power flow simulation process in Section II-B2.

1) Power Grid Synthesis: The power grid synthesis is based on tempo-spatially resolved data of the electrical load as well as on a number of assumptions on power grid topologies. The synthesis procedure starts at the lowest voltage level by creating geographic areas with similar power demand using a weighted *k-means* algorithm [21]. A substation is then placed at the load center of each area. Within this area, demand points (*buses*) shall be connected to the substation. For this purpose, the *DBSCAN* algorithm [22] is used to perform a density-based clustering of these buses. Depending on the desired network topology, buses in each cluster are connected by *branches* in different ways. For rings, as they are common in the LV and MV grid, this is done by solving a *traveling salesman problem* [23] starting and ending with an area's substation. Equivalently, radial networks, as they are most common in the MV layer, are generated by creating a *minimum spanning tree* [24]. Meshed networks, as most common in the HV grid, are generated by employing a *Delaunay triangulation* [25].

For each area to be technically feasible, three main conditions need to be fulfilled. Firstly, the aggregated power demand of all N consumers and the power losses in all M branches within this area must not exceed the maximum power $P_{\text{S,max}}$ the corresponding substation can supply. Secondly, the total power flow P_j through each branch j must not exceed the nominal power rating $P_{\text{S},j}$ of the respective branch so that $P_{\text{S},j} \geq P_j$ for each j. Finally, the voltage magnitude $|V_i|$ at each consumer i must be within a predefined range $|V_{\text{min}}| \leq |V_i| \leq |V_{\text{max}}|$. If one of these conditions is violated, the corresponding area is split up into two and an additional substation is placed.

After all areas in the lowest voltage layer have been planned, the algorithm continues at the next higher voltage level. For synthesizing this layer, the previously created substations complement the set of existing buses. These points are then again grouped into clusters and connections between buses and supply stations are established. Repeating this procedure for each voltage layer up to the highest level finally leads to the RNM.

2) Power Flow Simulation: The power flow simulation computes the capacity utilization at every bus and branch as well as the voltage magnitude and phase angle at each consumer and substation. Calculations may cover an arbitrary period of time and are discretized according to predefined time intervals. The result informs about the current state of the power grid and identifies times and locations of grid congestion and voltage drops.

The power flow model is based on the AC power flow simulation *JPOWER*[1] which uses the *Newton-Raphson* algorithm for analyzing the load flow [26]. To reduce the computational requirements, calculations are performed consecutively for independent parts of the grid such as distinct rings or branches. The outputs generated for one voltage layer are then taken as inputs for the next level.

The simulation is initialized by defining a substation corresponding to a ring or radial branch as slack bus and by declaring each consuming bus i a PQ bus. PQ buses are initialized by their respective active and reactive power demand, $P_{\mathrm{D},i}$ and $Q_{\mathrm{D},i}$, while voltage magnitudes $|V_i|$ and phase angles Θ_i are initialized with $1.0\angle 0°$ pu.

The power flow simulation starts at the lowest voltage level by determining the active and reactive power on both ends of every branch within a ring. The power difference between both ends of a branch j is thus the power loss $P_{\mathrm{L},j}$ and $Q_{\mathrm{L},j}$. Total active and reactive power in one ring are then calculated according to

$$P_{\mathrm{S}} = \sum_{i=1}^{N} P_{\mathrm{D},i} + \sum_{j=1}^{M} P_{\mathrm{L},j} \quad (1)$$

$$Q_{\mathrm{S}} = \sum_{i=1}^{N} Q_{\mathrm{D},j} + \sum_{j=1}^{M} Q_{\mathrm{L},j} \quad (2)$$

After calculating the power flows within one voltage layer, the process is repeated for the next higher level. For this purpose, P_{D} and Q_{D} at each substation in the higher level are set to the previously calculated values P_{S} and Q_{S} of the corresponding substation in the lower voltage winding. It is assumed that shunt capacitor banks are installed at each station. This justifies setting the initial values for $|V_i|$ and Θ_i to $1.0\angle 0°$ pu for each voltage level.

If at any PQ bus the voltage magnitude violates the third condition defined in Section II-B1, another simulation iteration is initiated by increasing $|V_i|$ at the slack bus up to $|V_{\max}|$. In case this condition still cannot be satisfied, the corresponding part of the grid is considered overloaded.

C. Simulation Coupling

Whenever a PEV reaches a destination with charging facilities, the traffic simulation sends a message via HLA to the power simulation indicating the location, arrival time, current *state of charge* (SOC), and estimated departure time. A charging module within the power simulation then determines the charging power depending on a specified charging strategy. This leads to a certain load at a specific power grid node which is used by the power flow simulation to determine the power flow.

[1]https://github.com/rwl/JPOWER/

Table I: Properties of the RNM.

Property	LV	MV	HV
Branch length, average (m)	31	210	5 280
Branch length, total (km)	3 789	4 198	491
Characteristic path length (m)	20	145	4 520
Clustering coefficient, average	0.05	0.00	0.08
Mean degree	1.98	2.13	4.33
# Nodes	123 403	18 725	43
# Edges	121 971	19 955	93
# Substations, supplying	11 726	824	10

III. Case Study: Influence of Electric Mobility on a City's Power Grid

This section demonstrates the functioning of the method at the example of Singapore. For this purpose, an RNM was synthesized as described in Section III-A. In Section III-B, scenarios are outlined which are used in Section III-C to analyze the power grid impact for different amounts of PEVs and various charging strategies.

A. Reference Network Model of Singapore

The bottom-up synthesis of a power grid requires data on the number[2], location[3] and power demand[4] of consumers connected to the various voltage levels. The raw data reveals a total peak power demand of 6 340 MW[5] for 117 852 geographically distributed consumers.

Applying the power grid synthesis approach described in Section II-B1 on the mentioned consumer, power plant[6] and power line[7] data results in the RNM characterized in Table I. To account for overcapacities, the RNM is designed in a way that for the peak power demand a maximum power line utilization of 80% is not exceeded.

B. Scenarios

The *basic scenario* represents the given electrical load of all consumers in Singapore without any power demand resulting from PEV charging. Additional scenarios include 25 000 and 490 000 PEVs corresponding to roughly 5% and 100% market share, respectively. For PEV charging, three different scenarios are distinguished comprising *household* (3.6 kW at households only), *superfast* (120 kW at every location) and *mean* (charging evenly distributed

[2]http://www.streetdirectory.com

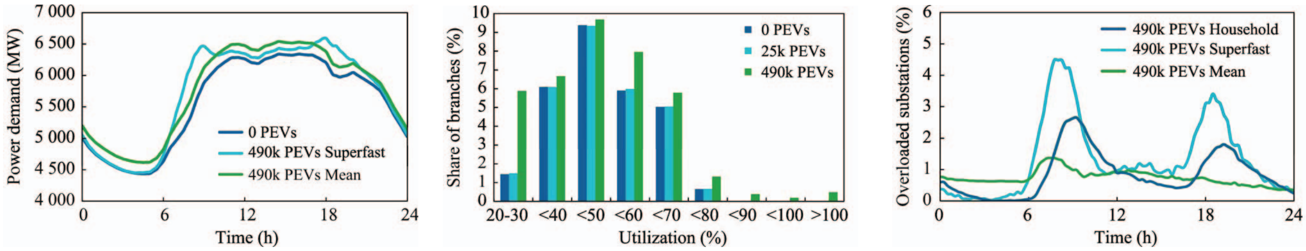
[3]http://www.onemap.sg

[4]EMA, Monthly Electricity Consumption by Sector and Half-hourly System Demand Data: http://www.ema.gov.sg/Statistics.aspx

[5]Peak power demand on 12th January 2014.

[6]EMA, Licensed Generation Capacity by Generation Company: http://www.ema.gov.sg/Statistics.aspx

[7]NEXANS, Power Cables 1-30 kV and High Voltage Cables for Power Transmission: http://www.nexans.de



(a) Load curves for different charging scenarios.

(b) Share of branches according to LV grid capacity utilization.

(c) Number of substations with voltage drops below the accepted threshold.

Figure 1: Simulation results.

over entire parking time) charging. Charging starts immediately upon arrival and is either completed once the battery's SOC equals 1 or if another trip is started.

Origin-destination pairs are sampled from the Singapore *Household Interview Travel Survey*[8], leading to 37 000 and 753 000 daily trips for 25 000 and 490 000 agents, respectively. These trips are simulated using SEMSim Traffic which results in an average daily driving distance of 48 km (standard deviation 27) and a mean energy consumption of 8.3 kWh (standard deviation 4.7) per agent.

C. Results

Figure 1a shows the influence of different PEV numbers and charging scenarios on the daily load curve. It can be seen that 490 000 PEVs exert a measurable influence on the overall load. The temporal demand distribution varies between both charging strategies with sharper peaks in the superfast charging case and a higher share at night times for the mean strategy. Compared to the overall generation capacity of 12.5 GW[9], the impact of 490 000 PEVs on the load curve can, however, be considered insignificant. It can therefore be concluded that on an aggregated level no supply bottlenecks need to be expected. The load curve for 25 000 PEVs is almost identical to the curve belonging to the basic scenario which is why it is not shown here.

Observations are different in the LV grid which can be seen in Figure 1b. The histogram shows the average number of branches with a certain capacity utilization for the case of superfast charging. While 25 000 PEVs do not cause a considerable impact, 490 000 PEVs noticeably move the distribution towards higher capacity utilization. This leads to around 1.7% of all branches being overloaded. The situation would look different in a similar view on the MV and HV grid which would not show any branches operating above their nominal capacity limits.

This effect becomes even more obvious when looking at the share of substations in the LV grid which are not able to keep the voltage magnitude at their consumers above 0.95 pu. During peak hours this affects about 5% (superfast), 2.5% (mean) and 1.5% (household) of all LV substations. In contrast, a similar plot for the scenario with 25 000 PEVs would not show any significant results.

D. Discussion

The results of the case study indicate that the HV and MV grid can be expected to remain largely unaffected even if the entire fleet of private vehicles in Singapore would be electrified. In contrast, the LV layer may be negatively affected by uncoordinated charging of large numbers of PEVs resulting in grid congestion and voltage drops. The comparison of various charging strategies, however, indicates that even large numbers of PEVs could be integrated into the power grid if appropriate measures for smart charging were taken.

It, however, needs to be considered that the investigated power system is not an exact representation of the real world. More accurate quantitative conclusions could, for instance, be drawn with access to greater amounts of real-world data. This should include data on the power grid, especially exact information on actually laid power lines and their overcapacities in the distribution network. Also more detailed tempo-spatial information on the existing power demand would be beneficial for correctly quantifying the additional local loads resulting from PEV charging.

IV. Conclusion and Outlook

In this paper, a simulation-based approach for investigating the impact of PEV charging on power grids was

[8]http://www.lta.gov.sg

[9]EMA, Licensed Generation Capacity by Generation Company http://www.ema.gov.sg/Statistics.aspx

presented. The methodology employs a nanoscopic agent-based traffic simulation which is coupled with an AC power flow simulation through the IEEE Standard High Level Architecture. The proposed approach is capable of simulating the transportation and power grid infrastructure on the scale of an entire city.

The effectiveness of the approach was demonstrated at the example of Singapore. The results show that an electrification of about 5% of the vehicle fleet would have a negligible impact on the power grid. The extreme case of 100% PEVs would still play a minor role with regard to the overall load curve as well as with respect to the HV and the MV grid. Effects in the distribution grid would, however, include grid congestion and voltage drops leading to decreased power quality.

Future work will include the integration of load balancing charging concepts including the application of smart charging strategies for stationary and mobile batteries. Finally, to further substantiate the conclusions drawn in this work, comprehensive sensitivity analyses investigating the influence of various power grid synthesis parameters will be conducted.

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