IMPROVED GRID OPERATION THROUGH POWER SMOOTHING CONTROL STRATEGIES UTILIZING DEDICATED ENERGY STORAGE AT AN ELECTRIC VEHICLE CHARGING STATION

Thomas MARTINSEN University of Tromsø, Norway thomas.martinsen@nmbu.no	Ninoslav HOLJEVAC University of Zagreb, Croatia ninoslav.holjevac@fer.hr	Bernt A. BREMDAL University of Tromsø, Norway bernt.a.bremdal@uit.no	Igor KUZLE University of Zagreb Croatia kristoffer.tangrand@uit.no
Josep M. GUERRERO, Aalborg University Denmark joz@et.aau.dk	Tomislav DRAGICEVIC, Aalborg University Denmark ntdr@et.aau.dk	Ivan PAVIĆ University of Zagreb, Croatia ivan.pavic@fer.hr	Qobad SHAFIEE Aalborg University Denmark qsh@et.aau.dk

ABSTRACT

This paper addresses the principal service aspects for electric vehicles (EV), as well as issues related to energy storage design, charging station integration into power system and load management issues. It builds on the research conducted in the Flexible Electric Vehicle Charging Infrastructure project (Flex-ChEV) supported by the ERA-Net Smart Grid FP7 program. The principal asset of the proposed charging station (CS) is a dedicated Energy Storage System (ESS) to compensate for adverse effects on the grid caused by peak charging demand and which could impose severe trials for the local DSO (Distribution System Operator). Furthermore, CS of this kind could serve multiple business purposes in a smart grid. It can serve as a hub for seamless integration of local renewable and distributed energy resources, it can provide added flexibility for the local grid through different ancillary services and it can act as an efficient traffic management support when there is a high influx of EVs.

INTRODUCTION

Power demand peaks from plug-in electric vehicles (EVs) that are likely to occur could severely strain the distribution grid [1]. Additionally, there is a global tendency to make power systems less dependent on fossil fuels by achieving additional increase in the shares of renewable energy resources. Both of these effects tend to push the future power systems more and more towards the boundaries of safe operation. Today's commercially available EV chargers and available charging strategies are not flexible and present significant disturbance sources for the grid. On the other hand, flexible chargers proposed in academic literature introduce several drawbacks mostly connected with compromising the comfort level of vehicle owners and potential degradation of car batteries [2]. In the Flexible Electric Vehicle Charging Infrastructure project (Flex-ChEV) we have investigated the potential benefits of flexible charging stations concept. The principal asset of this type of charging station (CS) is a dedicated Energy Storage System (ESS). The hypothesis is that a dedicated ESS could compensate for the adverse effects on the grid caused by EV charging. What design criteria must apply to make the CS/ESS concept technically sound and robust enough for large-scale deployment? Moreover, compared to standard CS solutions, what design criteria will yield a better option for both DSOs and CS service providers?

Answering these questions includes concerns related to the additional investments and maintenance in storage technologies. However, an integrated ESS also offers multi-service opportunities that may provide added value through provision of ancillary services [3], [4]. A general supply of flexibility services to the DSO is one possibility. Another possibility relates to neighborhood voltage and energy support where the ESS could provide storage services for local prosumers and suppliers of energy based on available wind and solar resources. To define all this it is important to determine the service requirements. Traffic and charging needs must be specified and their fulfillment assured since this is the primary function of the CS. Furthermore, the status of the local grid must be assessed and the intrinsic needs of the DSO must be made transparent. Our focus is on the technical capacities needed and the benefits of different power smoothing control strategies that must be adapted to match the configuration and loading in the grid as well as the traffic pattern observed.

Connecting high power chargers to EV causes increased power demand on several time scales. When plugging in, a power spike at a timescale of seconds occurs. The prevailing concern is that the combined impact of a large number of randomly connected EVs in the distribution network could generate a peak in power demand that could cause critical problems in the distribution grid and consequently increase costs drastically [5]. The solution could lay in modifications of the primary control that is proposed by the project. At an hourly time-scale, demand for power and energy for charging may exhibit two peaks during a weekday (morning and afternoon peak) and overlapped with the demand curve of a typical customer can enlarge the peak demand. At both timescales a dedicated ESS installed within the CS coupled with smart charging strategy can provide a needed energy buffer.

In the following, we provide an overview of the research conducted within the project and the results obtained by the working groups (WG). An important aspect of this is the control structure developed.

THE RESEARCH PROJECT

The original concept pursued is shown in Figure 1. As depicted the control hierarchy of the CS constitutes an essential part. Based on this concept description the FlexChEV project was divided into 5 scientific work packages. Modelling and optimization of ESS technologies (WG1) and large-scale study of the impact of EVs – CS on utility (WG3) chaired by University of Zagreb, Croatia. Modelling and control of EVs – CS with dedicated ESS (WG2) and experimental verification for EVs – CS with several types of ESS (WG5) chaired by University of Aalborg, Denmark. Ancillary services and business instruments (WG4) chaired by University of Tromsø, Campus Narvik, Norway. The working groups cover together all major aspects of flexible CS including primary and secondary control layer, various ESS technologies and grid challenges.

1) Primary control with dedicated ESS

The Aalborg University team has been analyzing and testing technologies and strategies for the primary control layer. Primary droop control is employed in the tested architecture for the purpose of power balancing between grid converters and flywheel serving as an EES by ramping the initial power peak that occurs when the vehicle connects to a CS. Moreover, distributed bus signaling strategy allows coordination of the components according to the DC bus voltage deviations [6], [7]. In order to eliminate the DC bus voltage variation caused by droop control, a secondary control loop is employed [8]. Reactive power support and fixable load control using hysteresis controller [9] have been studied as services that can be provided to the utility grid [10]. These services are provided by the dedicated flywheel ESS which was chosen to be a most appropriate storage technology for this flexible CS application,. With it the regular charging patterns recommended by the battery manufacturers will not be compromised and the lifetime of battery will be preserved. Aalborg University has, as a part of the project, assembled a reduced scale experimental platform to verify the feasibility of the proposed strategies and the simulation results. The power rating of the platform was 2.2 kW including two Dansfoss converters run by a dSPACE system which executes the control in real time [11].

2) Secondary control, impact of ESS on utility

University of Zagreb group has been observing the problem with integration of novel technologies [12], e.g., renewable Energy Sources (RES), EVs, Heat Pumps (HP), Charging Station (CS) into the electrical power system from two different perspectives: *i)* microgrid integration on distribution level [13] and *ii)* large-scale integration on transmission level [14]. As part of the first approach detailed MILP optimisation model of microgrid has been developed. The main goal was to provide a strategy that compensates for all of the disturbances on the microgrid level and communicates with the distribution grid only through a point of common coupling. To do so stochastic environment with Model Predictive Control (MPC) has been added. This enables integration of different technologies on a microgrid level and at the same time reduction of operational costs taking into account forecast errors.
Second approach (*ii*) considers large-scale integration of EV and RES into the power system on transmission level. Conventional (hydro-thermal scheduling) MILP model was expanded with RES and EV. There different modes of EV charging have been considered: standard uncontrolled charging, Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) [15]. Also, provision of different services (power and energy primary and secondary reserve) by EV has been enabled and its impact was investigated.

3) Ancillary services and business instruments

The primary objective of a CS is to offer battery recharging services for EVs. Service capacity must be defined according to anticipated number of arrivals at any time. This in, turn must be balanced against cost issues. The levelized cost of energy (LCOE) for an EV CS depends on several factors. Including an ESS with large energy capacity will reduce the power charges and grid station investment [20]. The impact of the ESS on the LCOE is highly dependent on the charging demand profile. That is, the economic benefit of the ESS increases with increasing difference between peak power demand and average power demand. Demand for charging and DSO requirements may vary considerably during the day, the week and the season. This is traffic dependent. Regional differences can also be significant and sitting and sizing problem is not easy to solve and mostly genetic algorithms are used [16]. The correct placement in the distribution grid of the flexible CS with integrated storage is of vital importance to unlock the full benefits. One of the goals of the project is to identify the size and placement (centralized, decentralized) of electricity storage integrated into the CS. Consumption and production decisions are a result of Convex AC Optimal Power Flow Method that stems from [18] that calculates economic dispatch of all units in distribution grid and can guarantee an optimum result. The case study was done on a typical Croatian distribution grids and it was shown that the battery storage reduces sudden demand or excess production spikes, voltage problems, equipment overloading and is, at the same time, flexible in terms of responding to market signals Additionally results from optimally placed battery regarding the distribution grid requirements need to be overlapped with the traffic data and an array of feasible locations. The analyses conducted afterwards results in a techno-economic framework for short-term and long-term planning of distribution networks with the inclusion of flexible CSs.

Service needs for EVs have typically been estimated by means of a queue modelling techniques such as [19]. However, [20] have shown that transient traffic conditions can occur, which can build rapid peaks in recharging demand. Poor service at a given charging spot may cause spill-over effects that tend to increase the unpredictability of the traffic and recharging patterns. The highly stochastic patterns that may occur can lead to a situation were free capacity in one CS in a region may not be utilized, while others may be unable to manage the demand. Human behaviour and available information provided to drivers play important roles here. Understanding this better is essential for creating a more precise basis for service capacity design and load shedding requirements for the individual CS as well as a portfolio of such. A method for this has been developed in the project [21].

RESULTS

1) Reducing power spikes from EV charger connection

Flywheel ESS is the most suitable technology for providing fast power compensation services with low energy demand. The technology is mature and economical and has high power density and no degrading problems caused by frequent charging and discharging. Flywheel converters, together with distributed bus signalling strategy and a secondary control loop offers promising results. Although, both centralized and distributed architecture is tested, the results show that the distributed approach [22] offers improved reliability and expandability and avoids a single point of failure for the centralized controller [6].

2) Improving grid stability with ESS

The detailed MILP model described before [13] shows that energy storage is of vital importance to unlock the full benefits of the installed equipment and enable the full usability even in peak hours. Controlled charging of EVs raise the limit of allowable RES integration. Increase in both RES and EV has a positive correlation and a positive effect on power system. The modelled microgrid can operate independently with very little unused energy [23]. In case there is a connection with the rest of the distribution system, the microgrid can exchange electrical energy with the system and its operation is driven by market signals. A microgrid controller capable of adjusting the operation of flexible units is of the utmost importance as it does not allow the microgrid to act as a variable source from the system perspective. Such controller achieves 7% better results compared to the same system without the controller.

Plug-in mode, i.e. uncontrollable charging of EV, is increasing energy and reserve requirements and increasing peak power- and reserve-demand. G2V and V2G modes are flexibility enhancers, especially when providing both energy and power reserve, so they affect system positively by decreasing system cost, peak demand, peak reserve, emissions, RES curtailment etc. Generally, V2G mode provides more flexibility to system than G2V, thus decreasing total operational cost even more. Interesting observation is that using EVs as a reserve provider in G2V mode is a better solution for the power system than using EVs without reserve provision in V2G mode [24]. To elaborate; multiple services provided by EVs can substitute frequent charging and discharging of EVs and at the same time decrease system cost and RES curtailment. Major advantage of controlled charging of EVs is the raise of the limit of allowable RES integration. Increase in both RES and EV has a positive correlation and a positive effect on power system.

3) Improving traffic

The simulation method developed supports the notion that seasonality can cause very transient effects in traffic behavior and thus recharging demands. Road congestion caused by a heavy exodus of vehicles from a city center on a Friday afternoon is a case in point. Not surprisingly, this work [21] shows that low traffic on main roads leads to more drivers seeking alternative routes until the flow rate improves again on main roads. Similar effects occur when recharging times increase. As a consequence the service rate for CSs along main roads will also determine the rate of arrival and distribution of loads among CSs. As the charging time increases more transient effects can be more dramatic and unpredictable. All this implies that CSs along main roads should design their service capacity high enough to avoid as much spill-over effects as possible. The other is that service capacity must balance this against both maximum and minimum traffic rate. Ironically, high intensity traffic that leads to congestion suggests lower CS capacity as drivers will seek alternative routes, if possible. Thus optimal ESS capacity must be balanced against service rate, charging speed as well as local and regional traffic patterns.

CONCLUSIVE DISCUSSION

The flexible charging station concept introduced solves the problem of reducing peak demand that is inherent to the addition of any new load to the power system. With the addition of dedicated ESS, flywheel only to reduce spikes or a large battery storage to reduce peak power as well, and development of smart control and management strategies these problems can be alleviated. If CSs are located and sized in an optimal way even further benefits can be gained. Primarily, the ability to offer different ancillary services to the distribution grid (voltage support, power and energy reserve) shows great potential. Simulation models done under the project have shown that participation of flexible CS and EV in the frequency regulation (primary and secondary control) results in great savings in the system. Additionally, it was shown that through a planning and operation model of a whole independent segment of the distribution grid that can cope with the uncertainty in the stochastic environment, the integration of CS becomes even more acceptable without the need for capital investments. Moreover, The CS concept with the ESS can also better cater for service needs that stem from transient peaks caused by highly stochastic traffic patterns. The reduction and determent of investments that would otherwise be needed to fulfill all the needs of the growing EV fleet, strengthened with the viable business model that offers additional ancillary service, benefits the financial justification of investing into the flexible CS.

ACKNOWLEDGEMENT

The work is a part of the Flex-ChEV project funded by EU's Smart Grid ERA-Net program under grant No. 13.

REFERENCES

[1] Y. Akimoto; T. Mizutome; Y. Ho ; T. Yamaguchi, A possibility of the power supply leveling by using electric vehicles as storage batteries, IEEE International Symposium on Industrial Electronics (ISIE), 2013, Taiwan
[2] E. Sortomme; M. A. El-Sharkawi, Optimal Combined Bidding of Vehicle-to-Grid Ancillary Services, IEEE Transactions on Smart Grid Volume:3, 2012
[3] S. Izadkhast; P. Garcia-Gonzalez ; P. Frías, An Aggregate Model of Plug-In Electric Vehicles for Primary Frequency Control, IEEE Transactions on Power Systems, Volume:30, 2015
[4] Z. Luo ; Z. Hu ; Y. Song ; Z. Xu, Economic analyses of plug-in electric vehicle battery providing ancillary services, 2012 IEEE International Electric Vehicle Conference (IEVC), Greenville, USA
[5] Rautiainen, S. Repo, P. Järventausta, A. Mutanen, K. Vuorilehto, and K. Jalkanen, Statistical Charging Load Modeling of PHEVs in Electricity Distribution Networks Using National Travel Survey Data, IEEE Transactions on smart grid, vol. 3, 2012
[6] T. Dragicevic, S. Sucic, J. C. Vasquez, J. M. Guerrero, Flywheel-Based Distributed Bus Signalling Strategy for the Public Fast Charging Station, IEEE Trans. Smart Grid, vol.5, 2014.
[7] Bo Sun, Tomislav Dragicevic, Juan Carlos Vasquez, Josep M. Guerrero, Mehdi Savaghebi, ''Distributed Bus Signaling Control for a DC Charging Station with Multi Paralleled Flywheel Energy Storage System, IEEE Power Electronics, Drives Systems & Technologies Conference (PEDSTC), 2015.
[8] Bo Sun, Tomislav Dragicevic, Juan Carlos Vasquez, Josep M. Guerrero, Two-Level Control for Fast Electrical Vehicle Charging Stations with Multi Flywheel Energy Storage System, IEEE IDCM 2015.
[9] D. Callaway and I. Hiskens, Achieving controllability of electric loads, Proc. IEEE, vol. 99, no. 1, pp. 184–199, Jan. 2011.
[10] Bo Sun, Tomislav Dragicevic, Mehdi Savaghebi, Juan Carlos Vasquez, Josep M. Guerrero, Reactive Power Support of Electrical Vehicle Charging Station Upgraded with Flywheel Energy Storage System, IEEE PowerTech, Eindhoven, 2015.
[11] Microgrid Research Programme, Aalborg University, *URL: www.microgrids.et.aau.dk*.
[12] Igor Kuzle, Ninoslav Holjevac, Tomislav Capuder, Model Predictive Control for Scheduling of Flexible Microgrid Systems, 9th Conference on Sustainable Development of Energy, Water and Environment Systems – SDEWES, 2014, p. 473-494A
[13] Ninoslav Holjevac, Tomislav Capuder, Igor Kuzle, Adaptive Control for Evaluation of Flexibility Benefits in Microgrid Systems, Energy, vol 86, Jun. 2015.
[14] Ivan Pavić, Tomislav Capauder, Ninoslav Holjevac, Igor Kuzle, Role and Impact of Coordinated EV Charging on Flexibility in Low Carbon Power Systems, IEEE International Electric Vehicle Conference, 2014.
[15] Ivan Pavić, Tomislav Capuder, Igor Kuzle, Value of flexible electric vehicles in providing spinning reserve services, Appl. Energy. 157 (2015) 60–74.
[16] S. Wen, H. Lan, Q. Fu, D. C. Yu, Economic Allocation for Energy Storage System Considering Wind Power Distribution, IEEE Transactions on Power Systems, Volume:30, 2015
[17] Thomas Martinsen A business view on an EV charging station with battery energy storage CIRED-16 paper 0374
[18] Nick M, Member S, Cherkaoui R, Member S, Paolone M. Optimal Allocation of Dispersed Energy Storage Systems in Active Distribution Networks for Energy Balance and Grid Support. IEEE Trans Power Syst 2014;In press:1–11.
[19] D. Said; S. Cherkaoui; L. Khoukhi, Queuing model for EVs charging at public supply stations, 9th IWCMC, Cagliari, Sardinia, 2013.
[20] Bremdal. B, Grasto, S., Seasonal impacts of EV charging on rural grids: A Case-Study from Hvaler, Norway. IEEE IEVC, December 2014, Italy.
[21] K. Tangrand, Bremdal B, Using Ant Colony Optimization to determine influx of EVs and charging station capacities." IEEE ENERGYCON, April 2016, Leuven, Belgium.
[22] Bo Sun, Tomislav Dragicevic, Juan Carlos Vasquez, Josep M. Guerrero, Distributed Cooperative Control for Fast Charging Station Upgraded with Multi Flywheel Energy Storage System, 17th Conference on Power Electronics and Applications, EPE'15-ECCE Europe. Sep. 2015.
[23] Daniel E. Olivares, Claudio A. Cañizares, Mehrdad Kazerani, A Centralized Energy Management System for Isolated Microgrid, IEEE Transactions on smart grid, Vol. 5, no. 4, 2014
[24] Ivan Pavic, Tomislav Capuder, Igor Kuzle, Low carbon technologies as providers of operational flexibility in future power systems, Applied Energy 2016