Integration of SmartParks in a Power System with Utility-Scale PV Plant

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Abstract—This paper demonstrates integration of aggregate Plug-in Electric Vehicle parking lots known as SmartParks, adjacent to a MW-scale Photovoltaic (PV) plant for mitigation of loading on synchronous generators during peak hours as well as enhancing the Available Transfer Capability of area tie-lines. Simulations are carried out in the real-time digital simulator, where the PV plant and aggregate SmartParks are connected to a benchmark two-area multi-machine power system, equipped with secondary frequency controllers i.e. Automatic Generation Controllers and benefiting from Phasor Measurement Units data. The results conclude that cost-effective energy storage technologies such as SmartParks bring the potential in coping with one of the open challenges impeding PV penetration growth.

Index Terms—Automatic generation control, vehicle-to-grid, PV–SmartPark

I. INTRODUCTION

W ITH the advent and implementation of energy storage technologies in conjunction to variable renewable energy sources, enhancements are to come in system stability and reliability [1]. The Vehicle—to—Grid (V2G) concept first put forth by [2] at Drexel University in Pennsylvania, USA, suggests that V2G could be beneficiary for its participants under specific conditions. The authors have performed techno-economic analysis and developed equations to better understand the capacity of PHEVs/EVs in supplying power over a duration time with minimum compromising of the vehicles main purpose i.e. transportation [3]. The result of their studies concludes that V2G integration becomes competitive in the case of ancillary service electricity markets of spinning reserves and regulation [4].

Two decades since introduction of the concept, hasn't V2G become a commodity in the deregulated market? Well, despite all breakthroughs to date and the European Union Photovoltaic Technology Platform think tank that emphasizes the fact that increasing penetration of Photovoltaics (PV) heavily depends on storage capabilities of EVs [5], nonetheless V2G is yet to

reach grid-parity on a global scale. What lies in the future then? Authors in [6] among many others are adamant that with development of proper accurate business models, V2G becomes profitable taking into account time-based pricing rate programs and intelligent unit commitment, of which the EV owner capitalizes on fluctuating power tariffs, while through active owner participation the utility benefits in various aspects as well, e.g. line loading regulation, peak shaving during peak load, maintaining system stability through frequency regulation and mitigation of power fluctuations generated from intermittent and relatively unpredictable renewables or as a consequence of system faults [7].

In terms of reliability and security of power supply, acquiring readily available energy sources or/and demand side management solutions is inevitable. Utility-Scale viable energy sources require rapid power ramping and balancing capabilities, while demand-side management techniques on MW-scale call for active participation of great number of industrial/residential customers through demand response programs. However, implementing either/both of aforementioned solutions by itself comes at the expense of vast capital and operation costs. The authors believe the path to having a cost-effective solution, while simultaneously maintaining high power supply security and reliability is incorporating Smart-Parks. A combination of commercial Plug-in Electric Vehicle (PEV) parking lots known as SmartParks [9] in each operating control area will be effectual in contributing towards this goal.

This paper demonstrates integration and operation of aggregate SmartParks for decreasing the generation loading on synchronous generators during peak hours as well as enhancing the Available Transfer Capability (ATC) of area tie-lines. Furhter, power fluctuations generated due to a large disturbance have been observed for three case studies. Section I gives insight into the challenges operating solar PVs and how cost-effective smart energy storage technologies such as SmartParks can contribute in overcoming some of these issues. In Section II the PV-SmartPark specifications is presented. Section III discusses the PV-SmartPark operation in a benchmark two-area multi-machine power system, equipped with secondary frequency controllers i.e. AGC. Eventually, results of three case studies have been presented in presence of a three phase system fault.

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Fig. 1. Test power system with PV-SmartParks

II. PV-SmartPark System

A. Power System with PV Plant

Fig. 1 shows a diagram of the power system. The entire system has been simulated on the real-time digital simulator (RTDS) platform. The two-area multi-machine power system and its components is described in [10], while the PV plant VSIs controllers' structure have been modified and replaced with help of Synchronous Frame Theory (SRF) and with control block diagram structure similar to [11]. Each SmartPark is a battery with bidirectional three-phase VSI. The aggregate of SmartParks in the balancing authority with a PV plant are connected to the transmission network i.e. Bus 10 through isolation-interconnection transformers; 2.08 kV/22 kV and 22 kV/230 kV for aggregate SmartParks, 0.48 kV/13.8 kV and 13.8 kV/230 kV for the PV plant.

The most heavily loaded Busbar i.e. Bus 9 is located in Area 2. The balancing authority in Area 2 is operating the SmartParks jointly with the PV plant as well as the system. This is possible through near real-time bidirectional information flow and control signal communication among multiple entities in different areas with the aid of multi-agent systems (MAS) in the smart grid.

B. SmartPark

The SmartPark control structure constituting of PI Controllers are based on the SRF theory in RSCAD; this is presented in [9]. SmartPark VSI controls bidirectional power flow by using current control SPWM technique. Its control scheme is typically a combination of two control loops i.e. the outer and inner loops. The outer control loop can be of various types dependent on the operational objectives from the PEV system. In this study, it is utilized in order to track reference active and reactive power commands, in which provide reference dq-currents to be tracked by the inner current controller. Eventually, the inner controller for a VSI is essentially chosen as a current controller to have CC-PWM. It provides the signals at its output required for generating switching pulses for the single-stage two-level VSI (2 LVSI).

SmartPark Stochastic Charge/Discharge & Assumptions: Since each SmartPark is modeled as a DC battery interfaced to the grid through a single VSI, its charging/discharging operation towards grid is similar to an EV, thus aggregate SmartParks operation are similar to fleet of EVs. In reality in a system neither all EVs charge at the same time, nor do they discharge simultaneously. The behaviour is dependent on tariffs and EV usage pattern. Considering the fact that residual capacity since last charge (initial SOC) in an EV is a random function of total driving distance since it being last charged, we have been able to utilize a set of statistical parameters from [12] to carry out a statistical study in estimating its distribution, in which will produce probability density function (3), dependent on (1) and (2).

$$SOC_i(t-1) \approx \left(1 - \frac{\alpha d}{d_{FR}}\right) \times 100\%$$
 (1)

$$f_1(d|\mu_1, \sigma_1) = \frac{1}{\sqrt{2\pi\sigma_1^2}} \exp \frac{-(d-\mu_1)^2}{2\sigma_1^2}$$
(2)

$$f_2(SOC_i|\mu_2, \sigma_2) = \frac{1}{\sqrt{2\pi\sigma_2^2}} \exp \frac{-(SOC_i - \mu_2)^2}{2\sigma_2^2}$$
(3)

where SOC_i is initial battery SOC at start of charging (residual capacity since last charge), d daily driving distance of EV, α total days EV has been driven since last charge, d_{FR} maximum range of EV. $(\mu_1, \sigma_1) \approx (48.5, 19.6)$ miles and $(\mu_2, \sigma_2) \approx (39.6\%, 5.2\%)$ is the mean and standard deviation estimated using data in [12] in order to calculate probability distribution function of d and SOC_i shown in Fig. 2, respectively. It is assumed that $\alpha = 2$ days and $d_{FR} = 160$ miles for the calculations. After two days of driving the EV mean $SOC_i = 39.6\%$ (Fig. 2).

Note that in order to introduce a valid case study such as above a set of reliable transportation data sets is required. However, due to confidentiality of such data few academic researchers have access to such data, of which in many cases is not publishable. In a recent article [12], the transportation datasets is used to study vehicle travel distances pattern of an urban location e.g. Seattle. Through a statistical analysis technique i.e. a quantile method it is realized that with availability of the 1st and 3rd quartiles i.e. interquartile range



Fig. 2. Statistics of transportation datasets from city of Seattle, USA utilized to estimate (a) Normal probability semilog plot of daily driving distance of private vehicles, (b) Normal probability semilog plot of EV battery SOC since last charge

TABLE I EV Charging Methods in North America

Charging Method	Typical Voltage $[V]$	Max Current Capacity [A]	Typical Chargin Power $[kW]$	Typical Charge Duration
AC Level I (1ph.)	120	12 to 16	1.44 to 1.92	5-8 hours
AC Level II (1ph.)	208 to 240	<80	<16.6	1-2 hours
AC Level III (3ph.)	208 to 600	<400	<240	10-15 minutes
DC Fast Charging	<600	<400	<240	10 - 15 minutes

(IQR), and the median of total of n observations it is possible to estimate the sample mean and sample standard deviation. With availability of the aforementioned parameters from [12] and with incorporating equations (14) and (17) in [13], the sample mean and standard deviation are estimated as discussed. The randomly generated sample observations (420 samples) correctness is tested through graphical assessment in Fig. 2 to identify whether the data set comes from the normal distribution or not. If the data are normal, the plot will be linear. Fig. 2 results verifies the correctness of the data set with its linearity. Eventually numerous simulation runs (monte-carlo) need to be executed in order to obtain the final average results.

According to the Society of Automotive Engineers (SAE) standard J1772, there are three AC charging levels as well as a single DC charging method, indicated in Table I [14]. Considering the power flow capacity and faster charging times, level II is the preferred method for most industrial and commercial facilities. For the option of a parking lot with a large fleet of EVs (SmartPark) exporting/receiving energy to/from the grid, multiple level II charging stations arranged along three single-phase distribution system laterals is an option.

The balancing authority requires aggregate SmartParks connected at PCC to inject active power to the grid dependent on SmartParks battery size and State of Charge (SOC) and in coordination with the PV plant. Each aggregate SmartParks is capable of having 20MW/20MVAr power transaction with the grid. Taking into account that each EV power capacity is 16.6kW, each aggregate SmartParks in a regional balancing authority contains 1205 EVs in order to have it operate at nominal rating at PCC to the grid. In order to generate the aggregate reference active power command (P^*) for aggregate SmartParks, PV plant real-time active power output is subtracted from already committed active power from PV hourly/daily sold to the balancing authority.

III. PV-SMARTPARK STUDIES

Calculation of reliability indices such as LOLE, LOLP, etc. depends on historical as well as forecasted data. There have been different methods introduced in literature for their estimation [15]. However, in this study, system reliability calculation in order to maintain high reliability, while meeting load requirements with possible minimum cost through optimization of PV-SmartPark size is not a concern, but there is a positive correlation among increase of reliability with increase of MW and MW h storage, taking into account energy system and operational constraints.

The load center is located at Bus 9 in Area 2, with a total demand of 1767 MW. The power is flowing through the tie-



Fig. 3. Generators response to SmartParks integration

lines from Area 1 to 2 with configuration of AGC in Area 2. The system frequencies and tie-line power flows are in correlation with the PV power generation variability. Under normal conditions, with no PV power generation, there is a power flow of 400 MW from Area 1 to Area 2. Area 1 AGC uses PV power generation information to decide the outputs of (G_1, G_2) in Area 1, which enables the maximum utilization of PV power generation in Area 2. This corresponds to a bilateral agreement among the two balancing authorities, of which should not be violated under any circumstance. The SmartParks have the capability to supply electricity during peak hours through discharge into the grid, contributing to reduction in conventional power plants operating costs, decrease in possible transmission line power losses, and enhancement of tie-lines ATC and power system reliability.

A. SmartParks Integration and Operation

In the base case (without SmartParks) while the PV-plant is injecting a specific amount of active power at MPP to the grid i.e. 82 MW, the generators G_1 to G_4 are producing 654 MW, 654 MW, 720 MW, and 698 MW, respectively. The tie-line power flow is 314 MW. At this instance, two SmartParks are connected to the grid at Bus 10, each injecting 20 MW. The responses of the area generators with respect to connection of the SmartParks to the area network is shown in Fig. 3. It is observed that while the system has maintained its stability, with connection of SmartParks the power contribution from the generators is reduced leading to lower operation and maintenance (O&M) cost.

B. With Application of a Large Disturbance

A severe type of fault i.e. a six-cycle, three-phase fault to ground is applied in a critical region i.e. midsection of the power tie-lines at 8. Table *III* shows the steady-state results for this for three cases: (1) base case i.e. AGCs only, (2) PV, (3) PV–SmartParks. By equipping the system with auxiliary cost-effective sources of energy storage i.e. SmartParks it is possible to mitigate the counterproductive effects of faults in the locations of SmartParks and increase system reliability. The generation in (G_3, G_4) have decreased accordingly.



Fig. 4. (a) active power of a SmartPark, (b) tie-line flow from Area 1 to Area 2, (c) system frequency

TABLE II
PV-SMARTPARK OFF/ON
STEADY-STATE RESPONSE

$S_{ref} = 500W/m^2$ $T_{ref} = 25 ^{\circ}\mathrm{C}$	OFF	ON
$P_{SP_1}[MW]$	0	19
$P_{SP_2}[MW]$	0	20
$P_{PV}[MW]$	82	82
$P_{G1}[MW]$	654	654
$P_{G2}[MW]$	654	654
$P_{G3}[MW]$	720	701
$P_{G4}[MW]$	698	678
$P_{tie}[MW]$	314	314
$f_{sys}[Hz]$	60	60

This indicates enhancement in Available Transfer Capability (ATC) [16] of the tie-lines, when SmartParks are operational. However, the power oscillations have remained approximately unchanged and damping is not provided. Further research is to be carried out in defining the characteristics of SmartPark in compliance with grid codes and standards. Eventually, goal is to represent an intelligent joint-user PV-SmartPark system.

TABLE III Improvement in Steady-State Results From Generators Response to SmartParks Integration

	Base Case	PV	PV-SmartParks
	[MW]	[MW]	[MW]
P_{G1}	684	654	654
P_{G2}	684	654	654
P_{G3}	737	720	701
P_{G4}	715	698	678
P_{tie}	369	314	314
ATC	NA	improve	improve

IV. CONCLUSION

With increasing penetration levels of solar PV including large scale PV plants in the power system, necessity of incorporating reliable cost-effective solutions in maintaining system stability becomes inevitable. In a typical day with vehicles parked 23 hours and driven only 1 hours [17], cheap energy storage from large fleets of electric vehicles forming Smart-Parks is a viable solution for grid support. In this study, integration and operation of SmartParks has been demonstrated in RSCAD. The results indicate effectiveness of this technology in mitigating the loading on network synchronous generators during peak hours as well as enhancing ATC of tie-lines without violating any bilateral contract among area balancing authorities.

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