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Dynamics of an integrated solar photovoltaic and battery storage nanogrid for electric vehicle charging

Laura Novoa, Jack Brouwer*

Advanced Power and Energy Program, University of California, Irvine, CA, 92697-3550, USA

HIGHLIGHTS

- A PV/EV/BESS nanogrid is proposed to maximize solar EV charging.
- A proof-of-concept testbed provides real-world EV charging demand data.
- Four BESS controls are proposed and evaluated for power quality and PV penetration.
- The nanogrid can supply 20 Level-2 EV chargers while imposing no burden on the grid.

ARTICLE INFO

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ABSTRACT

In this paper, the performance of a renewable Solar Photovoltaic (PV) nanogrid — here defined as a small-scale power system, which comprises a single domain for control, reliability, and power quality — is assessed for Electric Vehicle (EV) charging. A nanogrid testbed, containing PV as the power supply, twenty EV charging stations, a Battery Energy Storage System (BESS), and a smart-inverter is connected to a primary feeder on the University of California, Irvine (UCI) Microgrid. We present four different smart-inverter control algorithms that govern battery dispatch for different energy management goals. The control algorithms were evaluated with respect to four figures of merit: (1) Renewable Penetration, (2) Voltage Profiles, (3) Net Power Flows, and (4) PV curtailed. A steady-state power flow model of the nanogrid was developed to study the local power quality. The control algorithms were able to successfully use the battery to shift the nanogrid peak load and also limit the nanogrid demand to a given threshold. It is shown that the nanogrid was able to offset the EV daily charging loads completely. In this same mode, the renewable contribution to EV charging was 80%, and the overall solar penetration (accounting for export and battery charge) was 89%.

Nomenclature

Abbreviations

AC	Alternating Current
AIRB	Anteater Instruction and Research Building
BESS	Battery Energy Storage
BEV	Battery Electric Vehicle
CAP	Cap Demand (BESS mode)
DC	Direct current
DER	Distributed Energy Resource
EV	Electric Vehicle
EVCS	Electric Vehicle Car Shade
EVSE	Electric Vehicle Supply Equipment
G2V	Grid-to-Vehicle
GHG	Greenhouse Gas
ISGD	Irvine Smart Grid Demonstration
MPPI	Maximum Peak Period Impact
PCC	Point of Common Coupling
PHEV	Plug-in Electric Vehicle
PLS	Peak Load Shifting Mode
PV	Photovoltaics
PVCAP	PV Capture (BESS mode)
RES	Renewable Energy Source
S2V	Solar to Vehicle
SCE	Southern California Edison
SLE	State Load Estimator
SOC	State of Charge
T&D	Transmission & Distribution

* Corresponding author.
E-mail address: jb@apep.uci.edu (J. Brouwer).

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UCI	University of California, Irvine
V2G	Vehicle-to-Grid

BESS control variables

Variable	Description	Units
$\boldsymbol{BESS_{Dch}(t)}$	Battery discharge power at time t	kW
$\boldsymbol{BESS_{Ch}(t)}$	Battery charge power at time t	kW
$\boldsymbol{EVSE(t)}$	Electric Vehicle Supply Equipment charging demand at time t	kW
$\boldsymbol{PV(t)}$	PV power output at time t	kW
$\boldsymbol{BESS_{kW}}$	Maximum battery discharge power	kW
$\boldsymbol{CAP_{kW}}$	Cap demand threshold	kW
$\boldsymbol{\phi}$	Percent of energy in the BESS charged by solar PV	%
η_{inv}	Inverter efficiency	%
η_{Ch} , η_{Dch}	BESS charging and discharging efficiency	%

1. Introduction

Environmental concerns and fossil fuel depletion have spurred the latest research interests in shifting traditional power generation and transportation paradigms. Microgrids and nanogrids are small-scale electric utility grid networks that operate as a single, controllable, entity capable of seamless islanding from the main electricity grid. Both offer a means to integrate renewable-based Distributed Energy Resources (DER) and EVs into a wide-area network [1,2], and are emerging to play a key role in this endeavor. The association of transportation electrification and renewable energy resources has a high potential for offsetting fossil fuel reliance and greenhouse gas (GHG) emissions [3], unlocking the full benefits of electric mobility.

Microgrids and nanogrids have the potential to meet the growing demand for reliability and resiliency in the power sector. Topologies containing DER can supply active power to local loads, reducing power losses in the Transmission and Distribution (T&D) systems and enhancing local network power quality, by providing ancillary services such as voltage support by reactive power injection, fault restoration aid supported by devices with embedded intelligence, and local control of voltage and frequency [4]. Increased reliability and resilience is inherent to a distributed system of smaller scale, most times integrated with grid-forming (i.e., providing a stiff source of voltage and frequency) energy storage or backup power components, while utility grid network connected, adding up to produce a more reliable power supply system for critical loads [5,6]. Moreover, a shift towards decentralized power, in a bottom-up configuration, balances local power supply and demand more directly and more efficiently, and may reduce utility costs for grid infrastructure upgrades, and consequently, lower overall consumer prices [5].

In parallel, transportation electrification offers numerous benefits. Electric vehicles, including Plug-in Hybrid Electric Vehicles (PHEV), and Battery Electric Vehicles (BEV), exhibit higher combined drivetrain efficiency, better low-end torque, and reduced criteria pollutant and greenhouse gas emissions, compared to gasoline and diesel engines [7]. Moreover, by concentrating emissions on the power generation sector, EVs can reduce in-basin pollutant emissions, and reduce GHG emission rates by enabling more integration of renewable and low-GHG emitting electricity generation [8]. Moreover, depending upon local renewable energy penetration combined with the right charging strategies, the dispatch of EV loads allows the grid to absorb intermittent and unpredictable renewable generation (solar, wind, and tide)that would be curtailed otherwise [9]. The various dynamic dispatch services that smart EV charging provides could enable increased efficiency and higher renewable power use throughout system [10].

In 2016, the U.S. EV market size was almost one-third (27%)of the world's EV market [11]. When taking into account PHEV and BEV, a total of 808,892 units were sold as of March 2018 [12]. As the number of EVs continues to increase over time, the necessary charging infrastructure will continue to grow as well. Moreover, large amounts of EV charging is expected to also affect the power quality, stability, integrity, and reliability of the power distribution system [13]. The synergies between solar PV generation and EV workplace charging when deployed together have been identified in Refs. [14,15]. In Ref. [14], one of the earlier works in the topic, the concept of Solar-to-Vehicle (S2V) charging is introduced and it is shown that a solar collector of a size of a parking spot can produce enough power to charge a commuter's PHEV battery. Later, authors in Ref. [15], demonstrated the mutual benefits of workplace S2V: PV can provide mid-day capacity to workplace charging, increasing the electrical range for the commute, and maximizing the environmental benefits of EVs, further reducing CO2 emissions. Mid-day charging also helps absorb otherwise curtailed PV by providing a (flexible, if controlled) source for electricity demand. Yet, there are still major challenges associated with the integration of these technologies into the power grid.

Microgrids currently have higher cost, policy, and technology barriers in many applications that restrain a broader market deployment. On the cost and policy side, there is a high initial capital investment cost associated with smart-grid enabling hardware and infrastructure that has traditionally relied on utility market and policies for a guaranteed return on investment [2]. On the technical side, there are challenges associated with design, control and operation of microgrids. For grid-tied systems, challenges involve protection coordination, the need for adaptive control strategies that will respond to unexpected external grid disturbances, and power flow control at the Point of Common Coupling (PCC). In islanded microgrids, voltage and frequency control, cooperative power-sharing amongst DER, and fault current limitations are typical challenges [5]. Communications play a significant role in microgrid control and can also impose challenges associated with bandwidth for data exchange, topology, protocol interfacing, and cybersecurity. Similar to the utility grid network, microgrids face challenges related to the intermittency of Renewable Energy Sources (RES) at high market penetration and with the randomly occurring and high power demand associated with electric vehicle charging. One of the most common issues for the reliable operation of a microgrid is to instantaneously balance energy supply and demand. Both RES and unpredictable EV loads can create peaks and valleys in the power system load curve and thus create undesirable increases in the capacity of grid management resources that are required (e.g., monitoring, voltage, and frequency controls, energy storage) [3,16]. In addition, depending upon the charging power level and market penetration of EVs in a particular location, overloading distribution infrastructure (e.g., feeders and transformers) may occur, posing a risk to the system reliability [13,15,17]. Lastly, challenges involving seamless islanding might occur due to the need for a stiff power supply at all times.

To tackle the above-mentioned challenges in microgrid topologies that contain high levels of EVs and solar PV, one common approach is the use of battery energy storage. Various BESS energy management solutions have been proposed by the research community [18–21]. In these methodologies, the battery typically stores surplus PV energy generated on-site to supplement (fully or partially) EV loads when PV generation is insufficient or not available. Thus, the batteries shift power from times when solar power is available in excess of EV charging demands to times when EV charging demand is greater than the solar power available and serve as a buffer for days with low solar potential. Amongst the topologies mentioned in the literature, most are grid-tied and allow for using grid power during times when the combined PV and battery output is not sufficient to meet the EV charging demand. Authors in Ref. [18] compared two BESS control systems for

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