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APPLICATION OF BI-DIRECTIONAL ELECTRIC VEHICLE AGGREGATION IN A CYBER SECURE MICROGRID CONTROLLER

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ABSTRACT
Electric vehicle (EV) aggregation to provide vehicle-to-grid (V2G) services is a topic that has generated research into the economics and viability of using EVs for more than transportation, but little has been demonstrated to this point. This is especially true of using bi-directional power flows to move energy to the grid from EVs or to provide variable charge and discharge control. Our work focuses on implementing bi-directional functionality to demonstrate both V2G services and islanded microgrid support. The use of an intelligent microgrid controller combined with an EV aggregator provides new control capabilities for EV participation as energy storage devices.

INTRODUCTION
Electric vehicles are gaining in popularity as fleet owners and consumers look to find relief from the variability and volatility of fossil fuels that are primarily from foreign sources. The Department of Defense (DoD), in particular, has been looking at electric vehicles as a mechanism to help reduce DoD dependence on foreign fossil fuels, driven by doctrine such as the DoD Operational Energy Strategy [1] and the U.S. Army's net-zero energy goals [2]. In particular, the Army has been replacing non-tactical vehicles at Continental United States (CONUS) installations with hybrid and low-speed electric vehicles. Programs such as the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) are developing mechanisms for installations to ensure secure, reliable power utilizing renewable resources and electric vehicles to provide energy surety. The DoD Plug-in Electric Vehicle - Vehicle to Grid (PEV-V2G) program is focused on expanding electric vehicle use at multiple bases in the mainland U.S. and Hawaii.

MICROGRID CONTROL
Microgrids provide a distinct opportunity to bring new capabilities, energy cost reduction, and resiliency to a power grid through distributed intelligence and autonomy. An integral aspect of a successful microgrid is providing the user the ability to easily access, monitor, and adjust the system as needed. Microgrids need the ability to integrate multiple types and sizes of generation sources and energy storage and may provide for prioritized load shedding. Generation sources may be controllable (such as a diesel generator); uncontrollable (such as photovoltaic or wind); or, in the case of energy storage, is controllable but could be a power source or load depending on need.

Microgrid Control for Islanding
Islanding is defined as when the microgrid disconnects from the utility grid and the microgrid continues to provide power to loads. This can be desirable when electrical power from the utility is unstable or no longer present. In addition to grid blackout (a clear indication of a service interruption), methods such as passive, under/over voltage, under/over frequency, etc., may also be used to detect when islanding should occur. [3]

Islanding must occur in such a way that it is safe for end-user equipment, provides for the safety of repair crews that may be faced with unexpected live wires, and safely reconnects with no damage to the utility. IEEE 1547 (IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems) and UL 1741 (Standard for

Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources) dictate how this should be done electrically.

In islanded mode, a microgrid controller monitors the status of the microgrid in real time and balances sources, storage, and loads. Devices can be added or removed, and the microgrid controller needs to recognize these changes and adjust control algorithms accordingly. It must prevent conditions where uncontrollable sources (photovoltaic or wind) exceed the loads, as this type of condition can damage operating generators on the microgrid.

Microgrid Control for Energy Economics

When islanded, optimization algorithms make decisions and issue control signals to meet critical loads and to minimize fuel consumption and reduce maintenance and personnel requirements by turning off unneeded generation. Microgrid controllers also manage sources and loads by ensuring uncontrollable renewable resources are used to the maximum extent possible. As the capacity of uncontrollable sources increases relative to the capacity of the islanded load, there is potential for the grid to lose voltage and frequency stability. The microgrid controller must sense this situation and take immediate action to correct the problem and avoid grid collapse.

Optimization algorithms rely on a communication system to provide a real-time picture of the loading condition. Droop control methods alone do not provide for the optimization that is required in modern microgrids.

When grid connected, microgrid controls have the ability to turn on generation sources or shed load from their normal consumption patterns in response to changes in the price of electricity. Incentive payments can come through variable rates in the cost of electricity, through rebates that are offered if the microgrid generates power during certain times of day, or through power factor or volt-ampere reactive (VAR) correction. Additionally the microgrid can participate in grid ancillary services such as Demand Response programs.

INTEGRATING ELECTRIC VEHICLES INTO MICROGRIDS

Electric vehicles bring a unique challenge to microgrids in that there could be a large number of rapidly changing devices due to the electric vehicles being connected and disconnected for mobility purposes. Electric vehicles can be charged, discharged, connected, or disconnected in real time without warning. This large number of devices could make for a complex microgrid control system if the control system is not broken down into manageable pieces.

This management can be accomplished by an aggregator, which is a subsystem control module within the microgrid controller. The main role of the aggregator, as the name indicates, is to aggregate the status of multiple vehicles to provide significant amounts of power capacity for the use by the grid. Consequently, the aggregator must determine how each individual vehicle gets used (in its primary transportation role) and how its charge/discharge management should be controlled to support vehicle use and grid services participation.

Vehicle-to-Grid Services

Vehicle-to-Grid (V2G) is the concept of supporting the electrical grid utilizing the battery storage capability of electric vehicles. V2G is specifically defined as the transfer of energy from the vehicle to the grid. While unidirectional power flow chargers are not true V2G systems they can provide a V2G-like behavior by controlling when a vehicle charges or doesn't charge, thus managing the load imposed by the vehicle on the grid. Bidirectional charging systems have the capability to act in a true V2G manner by actually flowing energy from the vehicle back into the grid. In unidirectional power flows, typical services include demand response, where the demand (load) imposed by vehicles charging is curtailed during peak demand periods of the grid. Frequency regulation is another service where, in a unidirectional system, charging is curtailed or increased when grid frequency deviates beyond a certain set point as dictated by the utility or independent system operator, causing the load to disappear from the grid or creating a load to offset excess generation. Demand charge mitigation, while not a true grid service provides a V2G benefit where load peaks upon which energy pricing is set are analyzed and predicted, and load is reduced in order to reduce those peaks and thus lower the demand charges portion of the energy bill for that defined billing period.

Bidirectional power flows can support these same services but with expanded capabilities. For example, in frequency regulation a unidirectional system can only turn a charger on or off, effectively adding or removing load from the system; but a bi-directional system can push power back onto the grid allowing an electric vehicle to function as a generation resource. Additionally, bidirectional systems can support other V2G services, such as localized load support, providing energy from vehicles back into a local grid or microgrid to power other loads.

DC Fast Charging with Bi-Directional Power

In October 2012, the Society of Automotive Engineers (SAE) published the J1772 standard for Electric Vehicle and Plug in Hybrid Electric Vehicle Conductive Charge Coupler [5]. This standard defined for the first time by SAE the application of Direct Current (DC) Fast Charging for electric vehicles, which opens up a new combination of possibilities for EVs to participate in V2G services.

With DC Fast Charging, vehicles and chargers that meet the SAE standard can now flow power up to 100 kW, far exceeding the Alternating Current (AC) maximum of 19.2 kW. This means that a passenger EV with a 20 kW battery can be charged in 12 minutes vs. 1 hour, or a medium-duty vehicle with an 80 kW battery in 48 minutes vs. 4 hours. This is a five-fold increase in power flow. It should be noted that while 100 kW is the maximum defined in the standard, reality is limited by the size of the converters in the charge station and the capability of the EV battery as defined by its chemistry and controlled by it battery management system (BMS).

DC Fast Charging significantly increases the power footprint of an EV fleet. Consider an EV fleet of ten vehicles, each with an 80 kWh battery. In an AC level 2 system, the power capability of the fleet is 192 kW (19.2 kW x 10 EVs). In a DC Fast Charge system with 60 kW power capability, that same fleet has a power footprint of 600 kW (60 kW * 10). That is three times the power capability the fleet can manage for V2G services. A fleet of 20 vehicles has over 1 MW of power capability, which is enough in most utility markets to represent a generation resource eligible for participation in energy markets.

While impressive for EV charging, the significance of DC Fast Charging is in its ability to support V2G services through bidirectional power flows. With vehicle batteries that can be charged and discharged at high power rates, grid services such as frequency regulation and demand response, as well as localized demand charge mitigation strategies become a viable option for generating additional revenue streams for EV owners, especially fleet owners.

EV Aggregation

EV aggregation is the concept of managing a collection of electric vehicles or charging stations (defined hereafter as the EV fleet) for power purposes. An aggregator is quite simply a control system that sits between an energy command system and the vehicle chargers dispatching energy power flow requests to the EV fleet. It does this by collecting EV status information from each fleet member, such as connection status, state of charge, current real power flow direction and kW, EV current maximum charge and discharge power available and other data. It aggregates this data into a fleet perspective, defining what the fleet energy status is and presents this fleet perspective to the entity supervisory control system. When that control system issues a power request to the aggregator, for example to curtail power usage by 200 kW, the aggregator evaluates that request with the current fleet situation and dispatches individual requests to each EV fleet member to change its power usage. With aggregation, factors such as vehicle use schedules and EV maximum power flows can be utilized to make the best decisions for the fleet while implementing the power request.

For example, consider an EV fleet of ten EVs that is currently absorbing 400 kW with each vehicle charging at 40 kW. A request comes in to curtail power by 200 kW. The aggregator evaluates the state of the EV fleet, determines that five vehicles are scheduled for use in the next hour, while five others are not scheduled for use until tomorrow. The aggregator instructs the five unneeded EVs to stop charging, resulting in a 200 kW curtailment of power usage.

Consider a further example where an additional command is received to curtail all power usage. The five EVs scheduled for use in the next hour still need to be charged. With bidirectional power flows, the aggregator instructs the five EVs that are not charging to discharge 40 kW each, resulting in a net power flow from the grid of 0 kW, while still providing power for the five near-use EVs to continue charging. This is the significance of bidirectional power flows; and, with DC Fast Charging, greater power levels can be utilized.

Another significant capability of bidirectional DC Fast Charging technology is variable charge control. In AC level 1 and most AC level 2 systems, charging is at either full power (as defined by the vehicle charge controller based on minimum and maximum rates established by the BMS) or zero. The parameters for the charging is in the vehicle BMS, where the power draw is based on the maximum power the battery can safely accept based on its state of charge and battery safety factors. The vehicle charge controller does not usually include the intelligence to draw less than BMS-defined maximum power for grid services purposes. In DC Fast Charging, the charging intelligence is in the charger, where variable charge and discharge control can be enabled. Thus, while a vehicle may be able to absorb 40 kW currently, the charger can send less power. The aggregator uses this information in its decision making. For example, consider an EV at zero state of charge with a maximum power flow capability of 40 kW and an 80 kWh battery. At maximum power flow, it would take slightly less than two hours to charge the battery to 80%+ SOC. The aggregator in its analysis sees that this vehicle is not scheduled for use again for four hours, so instead of charging the vehicle at maximum power, it instructs the charger to charge at 20 kW as a part of its power balancing equation. This frees up 20 kW that can be used elsewhere in the fleet while ensuring the EV is fully charged at its next scheduled use time. This flexibility in power management adds complexity to the aggregator decision-making process but adds significant capability in supporting V2G services.

Balancing Microgrid Control with EV Aggregation

The aggregator behaves as a single controllable point for the microgrid controller, which relies on the aggregator for tracking individual vehicles and their usages. This allows for the optimization of the microgrid as a whole without the microgrid getting bogged down with the potentially large number of vehicles that could be added or subtracted from the whole.

The aggregator relies on the microgrid controller to provide the network backbone and communication of data with other devices. Additionally, the microgrid controller has the responsibility for transferring any utility generated signal. Either the Aggregator or the microgrid controller can provide the user interface for status and policy input. Policy input could be direction for how equipment might operate in a contingency condition or for users to input when vehicles are expected to be used or needed to be fully charged.

REDUNDANCY AND RELIABILITY

A key feature of a microgrid is its ability to seamlessly isolate from the utility and provide reliable power with little or no disruption to loads within the microgrid. When the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid in an equally seamless fashion.

The microgrid must be as reliable as the utility grid and capable of operating as a self-controlled entity. A distributed control system with peer-to-peer architecture insures no single component, such as a master controller or a central storage unit, is required for operation of the microgrid. With a peer-to-peer architecture, a microgrid can continue operating with the loss of an individual component or generator. With an additional power source, it can insure even higher levels of reliability.

A plug-and-play capability means that components can be placed at any point within the microgrid without expensive re-engineering of its controls. A microgrid should offer these functionalities at much lower costs than traditional approaches by incorporating peer-to-peer and plug-and-play concepts for each component within the microgrid. This is in sharp contrast to the traditional model, which groups assets at a single point in order to make the electrical integration tasks simpler.

A peer-to-peer distributed controls architecture is capable of taking existing, disparate power sources and loads and integrating them into an intelligent, power-sharing micro-grid with decentralized decision-making to manage and optimize system power. Such an approach is more robust to grid failure than a single master controller and can distribute decision-making. In all cases, any optimizing controller should be designed for a fail-safe mode in the event of communication or equipment failure.

SECURITY IN MICROGRID CONTROL

Press reports of cyber-attacks on power grids and critical infrastructure are rampant. On May 16, 2013, the Department of Homeland Security testified that, in 2012, it had processed 68% more cyber-incidents involving Federal agencies, critical infrastructure, and other select industrial entities than in 2011 [6]. Although there has been no record of a cyber-attack bringing down a U.S. power grid, the increased cyber trend cannot be ignored [7]. Furthermore, a microgrid must be inherently more secure than the utility grid, making a security strategy of utmost importance.

To minimize cost and reduce the human interaction, microgrid operations and control systems need to be increasingly automated, with two-way communications to the Internet or other computer networks. The approach to cyber security is to leverage an internal risk management/configuration management methodology to internally cross-check the process, products, and documents provided by the design and with procured equipment. At a minimum, the best cyber security practices, guidelines, and checklists need to reflect appropriate consideration of Information Assurance Controls such as DIACAP and NISTIR 7628 [8][9]. Subsequently, Security Best Business Practices (BBPs) for network control systems must be identified to ensure that Security Technical Implementation Guidance (STIG) and Checklists must be understood and implemented.

ISA/IEC-62443 is a series of standards, technical reports, and related information that define procedures for implementing electronically secure Industrial Automation and Control Systems (IACS) [10]. This guidance applies to end-users (i.e., asset owner), system integrators, security practitioners, and control systems manufacturers responsible for manufacturing, designing, implementing, or managing industrial automation and control systems.

Electric vehicles potentially pose a security risk to microgrids since each vehicle has the ability to connect and transmit data to the microgrid. System security architectures must ensure proper techniques exist to verify that vehicles are authorized to be on the grid.

SUMMARY

Electric vehicles have the potential to help our nation become less dependent on imported fossil fuels. By "fueling" from the utility grids, such vehicles help diversify the transportation energy base and can provide economic incentives to owners through grid services offerings. V2G, however, still has a ways to go. Most EVs sold today are not equipped to feed power back into the grid, and most grids are not equipped to accept it, let alone pay car owners for it.

Technical and human factors issues are being addressed in pressing ahead with bidirectional vehicles used for transportation and grid support. It is estimated that an EV is parked 95 percent of the time. V2G would allow the parked EV to charge and discharge its battery to the grid in response to requests from an entity such as a grid system operator. However, if the battery has recently been discharged when it is needed for transportation, there could be an understandable concern for user adoption.

Several ongoing research projects are intended to advance V2G technologies. The Department of Energy (DoE), in collaboration with the DoD, is researching a combination of EV and microgrid technologies. Programs such as the Smart Power Infrastructure Demonstration for Energy Reliability and Security (SPIDERS) are developing mechanisms for installations to ensure secure, reliable power utilizing renewable resources and electric vehicles to provide energy surety. The DoD PEV-V2G program is focused on expanding electric vehicle use at multiple bases in the mainland U.S. and Hawaii.

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