Energy Research and Development Division
FINAL PROJECT REPORT

DISTRIBUTION SYSTEM VOLTAGE MANAGEMENT AND OPTIMIZATION FOR INTEGRATION OF RENEWABLES AND ELECTRIC VEHICLES

Research Gap Analysis

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Prepared by: California Institute for Energy and Environment

PREPARED BY:

Primary Author(s):
Larry Miller
Lloyd Cibulka
Merwin Brown
Alexandra von Meier
Reza Arghandeh

California Institute for Energy and Environment
University of California
2087 Addison Street
Berkeley, CA 94704
510-643-1440
http://uc-ciee.org

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Prepared for:

California Energy Commission

Consuelo Sichon
Contract Manager

Fernando Piña
Office Manager
Energy Systems Integration Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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PREFACE

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ABSTRACT

California is striving to achieve 33% renewable penetration by 2020 in accordance with the state's Renewable Portfolio Standard (RPS). The behavior of renewable resources and electric vehicles in distribution systems is creating constraints on the penetration of these resources into the distribution system. One such constraint is the ability of present-day voltage management methodologies to maintain proper distribution system voltage profiles in the face of higher penetrations of PV and electric vehicle technologies. This white paper describes the research gaps that have been identified in current Volt/VAR Optimization and Control (VVOC) technologies, the emerging technologies which are becoming available for use in VVOC, and the research gaps which exist and must be overcome in order to realize the full promise of these emerging technologies. This white paper is intended to provide information that will help target future solicitations for research toward applications that will help California better reach its renewable energy goals.

Keywords: California Energy Commission, distribution, distribution automation, renewable energy, RPS, Renewable Portfolio Standard, solar generation, photovoltaic generation, electric vehicles, renewable penetration, Volt/VAR Control, voltage optimization.

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TABLE OF CONTENTS

LIST OF FIGURES

INTRODUCTION

Purpose of Report

The purpose of this White Paper is to assist the California Energy Commission in developing potential research projects addressing distribution system Volt/VAR optimization and control (VVOC) that incorporate impacts from high penetrations of renewables and electric vehicles. California utilities currently use various techniques to maintain end user voltage levels, which are not well suited to handle high levels of generation such as PV, or new customer loads such as plug-in electric vehicles (PEVs), that are starting to proliferate on distribution systems. The stakeholders on the Energy Commission's Technical Advisory Committee (TAC) recommended that a comprehensive review of the capabilities and research needs on this topic be considered a high priority.[1]

This report is a white paper on the research gaps that limit maximum penetrations into distribution systems by renewable resources and electric vehicles. Gaps exist in both current and emerging technologies for VVOC. The report also discusses the new functionalities of advanced technologies that can be used to assist in VVOC.

Historical Perspective

The electric utility industry is undergoing radical change. The historical division of the electric grid into generation, transmission, and distribution is breaking down as distribution level generation becomes more prevalent. In California, climate change and the resulting mandates for carbon-free renewable energy sources have created a chain of market and policy forces which are imposing new requirements at all levels, but especially at the distribution level. Distributed renewable generation has created new challenges for a distribution system in which voltage control has been largely based on a simple premise – that voltage drops as one moves farther from the substation transformer. As renewable penetration increases, this simple premise becomes an increasingly poor assumption.

Unfortunately, distributed renewables aren’t simply a substitution of one fuel source for another. Wind and solar power are both variable and intermittent. They are not dispatchable and are largely beyond the control of utilities. For public policy reasons, these new resources are in the category of “must take” power, so managing the distribution system requires accommodating the unique features and issues created by extensive distributed renewable energy.

At the utility scale, the drive to reduce the carbon footprint of electric energy is leading to wind and solar farms in areas where the natural resources are plentiful, but not necessarily where power is needed or where transmission capacity is available. Siting difficulties and significantly increased costs have led to an increased emphasis on conservation, demand response, and the

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[1] A series of five TAC meetings were held by CIEE to provide status on research activities and to reassess research needs and priorities, the most recent held in June 2012 at Folsom, CA.

coordination with non-utility resources to both minimize capital costs and delay the need for new infrastructure. Conservation and demand response as alternatives to expanding infrastructure have become marketable commodities. These largely occur at the distribution level and are controlled by end-use customers or third parties, and so the process of influencing customers to conserve, participate in demand response, or cooperatively operate renewable resources has become a part of overall distribution system management and an element in accommodating renewables.

In similar fashion, the advent of plug-in electric vehicles (PEVs) is another significant concern for management of distribution voltage. An electric vehicle can require 10, 20, or even more kilowatt-hours to recharge. A typical Level 2 charger can draw 30 amperes at 240 Volts, or over 7 kilowatts (kW) of instantaneous demand. Recharging a vehicle can easily consume more power than the typical electric load of an average house, radically changing historic load patterns and potentially creating significant issues if not managed properly. Again, since PEVs are customer owned, management of charging regimes or operating a Vehicle-to-Grid (V2G) system will require utilities to obtain more active cooperation from end-use customers as a part of distribution management.

The accommodation of renewable resources and PEVs is imposing new requirements on the distribution grid and these new requirements are difficult or impossible to meet without the addition of new technologies. New technologies include those such as storage which can directly mitigate variability and intermittency of renewable resources. They also include demand reduction and other types of customer interaction. These technologies typically require both communications systems and centralized computer control. Arguably, one premise of the Smart Grid is that new digital technologies will provide the answers to the problems of accommodating renewable resources.

This paper is a study of the research gaps which limit the methods that are currently being used, are planned, and are potentially possible in the next several years for the control and optimization of voltage in distribution systems. Particular emphasis is on the changes that are or will be happening as a result of the increasing penetration of renewable resources and PEVs.

Current Volt/VAR Systems

Systems currently in use by California Investor Owned Utilities (IOUs) are based on local control of devices or centralized control based on measurements at the device. Three types of devices form the infrastructure – load tap changers (LTCs), capacitor banks, and voltage regulators. LTCs are located at substations and set the substation voltage, often based on time and/or load current at the substation. Capacitor banks can be either switched or fixed. Switch controls are commonly based only on time of day, although they normally include a voltage override function which will switch the bank off if the voltage exceeds an upper threshold or turn on a bank when the voltage drops below a lower threshold. Voltage regulators are less common and generally applied to special situations as needed.

More advanced commercial systems are available. While such systems generally utilize the same devices (LTCs, capacitor banks, and voltage regulators), several are based on system models (mathematical representations of system components such as conductor segments, transformers, switches, etc.) and utilize information from sensors to optimize performance across a feeder. Other types exist, such as Utilidata's Adaptivolt, which does not use a system model, but depends on analysis of real-time information from a small number of sensors and proprietary algorithms to manage and optimize the voltage. None of the commercial offerings appear to be able to systematically incorporate large penetrations of distributed generation into the voltage control system.

Advanced Technologies

The advent of significant amounts of distributed generation (DG) along with the introduction of PEVs has been a driving force for a number of advanced technologies which are becoming available for use in distribution management. These technologies can help mitigate the impacts of variable DG which include not only voltage control but other issues such as fault location and reverse power flow.

One of the most promising of the advanced technologies is the use of advanced inverters which are capable of being set to operate at any desired phase angle between voltage and current and thus source or sink reactive power. Under current restrictions set by IEEE 1547, active voltage control by inverters is not permitted, but this and other restrictions on inverters are widely expected to be altered in the near future. With appropriate control methodologies, the use of advanced inverters can potentially play a major role in raising the tolerance of distribution systems to higher penetrations of DG. One of the advantages of this technology is that the hardware for control (although not necessarily any required communication system) is already likely to be resident in the DG itself.

Energy storage is another advanced technology capable of mitigating distribution issues. At the distribution level, batteries are the primary technology for energy storage. While battery systems are not new, their cost has limited them to demonstration projects and a few specialized applications. A recent decision by the California Public Utilities Commission (CPUC) to set targets for storage procurement by California IOUs is likely to stimulate increased use of distribution level storage. In the longer term, the availability of second-use PEV batteries may result in a significant reduction in the cost of storage systems.

PEVs offer both issues to be addressed and potential responses to the high cost problem with battery storage. The need to recharge the batteries in PEVs can seriously exacerbate peak loading issues if a typical PEV owner simply recharges the battery upon arriving home in the late afternoon, when many utilities experience peak loading. On the other hand, recharging during the low loading periods at night may, in fact, ease a problem of excess power generation due to substantial nighttime wind power generation. It is clear that management of charging time for PEVs will be of major interest to utilities. Finally, V2G storage offers the potential of a large amount of storage capacity by using some of the idle capacity of PEV batteries.

Solid-state power flow control is an emerging technology which offers a potential evolution in the way electricity is controlled on the grid. Our current grid system does not control the flow of power. Current flows over whatever paths from generators to loads have the lowest impedance. The development of distributed flexible AC transmission systems (D-FACTS) offers the potential of altering current flow in a system. One form of D-FACTS is the distributed static series compensator (DSSC), which typically comprises a number of devices that clamp onto a line and controllably alter the capacitance or reactance of the line, thereby affecting the voltage and power transfer on that line.

Emerging VVOC systems

While systems currently in use by California utilities are largely based on local control of devices with minimal communications, much more sophisticated automatic VVOC systems are already commercially available and generally form a subset of more comprehensive Distribution Management Systems (DMS). As a result, "emerging VVOC systems" are more likely to be "emerging advancements" to existing commercial systems. Thus, the authors expect that the VVOC systems of the future will be similar to the model-based centralized systems that are currently available but with the addition of capabilities to effectively incorporate the advanced technologies previously discussed.

High penetrations of renewable generation and increasing numbers of PEVs are expected to raise challenges to distribution management in multiple areas, not just VVOC. One obvious way that VVOC systems may directly benefit from the use of advanced technologies is through the use of inverter capabilities to source and sink VARs. Other technologies may be added to distribution systems for reasons other than voltage control and will represent technologies whose impact must be considered by VVOC systems rather than additional "handles" to control voltage. Local control of individual devices is expected to become increasingly inadequate as DG penetrations increase and other advanced technologies are added to the distribution system.

Distributed storage is one example. The recent CPUC decision to mandate 1,325 megawatts (MW) of storage by 2020 is expected to drive the wider use of storage, some of which will be at the distribution level. Selected locations will almost certainly be those feeders with higher penetrations of DG. Due to the relatively high cost of storage, effective control algorithms are expected to target multiple applications and to prioritize those applications based on perceived value at any point in time. Thus a VVOC system may be confronted with the need to seamlessly and effectively operate even as a storage unit switches from being a source to a sink.

PEVs are another example. On feeders where concentrations are significant, utilities will be highly motivated to convince as many PEV owners as possible to allow the utility to influence charging schedules. Line loading will change dramatically from historical norms and heuristic VVOC systems are likely to be increasingly inadequate to meet the need.

A critical issue underlying the whole concept of successful VVOC methodologies is distribution system model validation. Successful VVOC algorithms will only be as accurate as the accuracy of the system models embedded in the software; so, for example, if the impedances of the line segments in a given feeder are not correct, the VVOC will not be able to maintain the desired voltage profile on that feeder. The issue of model validation is universal; it is essential to the success of all other distribution system operating and planning methodologies that are envisioned for the distribution system of the future.

RESEARCH GAPS FOR EXISTING SYSTEMS

Existing systems are based on the use of capacitor banks, LTCs, and VRs. In California, these devices are essentially locally controlled. Even though SCE controls capacitor banks from a central controller, control is based on local data, not a model or a larger view. For purposes of this paper, "existing systems" are those where devices are largely locally rather than centrally controlled and are primarily time based on load schedules derived from historical data. The research gaps are those that are needed to be filled to increase the levels of renewable penetration of these locally controlled systems.

Simulation and Demonstration of Locally Controlled Systems with Added Inverter VAR Control

Active VAR control by inverters used in DG systems is currently disallowed by IEEE 1547, but this is expected to change in the near future. As DG penetrations increase on a feeder, the use of the inverters in these systems is likely to be the most cost effective and quickest means of continuing to manage voltage without installing a new stand-alone VVOC system.

EPRI has an ongoing project to develop and refine a list of possible control functions for advanced inverters that can source and sink VARs (Ref: EPRI). Several of these functions are applicable to local sensing and control. Still needed, however, are simulation of the impact on an entire feeder and proof-of-concept demonstrations. In particular, active voltage control has been prohibited by inverters due to a variety of concerns about the impact on other portions of the feeder. There is little actual experience on these effects and, in particular, the effect of several DG systems, each with active control of VARs based on local sensing. One possibility, for example, is an unstable system due to multiple inverters each attempting to counteract the change caused by another.

Due to the large variation in the characteristics of different feeders, a variety of feeder types with significant DG penetration would need to be evaluated. An additional challenge is created since many of the currently installed DG systems are not utility owned and thus not under utility control. Absent any requirements for cooperation in the original installation, arrangements with owners will require additional agreements and most likely compensation in some form.

Objectives of research to fill this gap should be to demonstrate algorithms that can be successfully used to assist in local feeder voltage control. In addition, simulation efforts should attempt to quantify what potential improvement in DG penetration capacity, if any, results from the addition of local inverter VAR control.

PEV Charge Management Strategies

PEVs have been only been available from major automotive manufacturers in the past two years and currently compose a miniscule part of the California vehicle fleet. However, as shown in Figure 1, California PEV sales over the next 10 years will account for more PEVs than the next 5 states put together, and the California PEV fleet is variously forecast to be from a few hundred thousand to nearly 1 million vehicles by 2020. The state has set a goal of 1.5 million by 2025.

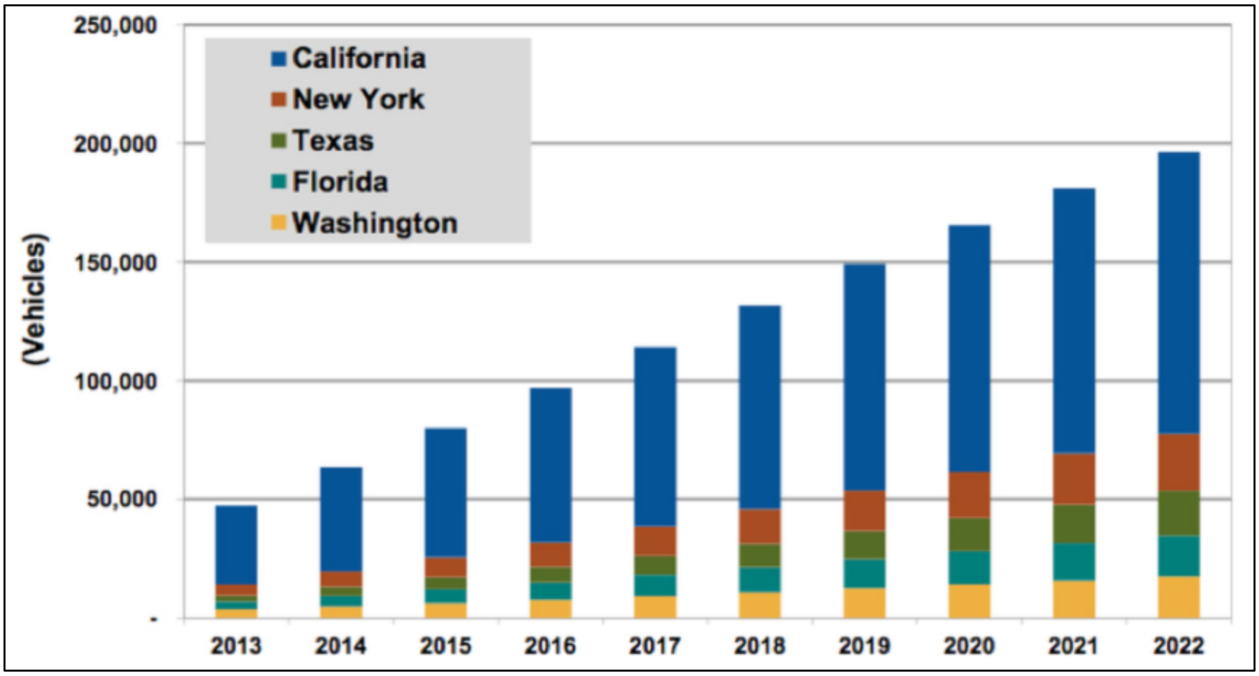

Figure 1: Electric Vehicle Sales Forecast
Source: Navigant Research

Level 2 chargers are likely to dominate residential charging; they operate at 240 V and can draw 7 kW or more, so that each vehicle can easily be the equivalent of an entire household load. In a worst-case scenario, the charging of these vehicles can substantially increase peak loads in the late afternoon or early evening. Conversely, in the best-case scenario, much of the load will occur at night during minimum load conditions and could help absorb potential excess generation from must-take providers. Utilities are highly motivated to be able to influence and potentially control the timing of vehicle charging.

Lacking incentives to do otherwise, vehicle owners are most likely to simply plug in their vehicle immediately after a drive whenever a charger is available. Most charging will occur at home upon returning from work. Various strategies have been proposed to provide incentives for customers to charge during off peak times or to allow utilities to control charging in real time, but little real world experience has been gathered about the effectiveness of different strategies to motivate customers. Studies are needed to determine the types and magnitude of incentives for owners to alter their charging behavior.

Not all PEVs will be charged during low peak loading periods. California utilities have implemented demand response programs for air conditioners whereby customers allow the utility to turn off the system or raise the thermostat during hot days. A similar program is desirable to shave peak loading by slowing the charging of PEVs during peak periods. Several questions must be answered in order to implement such a program. These include such things as how to physically control chargers, what are cost effective communication strategies, and how to allow customers to override.

Finally, small-scale demonstrations on feeders where clusters of early adopters exist will be needed. Such demonstrations should demonstrate not only the technical soundness of charge management strategies but also the effectiveness of incentives aimed at influencing vehicle owner behavior. The ability to influence owner behavior may well be the dominant factor in the success of a utility's charging strategy, more than the technical performance of the algorithms and infrastructure.

Impact of High Penetration of Residential PV

The technical limit for maximum penetration of DG on a particular distribution feeder depends strongly on both the precise nature of the feeder and the location of the DG. For large commercial installations, a specific study is often done to determine the impact of that installation on voltage control and other important functions of the feeder. For smaller installations, specific studies may be impractical and less labor-intensive approaches are used to determine viability. Often, rules of thumb (e.g., 15% of peak loading on a feeder) are used as guidance, even though one size definitely does not fit all. For medium and large installations, utilities have a degree of control either through actual ownership or through the interconnection process which allows them to mitigate possible voltage impacts through location selection or the use of voltage or power factor control by the DG system.

In contrast, residential PV systems are not under utility control or influence in any significant way. The systems are owned by end-use customers or third parties operating the systems for profit, are individually very small but may collectively be significant, and are likely to be geographically distributed throughout all or part of a feeder. The use of power factor or voltage control is impractical, as these small systems will most often use inverters without such capabilities.

Costs of residential systems have dropped to the point where 100% financing can be less costly than the retail value of the energy produced. With currently available incentives, many homeowners can now install a system for no cash outlay and then produce a net savings since finance payments will average less than the reduction in the electric bill. Companies have determined that there is a viable business in financing, installing, and maintaining systems thereby dramatically simplifying the process and reducing the risks for homeowners. As a result, residential installations may come to dominate many distribution feeders, at least in areas where conditions are favorable.

The DG penetration of a distribution feeder is typically defined as the ratio of DG rated power to the annual peak loading expressed as a percent. As penetration increases, voltage profiles will change and, at some point, exceed the ability of the system to maintain the desired voltage range. Alternatively, electromechanical devices may increase their average rate of cycling and thereby decrease life or maintenance intervals. Stochastic simulation studies are needed to determine the penetration limits of randomly placed residential PV systems on prototype feeders that can collectively represent the bulk of California distribution feeders.

Since California is strongly supporting the expansion of PV systems, it is unlikely that utilities will be allowed to prevent the continued installation of systems once a theoretical (or real) limit has been reached. Instead, utilities are likely to be required to upgrade capabilities to handle increased penetration. Stochastic penetration studies are expected to aid utility planners by predicting when feeders are likely to require upgrades based on forecasted growth of PV installations.

Filling the Existing Systems Research Gaps

The currently installed VVOC systems in California utilities have limited capability to manage and optimize voltage control in the presence of significant levels of DG. In particular, they are limited in their ability to respond to voltage increases and to rapid changes in the output of DG. Filling the research gaps described in this chapter would be aimed at a common objective, namely to improve the capacity to handle increased penetration of DG without the need to completely change the approach and incur the additional associated expense. With the added capabilities that would be provided, the existing locally controlled systems could be expected to continue to function adequately for some additional years, delaying the need for major changes.

ADVANCED EQUIPMENT FUNCTIONALITIES

Inverter Based DG

One of the most promising technologies for VVOC in high renewable penetration feeders is the use of inverters to generate (source) or absorb (sink) VARs. Virtually all generation installed at the distribution level utilizes an inverter to interface with the grid. Modern inverters, especially larger ones found in commercial and industrial installations, are capable of generating currents at any desired phase with respect to the grid voltage subject to their maximum Volt-Ampere (VA) limits. If the inverter has a maximum rating greater than the real power being generated, the inverter has available capacity to provide VAR support. The amount of VAR support can be considerable, even when the real power output is fairly near the inverter limit.

Inverters, like most generators, can produce both watts and VARs, but the tradeoff between these quantities is defined by the equation $P^2 + Q^2 = S^2$, where S = rated output. The chart in Figure 2 shows the VAR capability of a typical inverter as a function of its real power output, expressed as a percentage of the rated output, based on this relationship.

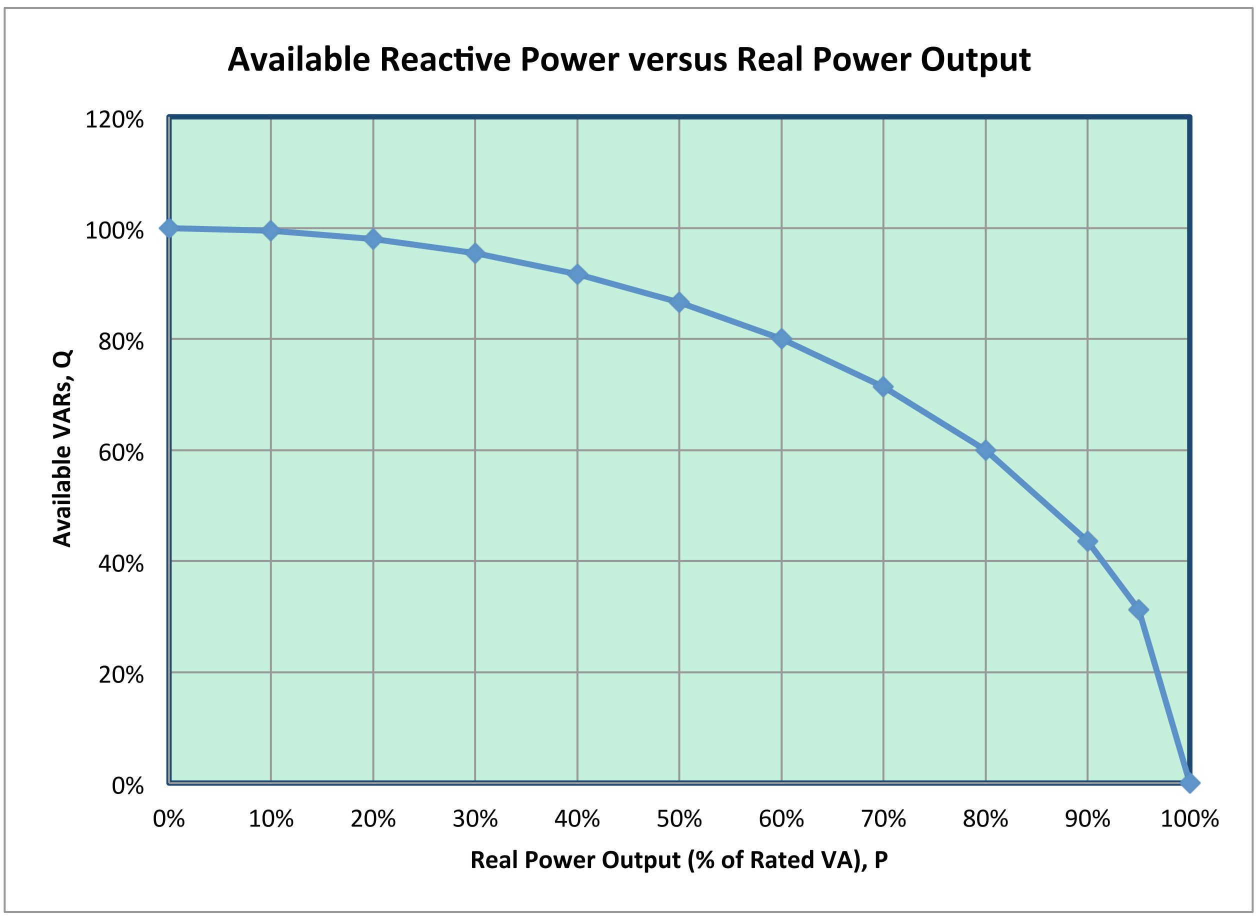

Figure 2: VAR Capability of a Typical Inverter

The obvious advantage of this functionality is that the more DG penetration on a feeder, the more devices there will be to help manage the voltage. This functionality is potentially available regardless of whether the voltage system is locally or centrally controlled. Unlike capacitor banks or regulators, there is no additional direct hardware cost for the devices, although there may be costs associated with communications, software, or incentives to the DG owners.

While the functionality may exist, its use to date has been very limited due to the restrictions of IEEE Standard 1547 (Ref: IEEE), which prohibits active voltage control. Allowed uses include the setting of a fixed power factor other than unity, but not varying the VAR output as a function of voltage. However, changes to IEEE 1547 are under consideration and active voltage control is widely expected to be allowed in the near future.

A number of approaches to active control by inverters have been proposed by EPRI (Ref: EPRI) and others. With appropriate sensors, an inverter can provide inductive or capacitive support as a function of voltage, current, power, frequency, or even rate of change of any of these parameters. In fact, the use of inverters dynamically based on rate of change of voltage is one of the possible functionalities defined by EPRI. While there are many ways to utilize this functionality of inverters, there is little data on real world experience and possible unintended consequences of operating a system with multiple inverters exercising active voltage control.

Storage

Energy storage is not an emerging technology in the sense that, in various forms, it has been used for decades on the grid. In recent years, however, the advent of variable and intermittent generation has triggered a resurgence of interest since sufficient storage could solve virtually all the issues created by wind and solar variability. Unfortunately, the cost of storage will likely preclude there ever being "sufficient" installed storage capacity to mitigate all renewables issues.

The CPUC has recently set targets for California IOUs to procure minimum amounts of storage. While minimum storage targets are mandated, cost will continue to be a major consideration and maximizing the economic value of the storage via multiple revenue streams from different applications will become a routine part of the planning process. Common distribution applications will include load leveling, renewable power stabilization, power arbitrage, and possibly transmission ancillary services, to name a few.

At the distribution level, storage technology is expected to be heavily dominated by battery systems. Battery storage can be located virtually anywhere, systems are easily scaled, and transportable systems can be placed where the need is greatest and relocated as conditions change. Typical systems will provide 2 to 4 hours of storage at rated power.

Historically, sodium sulfur (NaS) and lead acid technologies have dominated utility battery storage systems. More recently, several flow battery technologies have been demonstrated and utilized in demonstration projects. Most recently, lithium technologies have become more prevalent due to higher energy densities and the production scaling up of the new technologies. Higher energy densities reduce the required footprint for any given amount of storage, an especially important advantage for transportable systems. As electric vehicle sales increase and the vehicle fleet ages, two factors are expected to exert downward pressure on future battery storage costs. First, the volume production of lithium batteries for electric vehicle use is expected to drive down the cost per kilowatt-hour. Then, as vehicle batteries are replaced, the used batteries are expected to retain up to 80% of their original capacity and represent a potential second use application as utility energy storage at substantially lower cost. As a result, the authors expect that lithium batteries will become the battery technology of choice, especially at the distribution level.

Power Flow Control

Distribution lines are evolving from purely radial systems to more interconnected ones. Networking offers many advantages, not least of which are alternate paths to restore power to customers in the event of an outage. One consequence of this is that the power flowing in each line in a networked system depends on a variety of factors. Voltage control in such a system is more complex than in a radial system. The addition of significant penetrations of DG to networked feeders has added still more complexity and, in many situations, power flow control offers solutions to voltage control problems.

Solid-state devices that provide control of power flow on transmission lines have been available for about twenty years. These devices, known as Flexible AC Transmission Systems (FACTS), are well established technically, but are expensive and their use has been somewhat limited. More recently, smaller, lighter, and less expensive devices have become available for use in distribution systems. These distributed FACTS ("D-FACTS") devices are series power flow control devices that change the effective impedance of transmission lines and thereby change the current flow. Rather than requiring a building, these series devices can be clamped around a power line and add either inductive or capacitive series reactance to a line. Wireless communications allow for coordinated central control.

Unlike passive systems such as capacitor banks, D-FACTS utilize active impedance injection. This is advantageous because it avoids the problem of subsynchronous resonance (SSR), which lines using capacitors for series compensation face. SSR is a low frequency transient created when the system reactance and the line capacitance establish a resonant circuit.

D-FACTS are particularly useful when large amounts of DG are present because they can rapidly change the amount and/or polarity of reactive support. Thus they can help compensate for rapid changes in DG output. Unlike capacitors, they can also operate to reduce voltages when DG power threatens to increase voltages beyond allowable limits under light loading conditions.

Vehicle-to-Grid (V2G)

The concept of "borrowing" and aggregating of batteries in customer-owned PEVs for purposes of providing services to the grid is called Vehicle-to-Grid (V2G). This concept is based on the idea that, at any point in time, there will be PEVs which are not in use and whose owners will be willing to allow their vehicle's battery to be used to assist operation of the electric grid.

Assistance can be of several types, each having a different impact on the battery and representing a different economic value. Peak shifting is often seen as a primary function of V2G where charged batteries are discharged during times of peak demand. In this application, available batteries are regularly asked to supply some percentage of capacity to provide additional power to the grid. The limitation is that battery life will be degraded to some degree, depending on the frequency and depth of the discharges. By contrast, use as a spinning reserve or for up/down frequency regulation will have much less, likely negligible, impact on battery life.

V2G requires that cooperating owners leave their vehicles plugged in when not in use. Charge systems must operate bi-directionally, i.e., they must be able to draw power from the battery and inject it synchronously into the grid, and also draw power from the grid to charge the battery, as needed. The charger must have two-way communications with the aggregator. The aggregator must have information about which batteries are available, the state of charge of each battery, and the amount of charge able to be drawn from each battery. A likely necessary condition is that the vehicle owner must be able to override the system on demand if the vehicle will be required for transportation purposes.

At this stage of development of the PEV market, V2G is a technology under evaluation. At least one California company, Nuvve, is operating a small-scale test of the technology with about 30 vehicles in Denmark (Ref: Wesoff). Bidirectional chargers are commercially available. The low-hanging fruit for the technology are the ancillary services applications that are expected to have a negligible impact on battery life. These applications are expected to encounter minimal customer or manufacturer resistance.

One of the major uncertainties about the technology is whether sufficient useful energy can be obtained from a fleet of PEVs to provide meaningful bulk power in applications such as mitigating variability of renewable sources or peak load shifting. Applications of this nature will typically utilize a higher percentage of battery capacity than ancillary services applications, and hence will have a larger impact on battery life. While this can be mitigated by limiting the maximum energy removed from a battery, it implies that more PEVs must participate for any given amount of bulk energy available. If, for example, extraction of energy from any battery is limited to 10% of a battery’s capacity, then the participating fleet of PEV batteries must contain 10 times the energy available for peak shifting. A limitation to 5% of battery capacity would double that requirement to 20 times the peak energy shifted.

RESEARCH GAPS FOR EMERGING SYSTEMS

Business Case for Automated Volt/VAR Control

The concept of an integrated and centralized VVOC system has clear advantages over localized collections of independent devices. However, utilities do not base decisions solely on qualitative advantages. As businesses that normally fund capital improvements through rate cases with the appropriate regulatory agency, they will typically use some form of cost/benefit analysis to determine the best way to meet a particular need. This is especially true when the benefits do not necessarily accrue to the same stakeholder as the costs, or when the benefits may be non-economic (not easily quantified in dollars and cents). In the case of VVOC, the transition from locally controlled devices to a centralized system will typically require incurring significant communications and other infrastructure costs. A major research gap is the lack of clear understanding of the costs and benefits of a VVOC system, who must pay the costs, and to whom the benefits will accrue. Not only must this be clear to the utilities, they must also be able to demonstrate in an objective fashion to the CPUC why the cost is justified.

This is very similar to the situation which occurred in the transmission area with Phasor Measurement Units (PMUs). The value of PMUs was clear, at least for some applications such as post-event analysis. Less clear were other potential benefits and how costs could be justified. A major step forward was taken with the completion of the Energy Commission-funded study known as the "PMU Business Case" (Ref: Novosel, et al.), which helped lay the foundation for developing the applications, values, and costs of PMUs in a straightforward fashion that could be easily understood and, arguably, was a major stimulation to the widespread incorporation of PMU measurements in the electric industry. There are clear advantages to a centralized, automated VVOC system, but there are also significant costs, and there are alternative approaches which may not have the same functionality but are less expensive. The fact that no California IOU has widely implemented the available model-based VVOC systems is strong evidence that the economics of such a system is not obvious to stakeholders. While there appears to be a general assumption that these systems represent the future of voltage control, there is no assurance that implementation will occur at a pace sufficient to meet California's needs for the increasing penetration of DG. A strong business case analysis for VVOC could speed the implementation of distribution control systems which could support significantly higher levels of DG penetration than the current approach.

Field Demonstrations of Active Inverter Voltage Support

A number of advanced inverter functions have been defined by leading researchers and technology developers, such as EPRI. Several of these functions are intended to generate leading or lagging VARs in response to selected locally-sensed conditions such as voltage, power, or even frequency. Sandia Laboratories has undertaken a series of laboratory tests to evaluate the functionality and interoperability of several of these functions (Ref: Gonzalez et al.). Testing to date has focused on the communications aspects of the functions and has demonstrated that, for the functions tested so far, the inverters operate as desired when evaluated using a grid simulator in place of a real-world grid. While such tests can verify that advanced inverters do provide the functions that have been implemented, the testing does not necessarily demonstrate that the functions will actually operate as intended in a real-world environment as a part of a much larger system.

The use of inverters to provide active VAR control in response to various sensed conditions represents a new paradigm for voltage control. Active controls are widely used in transmission systems, notably Power System Stabilizer (PSS) systems installed on large generators. Experience has shown that such active systems can display unexpected behaviors, particularly when multiple systems interact. Wide-area low-frequency oscillations are a classic example of undesired interactions of active systems. In general, virtually any complex system with internal feedback loops may exhibit various types of oscillations under the right conditions.

The use of inverters in DG systems is expected to be of significant value in mitigating the impacts of high penetration of renewables, and thus allowing higher penetration levels. It is therefore likely that distribution lines containing multiple large DG systems will be prime targets for this capability. Such capabilities need to be demonstrated in a field environment.

A first step would be a field demonstration of a single DG system to evaluate the effectiveness and limitations of Volt/VAR control by an inverter. One obvious limitation is that the maximum rating of the inverter cannot be exceeded. Thus, when a DG system output is near its maximum real power limit, the reactive power available will be limited unless real power output is curtailed or the inverter has excess capability beyond that supplied by the PV cells or wind turbine.

A more difficult but potentially more important demonstration is one in which multiple DG systems on the same feeder are all utilized for Volt/VAR control. In addition to validating the concept, a major objective would be to exercise the system under a variety of conditions to determine if there are, in fact, any unanticipated consequences.

V2G Battery Studies

As previously discussed, some applications for V2G, e.g., spinning reserves, are unlikely to impact battery life or to significantly inconvenience owners even occasionally. For other applications such as peak shifting, the "make-or-break" issue is likely to be whether a sufficient number of PEV owners can be persuaded to allow their very expensive car batteries to be utilized for the benefit of the grid. While various incentives can be imagined to encourage consumers, the key concern is likely to revolve around the degree to which participation in V2G shortens the useful life of the battery. Perhaps an even more important consideration than the PEV owner is the PEV manufacturer who must warrant the battery. If manufacturers are not convinced that V2G will not increase warranty costs, they may restrict warranty coverage on batteries used for V2G. While EV manufacturers typically warrant their batteries for 100,000 miles, that is for "defects in materials or workmanship," not loss of capacity. Nissan offers a 5 year, 60,000 mile warranty on the capacity of their Leaf battery remaining above 9 bars (~70%) on its capacity gauge. More recently, Nissan has offered a replacement guarantee based on 9 bars minimum guarantee "forever" for a fixed monthly cost, currently $100.

Studies are needed to determine the impact on battery life when additional discharge cycles are superimposed on real-world driving patterns, with the objective of determining the impact on life as a function of depth of discharge of the additional cycles. Such information will be necessary to convince both manufacturers and vehicle owners they will not be negatively impacted by such a V2G application, and/or to assist in the design of policies to facilitate or limit applications for V2G.

Filling the Emerging Systems Research Gaps

The emerging systems for VVOC which incorporate centrally-controlled, model-based systems or other advanced forms of central control are likely to be required at some future level of DG penetration. While such systems are currently commercially available, California utilities are unlikely to make the transition until either forced to for technical reasons or because there are good business justifications to do so. Filling the research gaps discussed in this chapter would be aimed at speeding this process by providing economic justification or reducing technical barriers.

CONCLUSIONS

This research paper discussed the research gaps that collectively limit the ability of VVOC systems to handle high penetrations of renewable energy and electric vehicles. Gaps were enumerated both for systems currently in use and for newer emerging systems that have yet to become part of the mainstream in California. The major emerging technolgies that will enable more advanced VVOC systems were also reviewed. A more detailed discussion of the technologies themselves can be found in the companion white paper entitled, "Distribution System Voltage Management and Optimization for Integration of Renewables and Electric Vehicles – Status and State of the Art."

The research performed in preparation for this paper included discussions with technical staff at each of the California IOUs and with suppliers of several VVOC systems. At utilities, it was clear that VVOC was very important, but there was no consensus on where the really significant research gaps existed. Gaps that were identified were relatively short-term and were expected to be resolved in the next year or two, generally too short a time frame for public interest research. These discussions and other associated study did lead to some conclusions relevant to future public interest research in the area of VVOC:

- Voltage control is an operational issue, not a planning issue. Utilities place a high priority on utilizing commercially available products for operations, as opposed to planning or engineering studies where they might consider less fully-developed systems for assessment. Unmet needs in operating systems tend to be directed back to the commercial suppliers of those systems for upgrades or enhancements.
- Capabilities of VVOC systems which are not yet available but for which the need already exists and has been identified by utilities are likely to become commercially available in the not too distant future. The major suppliers of VVOC systems appear to have recognized the impacts of high penetrations of renewables and are rapidly upgrading their offerings.
- Currently available commercial VVOC systems already offer significantly more capability than the currently installed systems at California IOUs. VVOC systems are really a subset of distribution automation systems which incorporate VVOC functionality, but also include outage management, fault location, and other features important to overall distribution system operation. Utilities may well choose to consider advanced VVOC systems only when they are ready to consider automated distribution management systems.
- The most dramatic advancement to VVOC in the next 3 to 5 years is expected to be the use of DG inverters to source and sink VARs. The theory is well established and proposed changes to IEEE 1547 to allow active voltage control by inverters are expected to be approved. Field demonstrations are needed on a variety of different types of feeders with significant levels of DG already installed.

- PEV penetration is currently too low to justify large amounts of attention or capital investment from utilities to mitigate the limited impacts seen so far. The primary focus for several years, possibly through 2020, will likely be on the adequacy of distribution transformer capacity and dealt with on a case-by-case basis. At a broader level, rate structures are being or will be adjusted to maximize off-peak charging. Any V2G applications are expected to be driven by third-party aggregators rather than utilities. However, PEV numbers are expected to continue to grow, especially in California, and will have a very significant impact in the decade beyond 2020.

GLOSSARY

Term	Definition
AMI	Advanced Metering Infrastructure
CPUC	California Public Utilities Commission
CVR	Conservation Voltage Reduction
DER	Distributed Energy Resource(s)
D-FACTS	Distributed Flexible AC Transmission Systems
DG	Distributed Generation
DMS	Distribution Management System
DSSC	Distributed Static Series Compensator
EPRI	Electric Power Research Institute
EV	Electric Vehicle
FACTS	Flexible AC Transmission Systems
IEEE	Institute of Electrical and Electronics Engineers
IOU	Investor Owned Utility
IVVC	Integrated Volt/VAR Control
kW	kilowatt(s)
LTC	load tap changer
LVR	Low Voltage Regulator
MW	Megawatt
NaS	Sodium Sulfur (battery)
PEV	Plug-in Electric Vehicle
PG&E	Pacific Gas and Electric Company
PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
PV	Photovoltaic
RPS	Renewable Portfolio Standard
SCB	Shunt Capacitor Banks
SCE	Southern California Edison Company
SGIG	Smart Grid Investment Grant
SSR	Subsynchronous Resonance
TAC	Technical Advisory Committee
V	Volt
V2G	Vehicle-to-Grid
VAR	Volt-Ampere Reactive
VR	Voltage Regulator
VVOC	Volt/VAR Optimization and Control

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