Energy Research and Development Division
INTERIM/FINAL PROJECT REPORT

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

Status and State of the Art

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PREFACE

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ABSTRACT

This white paper describes Volt/VAR Control and Optimization (VVOC), the various methods for achieving it, the devices used, and the current state of the art in light of the impact of increasing penetrations of renewable resources and electric vehicles in distribution systems as California strives to achieve 33% renewable penetration by 2020 in accordance with the state's Renewable Portfolio Standard (RPS). 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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Purpose of Report

The purpose of this White Paper is to assist the California Energy Commission in developing potential research projects addressing distribution system voltage and VAR control and optimization (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 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 paper is a report on the current and emerging technologies for VVOC and a summary of current practices and related development projects of California investor owned utilities (IOU). A particular focus is on the needs imposed by high penetration of photovoltaic (PV) power sources. This report will help define research plans and solicitations.

Background

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 distribution. 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 increasingly a 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 and demand response to both minimize capital costs and delay the need for new infrastructure. Conservation and

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[1] A series of 5 TAC meetings were held by CIEE to provide status on research activities and reassess research needs and priorities, most recently in June, 2012 at Folsom, CA.

demand response as alternatives to expanding infrastructure have become marketable commodities. These are largely controlled by end use customers and so the process of influencing customers to conserve or participate in demand response has become a part of overall distribution system management and an element in accommodating renewables.

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). Recharging a vehicle can easily consume more power than an average house radically changing historic load patterns and potentially creating significant issues if not managed properly.

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. They also include demand reduction and other types of customer interaction. These technologies typically require both communications systems and 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 methods that are currently being used, are planned, and are potentially possible in the next several years for the control 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.

Objectives of VVOC

Voltage control in distribution has always had 2 main objectives. First and foremost is the maintenance of voltage within acceptable limits under all load conditions. At the 120 Volt level, this means remaining between 114 and 126 Volts. A second objective is to maintain the power factor at as close to unity as possible, and thereby minimize losses. Voltage optimization is the incorporation of techniques to minimize losses in the distribution system. It normally incorporates Conservation Voltage Reduction (CVR) which reduces the voltage variation across a feeder, usually to the range of 114 V to 120 V or even narrower, with the aim of reducing both load power and system losses.

The presence of increasing amounts of distributed generation resources (DER), electric vehicles (EV), and the overall push to a Smart Grid have both complicated voltage control and led to additional objectives for a VVOC system that contribute to the overall performance and reliability of the grid. A more advanced VVOC system would have a broader set of objectives including the following:

- Maintain Acceptable Voltage
- Improve Efficiency and Minimize Consumption
- Enable Renewable Penetration
- Coordinate all Devices
- Self-Monitor
- Allow Operator Override
- Support Self-Healing and Feeder Reconfiguration
- Allow Selectable Objectives

Maintain Acceptable Voltage

This is the primary function of any voltage control system, with or without optimization and is expected to be met at all times under normal operation. Regardless of load, voltage should remain within the ±5% range of nominal at all points along the feeder. It is this objective which is put most at risk by high penetrations of renewables by increasing the voltage at the point of insertion possibly to the point of violation or, conversely once compensated for, by dropping below the minimum voltage as a result of a loss of renewable power if the wind stops or a cloud passes over.

Improve Efficiency and Minimize Consumption

Efficiency is improved by reducing losses in the system. Any power factor other than unity has increased losses. Reactive power does not do useful work but the reactive current passing through real wire resistance creates heating and wastes energy. While a power of factor of unity is ideal, a realistic system should be capable of operating in the 97% - 98% range.

In recent years, conservation voltage reduction (CVR) has also been encouraged as another form of efficiency improvement based on maintaining voltage in the lower half of the acceptable range, 114 V to 120 V. CVR is based on the idea that lower voltage reduces power consumption.

Resistive loads such as incandescent lights increase power consumption proportional to the square of the voltage and constant current loads consume power proportional to voltage. Therefore, reducing the voltage is expected to achieve some level of both demand reduction and lower distribution circuit losses. It is usually assumed that the voltage reduction will not have a negative impact on customers.

CVR however will not reduce consumption in all loads. A constant power load will increase current and hence distribution system losses as voltage decreases even though the device itself draws constant power regardless of voltage. Inverter based power supplies and compact fluorescents fall act like constant power loads. In heavily loaded motors, lower voltage can actually increase power consumption causing current to rise at a faster rate than voltage decreases. Residential air conditioners fall into this category. The red line in Figure 1 shows the effect of voltage on real power consumption while the bright green line shows reactive power. Studies of CVR projects have demonstrated a reduction in total power consumption in the range of less than 1% up to about 3%. It is not clear whether, as load characteristics evolve and electronic and other constant power loads become a larger percentage of total loads, whether the efficiency gains of CVR will be reduced or eliminated in the future.

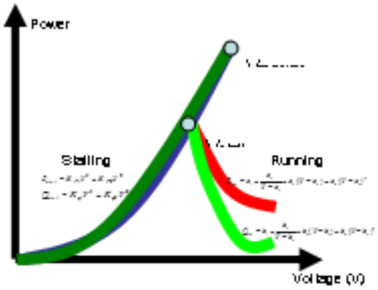


Figure 1 Motor Load Losses
Graphic: WECC Load Modeling Report

Enable Renewable Penetration

Conventional voltage control methods can perform poorly in the presence of significant generation on a distribution feeder since they are based on the premise that voltage naturally decreases with increasing distance from the feeder. An equally important assumption which is violated by renewable resources is that variations in load are the only cause of changes in current so that historical load data combined with ambient temperature is a good predictor of current flow through the system. As a result, the ability of the system to adequately control voltage is one of the factors limiting renewable penetration on a feeder. Even within the ability of a system to maintain voltage, the variations in apparent load caused by the variability of wind and solar may cause more frequent cycling of electromechanical devices used for voltage control and shorten both operating life and maintenance intervals.

A more ideal VVOC system would include the ability to compensate for voltage variations created by varying power contributions from DERs.

Coordinate all Devices

Voltage control does not require coordination between devices. It is common for devices on a system to be independently controlled based only on local conditions or on real and reactive power to be separately controlled. Unfortunately, it is also possible for independent systems to work in opposition to each other and for the net result to be considerably less than optimal. The expanded penetration of various types of DER combined with potential variability on time scales of seconds or minutes increases the value of coordinated control. Coordination becomes even more important if CVR is implemented as the margin for error is effectively cut in half.

Self-Monitor

Many existing voltage control systems depend entirely on local controls with no communication to any central station or monitoring system. Any failure of a device can result in excessive losses or on violations of the acceptable voltage limits. An ideal control system will alert operators to failures so they can be corrected as quickly as possible. Inherent in this objective is some form of communication between devices and system operators.

Allow Operator Override

After a fault or during some other form of emergency condition, operators may desire to have the system operate in some abnormal fashion. The system should allow the operator to override normal operation as needed.

Support Self-Healing and Feeder Reconfiguration

Self-healing is the process whereby a system of sensors and automated controls, together with advanced software and real-time data detects and isolates faults and then automatically reconfigures the distribution network to minimize loss of load. Feeder reconfiguration has historically been an infrequent occurrence, usually limited to repair or construction activities. However, newer Smart Grid operational concepts such as Fault Location Isolation and Service Restoration are steps toward a self-healing grid and are expected to make feeder reconfiguration a much more frequent event. An ideal VVOC system will adapt to these changes and continue to operate after the reconfiguration without requiring operator or field service actions.

Allow Selectable Objectives

Any control system begins with one or more specific objectives. For a VVOC system, the normal objective, incorporating CVR might be, for example, to minimize the maximum voltage on the feeder while maintaining a certain minimum. However, at certain times, it may be preferable to change objectives. Abnormal operating conditions may also dictate a change in objectives. Simply turning CVR on or off is a change in objectives. It is desirable for the system to have a choice of objectives to match anticipated needs and for an operator to be able to select a different objective rather than override and substitute operator oversight for automatic operation.

Infrastructure Elements for Volt/VAR Control

A variety of devices can be used to control voltage and reactive power, but the bulk of voltage regulation today is provided by 3 basic types of devices – load tap changers (LTC), voltage regulators, and capacitor banks. Advanced inverter based devices, including most distribution renewable generation and storage devices are also potentially capable of providing reactive power and thereby contribute to VAR control. Operating restrictions imposed by IEEE 1547 have restricted the use of this capability, but restrictions are expected to be relaxed in the near future as IEEE 1547 proposed changes are currently under review. It is widely expected that the ability of advanced inverters to provide VAR support will become a key feature of advanced voltage control methodologies designed to operate with high penetration of renewables.

In addition to the elements mentioned above, which are expected to constitute the primary infrastructure for voltage control, two other types of elements are finding applications in particular circumstances especially related to the impacts of DER. Low Voltage Regulators installed at the service entrance to a building provide a distributed voltage control strategy. Distribution Flexible AC Transmission System (DFACTS) devices can work in conjunction with larger distributed generation facilities to increase allowable penetration.

Load Tap Changers

LTCs are transformers with a selection of taps which allow the secondary voltage to be changed in small steps. A de facto standard appears to be a range of ± 10% in 32 steps or 5/8% per step. LTCs can be designed to switch either on load or off load. In common practice, an on load LTC located at the substation sets the primary voltage for the distribution feeders from that substation and is part of the voltage control system. Functionally, LTCs can be a single unit or a transformer followed by a voltage regulator. The unit can also operate on all 3 phases or can consist of 3 separate single phase units. Units are primarily oil filled electromechanical devices, but thyristor controlled solid state versions have become available.

Voltage Regulators

Voltage regulators are devices to accept a variable input voltage and provide a constant output voltage. The most common design for a regulator is an autotransformer where the output voltage is equal to the input voltage ± 10% and the regulator can be changed only in steps, often the same ± 10% in 32 steps or 5/8% change of voltage per step as used in LTC transformers. Voltage regulators automatically adjust the step position to maintain a constant voltage within a desired band. The size of the band is usually larger than a step to minimize the frequency with which the regulator changes steps. Regulators can be single or three phase and different models can operate at any of the various voltages in the distribution system.

Capacitor Banks

Losses are lowest in a distribution system when the power factor is at or near unity. Distribution loads with a reactive component tend to be inductive, so a shunt capacitor functions will raise the inductive impedance and move the power factor toward unity. The capacitor contributes VARs to help support the voltage.

Shunt Capacitor Banks (SCBs) can be fixed or switched. A fixed bank is always on while a switched one can be switched on or off either locally or remotely. Figure 2 shows the effect of switching on capacitor banks on the voltage along the length of a feeder. Banks are rated in kVARs at a specified voltage. The actual level of kVAR support is proportional to the square of voltage, so one of the disadvantages of SCBs is that they provide the least support in cases where the voltage is low. Typically, capacitor banks are not large enough to move the power factor all the way to unity when the feeder is heavily loaded, although under light loading conditions, it is possible for a capacitor bank to overcompensate, i.e. to swing the power factor beyond the unity point and create a net capacitive reactive. SCBs are digital in the sense that they can be on or off, but cannot have only a portion of the bank on. They are, however, relatively inexpensive and easy to install, so they are often used in much larger numbers than LTCs or voltage regulators.

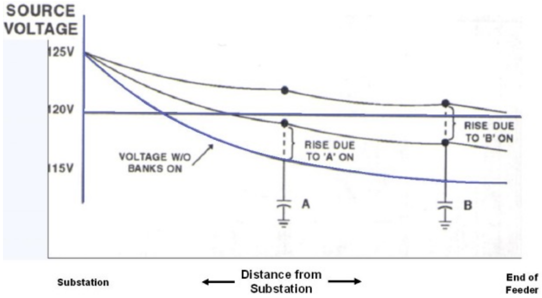


Figure 2 Capacitor Bank Voltage Impact
Courtesy: Wikipedia

Inverter Based Distributed Energy Resources

Photovoltaic solar power systems and many distribution sized wind turbines utilize inverters as the interfacing component to the electric grid. Modern power inverters are capable of four quadrant operations, i.e. they can provide reactive power in addition to real power at any level within the maximum VA rating limit. Even when outputting all the real power currently available from the wind turbine or PV panels, an inverter which has available margin left can provide significant VAR support. With appropriate controls, an inverter can even provide VAR support even at night (or on a windless day) when no real power is available and the inverter must draw a small amount of real power from the grid. Under current IEEE 1547 restrictions, inverters are not prohibited from providing VARs, but are not allowed to actively regulate the voltage, so that inverters today are primarily operated with a fixed power factor, most often unity.

Inverters can not only provide VAR support, they can do so on a much more rapid time scale than conventional electromechanical devices. Thus they can potentially assist in mitigating fluctuations without the resulting transients from switching capacitor banks or impacting either service life or maintenance schedules. Thus, inverter based DER, which creates issues for conventional voltage control methods, can contribute directly to the solution of these issues at minimal cost since the actual hardware is already installed and integral to the DER.

Inverter based DERs include distributed energy storage and community storage as well as PV. Future systems may well incorporate the ability of storage systems to provide VAR support in during both charge and discharge functions.

Low Voltage Regulators (LVRs)

An LVR is a voltage regulator intended to operate at the end use voltage. They can be single or 3 phase. At least one manufacturer offers products intended for this use for both customer and utility applications. Energy savings of 5% to 15% are claimed with end use facilities receiving power at a regulated 114 V equivalent.

In principle, a completely distributed solution to regulation without any central intelligence could be achieved by simply placing an LVR in front of each meter. While the cost is unlikely to allow widespread use of distributed regulation at this level, there are specific applications where this can be a cost effective solution for distribution voltage issues. LVRs are well suited to rural areas or at the end of a long feeder, can be quickly installed, and are relatively inexpensive compared to other alternatives. They may also be appropriate for areas where PEV charging additions would otherwise disrupt the existing voltage controls.

D-FACTS

Flexible AC Transmission Systems (FACTS) are solid state devices capable of controlling power flow by actively providing a controllable series or shunt impedance on a transmission line, depending on the type of device. Distribution FACTS (D-FACTS) are smaller, less expensive versions more appropriate for distribution level applications. Such devices are fast acting, can provide a controllable amount of impedance at any desired phase with respect to line voltage, and do not have the cycle life constraints of LTCs or capacitor banks. Voltage control is one of a variety of purposes for which they are useful. They are well suited for applications where a large DG facility may cause excess voltage under light loading. However, due to cost, D-FACTs are unlikely to be installed purely for voltage control, so that it is likely that they will be used as part of a voltage control system only when they have been installed for other power control purposes.

Volt/VAR Control and Optimization Methods

There are 3 principle methods of exercising voltage control across a distribution feeder: local or “standalone” control, separate Volt and VAR dispatch, and model based integrated control The two former methods have been the primary means in California and elsewhere, while model based integrated control is considered to be the primary means for effective control and optimization of a system with significant penetration of distributed generation (DG). Model based systems use real or near real time data from SCADA or other means to optimize voltage across a feeder. Current practices by the California IOUs are still largely unaffected by rising DG penetration, but pilot studies have been undertaken to examine the impact and potential of integrated Volt/VAR Optimization and Control (VVOC).

Types of Control Systems

Local Control

Local or standalone control is when the settings of a control element are based entirely on conditions at the immediate site of the element. For a switched capacitor bank, control means the conditions under which the bank is turned on or off. Local control can use voltage, current, or time to control the bank. Time is frequently used on the assumption that the daily load variation will have a certain time period each day when the capacitor bank will provide reactive support for the voltage. For time based systems, it is normal for a local voltage sensor to provide input to a voltage override capability which will turn off a capacitor bank if voltage exceeds an upper threshold or turn the bank on when the voltage drops below a lower threshold. Like a time based system, current or power sensing assumes that heavier loads need more reactive support while voltage sensing assumes that below some voltage threshold the bank should be turned on and above another threshold the bank should be turned off. More than one method may be used, such as a time based system with voltage overrides at high and low voltage thresholds.

Local control of an LTC is normally based on current or power flow at or near the LTC. The LTC is preprogrammed to provide an output voltage measured at a reference point which is increased as the load increases to compensate for the additional line drop as current increases. Local control of a voltage regulator is similar to that of an LTC.

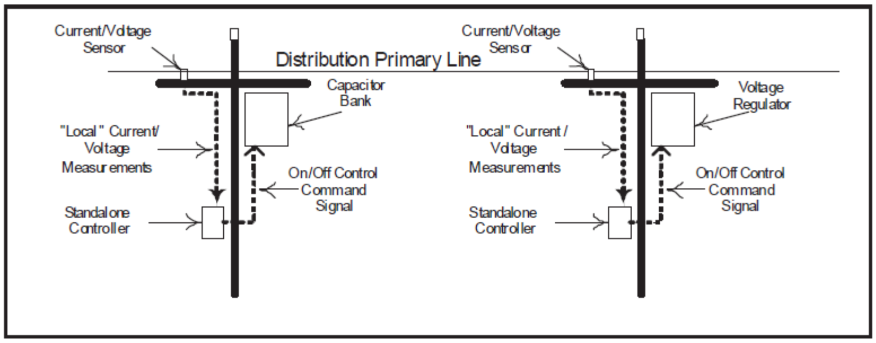


Figure 3 Examples of Local Control
Courtesy: Smart Grid in the VVC Era

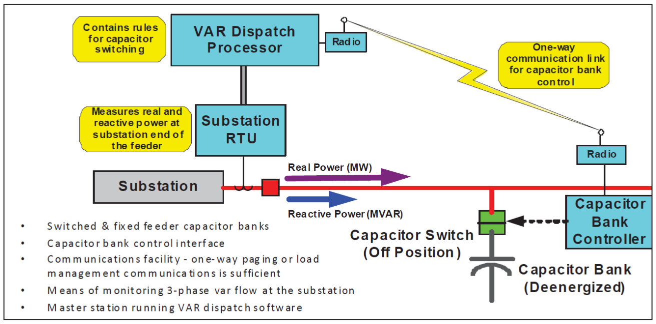
Local control of an inverter based system to change the VARs produced by the inverter is uncommon given the current restrictions of IEEE 1547 but, in theory, could be based on time, the current power output of the inverter, and/or a preprogrammed ratio of real to reactive power. In the event that the current restrictions are relaxed, local control based on voltage, current, or phase angle may become common.

The primary advantages of local control are simplicity and cost. No communication systems are required. Each element of the system acts independently. In the absence of DG, the voltage will follow a well-defined profile as a function of load and variations from the nominal profile will only depend on changes in the load mix. However, as load mix evolves over time, changes to the voltage profile may require on site modification of settings. Further, the lack of monitoring may allow violations to go unnoticed.

When compared to the list of objectives for an ideal VVOC system, the limitations of local control are numerous. Local control can maintain acceptable voltage across a feeder, but may become increasingly problematic as DG penetration increases. The impact of increased penetration is likely to increase the cycling of LTCs, regulators, and capacitor banks with resulting decrease in maintenance intervals and service life. The lack of coordination between devices can lead to one device tending to counteract another and, in extreme cases, to "hunting" where devices interact in such a manner to introduce instabilities in the voltage system. This is one of the concerns that led to restrictions on allowing inverters to actively provide Volt/VAR control. Monitoring of the system requires, at minimum, a unidirectional communication system to transmit status to a monitoring system, and, if reconfiguration of the feeder takes place, on site adjustment or even relocation of system elements maybe necessary. In summary, complete local control can maintain voltage within specified limits, but is poorly suited to other objectives of an efficient, optimized system.

Separate Volt and VAR Dispatch

A common approach to a more integrated and automated system is independent central dispatch of Volts and VARs. Voltage dispatch is used for LTCs and regulators while VAR dispatch manages capacitor banks. Each element has communication with one of the dispatch systems. The dispatch system sets the state of each element. If measurements at the element are not used, a one way communication link is sufficient. Figure 3 shows a typical VAR dispatch system. Control actions are usually based on a predetermined set of rules. Since the system in this figure shows only one way communications then, in this system, the rules must be based on measurements made at the substation, most probably power factor. Figure 4 shows a voltage dispatch system. In this example, there is end of line monitoring and the control actions would set the substation LTC



- Switched & fixed feeder capacitor banks
- Capacitor bank control interface
- Communications facility - one-way paging or load management communications is sufficient
- Means of monitoring 3-phase var flow at the substation
- Master station running VAR dispatch software

Figure 5 VAR Dispatch System
Courtesy: VVC in the Smart Grid Era

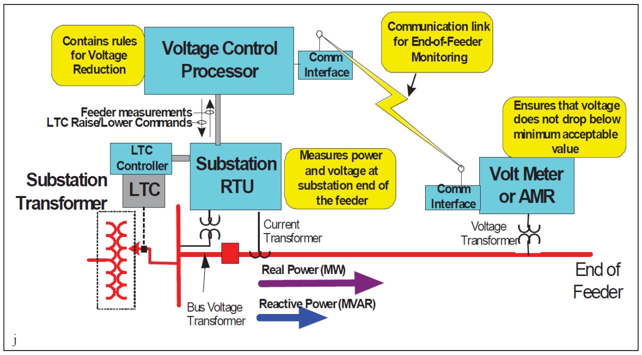


Figure 4 Volt Dispatch System
Courtesy: VVC in the Smart Grid Era

based on keeping the end of line at or above minimum voltage. For either system, additional monitoring may be utilized to provide better control in more complex systems.

Even though there is communication between elements and dispatch systems, this approach shares a major feature with that of local control. Each element is controlled by a set of rules for that element alone. Without a system model, each unit is independently operated in a predefined manner based on the available measurement data.

Separate Volt and VAR dispatch offer several advantages over local control. The addition of communications allows self-monitoring of the system, at least where 2 way communications exist. The ability to monitor key locations and to set equipment based on other than local conditions tends to improve overall efficiency and performance. Since control is resident at a central station, operator override is possible if needed. On the other hand, this approach does not significantly improve management of the impacts of distributed generation and may be unable to compensate for rapid fluctuations in generated power. Like local control, fixed rules do not allow automatic adjustment to a reconfiguration.

Model Based Integrated Volt/VAR Control (IVVC)

The electrical transmission system operation is based on extensive data monitoring, communication systems, and near real time models of the system to provide situational awareness in the form of state estimation. Distribution systems, on the other hand, have been characterized by much more limited communications and data monitoring. The increasing penetration of DER, however, is creating distribution systems which are beginning to share characteristics with transmission system. The Smart Grid is one of the responses by operators to manage the challenges and model based operation of distribution systems is a logical outgrowth of this increased need for "smart" operation of distribution. With appropriate sensors, communication systems, and controllable devices, a model of a feeder allows coordination of all the elements to best achieve a set of objectives, including CVR, as part of an overall distribution automation system.

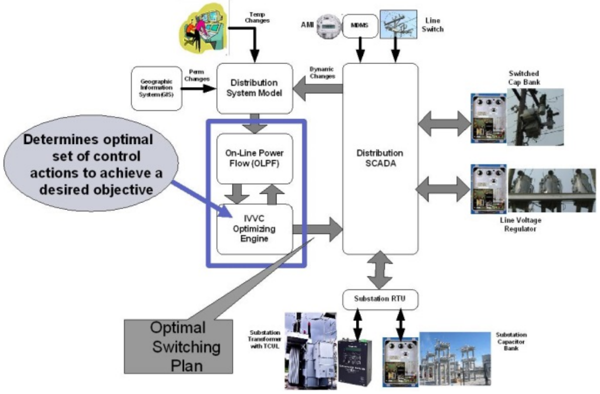


Figure 6 Model Based Distribution Operation
Courtesy: VVC in the Smart Grid Era

A model based system is well suited to managing significant amounts of renewable DG because such a system can provide a coordinated response of the various control elements to DG imposed variations. In particular, if inverter capabilities to provide VARs to assist in voltage control become accepted practice, the concerns over possible interactions between various elements will likely require real time information about the system and the ability to provide coordinated actions.

While a particular model based VVOC implementation may not achieve all the objectives of an ideal distribution automation system, the approach lends itself to very broad capabilities. Coordinated control and effective data monitoring are likely to offer the most effective loss reduction and conservation. Self-monitoring is inherent and feeder reconfiguration will automatically update the model.

In spite of their advantages, model based VVOC systems are not widely used today. They are a relatively new development and the simpler, less expensive systems are already in place and have been adequate in the past. The growth of Smart Grid infrastructure, especially the increasing use of data monitoring and communication systems, will be an enabling factor. This combined with increasing penetration of renewables, the addition of other DER such as storage, and expanded use of demand response will exert pressure for utilities to migrate toward systems which provide the coordinated distribution automation offered by model based systems.

Current Practices of California IOUs

Pacific Gas and Electric Company (PG&E)

PG&E has the largest installed base of PV of any U.S. utility with 1000 MW in 79,000 installations, about 30% of the national total. Average penetration is less than 5% measured against peak load of approximately 20,000 MW. While overall penetration is low, there are a few local clusters and about 4% of its 3,100 feeders have penetrations at 15% or higher with a few with penetrations over 60%. The vast majority of PV systems are on the customer side of the meter, although PG&E has 2,500 MW of DG under development.

To date, PG&E has continued to manage voltage control largely through their historic method of standalone controls for LTCs, voltage regulators, and capacitor banks. Each unit is independently controlled. Control is normally time based, turning capacitor banks on or raising voltage during periods of expected high load. Voltage override sensors will turn a capacitor bank on if voltage is low or off under high voltage conditions. LTC voltage is normally adjusted based on the load seen by the LTC. Local temperature sensing is also utilized in some situations to provide additional adjustment.

PG&E is currently evaluating more advanced methods. A 3 year project will spend the first year benchmarking what other people are doing. Pilot testing of products and control systems will be performed on up to 15 feeders. Testing will include evaluating 3 different system approaches: modeling, feedback from AMI, and primary metering. If successful, large scale deployment of more advanced systems would be expected to take 10 years or more.

Southern California Edison (SCE)

SCE is similar in size to PG&E with 22,000 MW of peak load in 2012 and 4350 feeders. At the end of 2012, SCE had just over 500 MW of distributed PV installations. Voltage control is implemented almost entirely with 13,000 capacitor banks aided by a few primary voltage regulators. Unlike PG&E, control of the capacitor banks is centralized with 2 way wireless communications linking each capacitor bank to centralized control. Voltage sensors at capacitor banks provide data feedback. Control, however, is still based on local data rather than an integrated model. The communication system provides the additional advantage of providing a level of self-monitoring capability of the distribution system.

For the last two years, SCE has had advanced pilot or demonstration projects for voltage control and optimization, primarily those under the Smart Grid Investment Grant program of DOE. Assuming success of these projects, SCE expects to begin deploying production versions of VVOC in 2015 and ultimately implementing advanced distribution automation in up to 900 out of a total of 1,500 substations. The remaining substations are those not expected to justify the cost. While AMI data is not expected to be utilized as a part of VVOC, SCE is using the data for system validation.

San Diego Gas and Electric (SDG&E)

The smallest of the 3 major California IOUs, SDG&E serves a peak load of just less than 5,000 MW on 906 distribution feeders. Voltage control at SDG&E is similar to PG&E. Substation LTCs adjust voltage based on local current. About ½ of their 1,400 capacitor banks are switched, the balance fixed. Control for capacitor banks is local and time based, with overrides for both high and low voltage. Line regulators are used primarily on rural feeders. Installed distributed generation includes 150 MW of PV and 50 MW of wind. While local voltage control is the current method of voltage control, SDG&E is installing a new wireless communication infrastructure to allow more sophisticated distribution automation as well as other Smart Grid features. This SGIG financed system is expected to cover approximately 90% of all customers and should be completed this year. A pilot project utilizing voltage sensors, wireless communication, and closed loop control for VVOC including implementation of CVR is currently under way. Deployment could occur within 3 to 5 years.

State of the Art

Distribution voltage management is a rapidly evolving function for utilities. The state of the art depends on the definition used for it. For utilities, the state of the art is largely set by the definition of what is or soon will be commercially available. The product offerings from several major suppliers are reviewed below.

For researchers and for developers of renewable resources, the state of the art incorporates the integration of advanced inverter capabilities, particularly the capability to provide active VAR support. Figure 7 is a conceptual drawing of a fully integrated system which uses LTCs, capacitor banks, regulators, and inverter capabilities in PV (and storage) systems Inverter use is discussed in more detail later in this chapter.

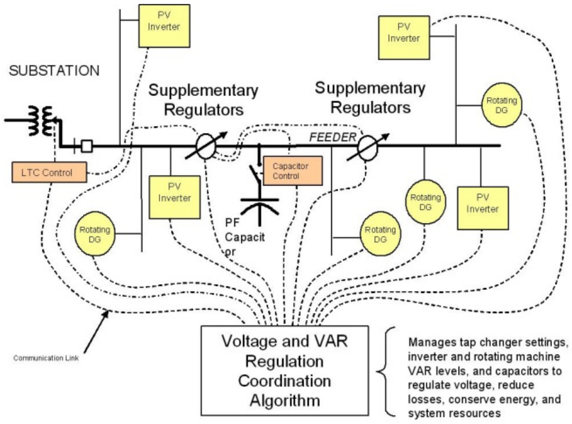


Figure 7 Fully Integrated Volt/VAR System
Courtesy: Wikipedia

While a centralized integrated model based approach to Volt/VAR control is arguably accepted as "most capable," there are other approaches which offer potential for advanced Volt/VAR control in the presence of high levels of PV penetration. Smaller companies with very limited installed bases are each competing to have their unique approach accepted. One of these is the digital signal processing approach taken by Utilidata, Inc. Another is "intelligent distributed control," a system of many small components such as the system offered by Varentech.

Advanced Inverters

Modern inverters, particularly those intended for larger systems, whether generators or storage systems have the capability to source or sink reactive power as well as real power. As such, it would seem highly desirable if the addition of DERs, which can complicate voltage control, could also assist in providing that control. Under the current restrictions of IEEE 1547, inverters are prohibited from actively providing voltage support, although revisions of these restrictions have been proposed and are expected to be approved in the near future. As such, the use of inverters installed as part of PV or battery storage systems may soon be a contributor to state of the art voltaghe management.

In anticipation of this, EPRI has, for over 2 years, been developing a list of proposed "standard" functions for smart inverters. The goal of this project is "*to enable high-penetration scenarios in which a diversity of resources such as photovoltaic and battery storage can be integrated into distribution circuits in a manageable and beneficial way even if they vary in size and come from different manufacturers.*" The expectation is that widespread implementation of these functions by inverter manufacturers would greatly aid Volt/VAR management under high penetration of renewables. Of particular interest is the Intelligent Volt/VAR function shown in Figure 8. This function would provide either capacitive or inductive VARs within the maximum power limits based on the locally sensed voltage. A total of 23 functions have been proposed to date. These include several different functions aimed at mitigating extremes of voltage caused by high penetration of renewables as well as functions to assist in the control of battery storage systems. While it is entirely possible to implement any of these functions external to the inverter, standardizing inverter functions will greatly simplify the voltage control problems at high PV penetrations.

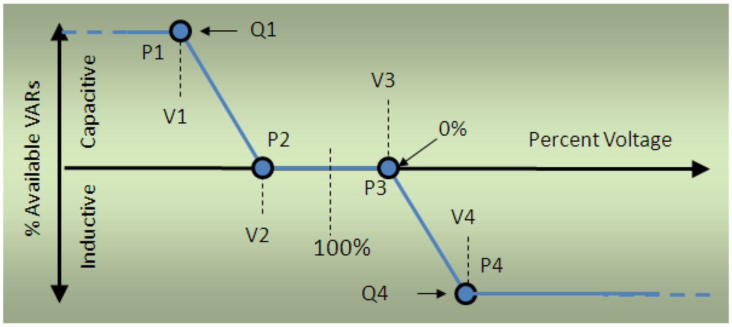


Figure 8 Intelligent Inverter Volt/VAR function
Courtesy: EPRI

Under the Smart Grid Investment Grant (SGIG) program, testing of advanced inverters is underway. A major project in California of this type is taking place at SCE's Inverter Test Facility, where a number of German made inverters with advanced features are being tested.

Commercial Volt-VAR Control

While there are many suppliers of operating software for use by utilities in distribution voltage management, a few providers dominate the market. ABB, Inc., General Electric Co., and Cooper Power Systems are representative of the dominant companies. Utilidata, Inc. is included because it uses a different technology than any which has been previously discussed.

ABB

ABB, Inc. offers the Volt/VAR Management Software (VVMS). This is a model based system that provides centralized control of both voltage and reactive power. It can provide standalone Volt/VAR management or be integrated into a distribution automation system. It is intended for the control of LTCs, VRs, and capacitor banks. System nodels can be built from a utilities Asset Management System and then update to feeder reconfigurations based on GIS or outage management system data sources. There is currently no provision for the VAR control of inverters.

Cooper Power Systems

The latest product for Volt/VAR management from Cooper is the Yukon IVVC. This accepts analog inputs of real-time voltages, watts and VARs from LTCs, regulators, capacitors, and other medium voltage sensors. It can also accept customer meter inputs. Yukon IVVC integrates both voltage regulation and power factor correction in real time. Optimization is achieved by assigning an "operational cost" to each of a set of real time measuremnets and then adjusting parameters to minize the operational cost. Optimization is heuristic, using historical along with current measurement data as a basis for predicting optimal settings. Control of inverters is not incorporated.

EDD

Electrical Distribution Design (EDD) offers a model centric distribution system utilizing a real-time virtual SCADA system based on the DEW-ISM software platform. The DEW-ISM is a single physical-based model merged with measurements to support all engineering, operation and planning tasks of the utility industry. The DEW-ISM uses graph-based, topology iterator framework that facilitates fast computation times for power system analysis and power flow calculation. The DEW-ISM model centric distribution system operation is demonstrated in the Department of Energy (DOE) and Orange & Rockland Utilities (ORU). The ORU is using DEW-ISM software platform for to implement automated storm detection, outage predictions, fault location, reconfiguration for restoration, fault isolation, coordinated volt/VAR control, conservation voltage reduction, and real-time power flow analysis, as part of the U.S. Department of Energy's (DOE's) funded project. This operation control platform can handle the coordination of a large number of SCADA enabled devices for any possible set of contingencies in almost real-time.

General Electric

General Electric has recently released a new product for Volt/VAR control called Integrated Volt/VAR Control (IVVC). This is a model based system which can fully integrate real and reactive voltage control. It is capable of controlling advanced inverters and includes "standard" models for inverters by manufacturer's model number. One of the claimed features of the system is that it can optimize, not only a given feeder, but an entire distribution system. Models can be built based on GIS information.

Utilidata, Inc.

Unlike companies such as GE, Cooper, and ABB, Utilidata is a relatively new, small company with a limited installed base of systems. They offer a Volt/Var optimization program called AdaptiVolt which takes a non-typical approach to VVOC. While it utilizes central control and fully integrates voltage and VAR control, it combines heuristic information with real time voltage data from only a very small number of nodes. The system is not model based, but utilizes an adaptive control algorithm based on the evolution of data over a short period of time, typically 10 – 15 minutes. The algorithm uses extensive digital signal processing to make decisions based on changes over time. It does not base decisions on the instantaneous voltages at a particular time. As a result, the system is capable of of distinguishing, for example, a short term change caused by a PV system intermittency from a change due to increased customer loading. One result of this approach is to minimize the corrective actions required.

Product literature claims a 30% - 40% improvement in the conservation voltage feeder profile compared to model based systems. A representative of the manufacturer also claimed that in a

DOE Smart Grid project, the system resulted in a significant reduction in the number of operating cycles taken by capacitor banks and voltage regulators while maintaining the flatter CVR profile in the presence of a PV system representing about 15% penetration. The small number of data nodes suggests that much less communicated data is required for operation. The system is capable of utilizing advanced inverter technology for VAR management.

While this report is not intended to recommend any specific manufacturer, the approach taken by Utilidata appears to represent a superior technology, at least from the viewpoint of CVR, the primary purpose for which it was designed. Unfortunately, hard data to support these claims has not yet been made available to the general public.

Varentech

The Varentech offering for distribution control is called ENGO, short for Edge of Network Grid Optimization. This decentralized system consists of small, inexpensive hardware components called ENGO-V that are distributed across a feeder. Each Engo-V module can provide monitoring, Volt/VAR control, and communications. An appropriate network of these provides a flat voltage profile across a feeder and claims to mitigate voltage dynamics due to varying PV output or industrial loads. The modules communicate with ENGO-S, the software management system for constant monitoring of the system, but each ENGO-V module utilizes power electronics and performs local control of Volts and VARs..

GLOSSARY

Term	Definition
AMI	Advanced Metering Infrastructure
CVR	Conservation Voltage Reduction
DER	Distributed Generation Resources
D-FACTS	Distribution Flexible AC Transmission System
DG	Distributed Generation
EPRI	Electric Power Research Institute
EV	Electric Vehicles
FACTS	Flexible AC Transmission Systems
IOU	Investor Owned Utility
IVVC	Integrated Volt/VAR Control
kW	kiloWatts
LTC	load tap changers
LVR	Low Voltage Regulators
PEV	Plug-in Electric Vehicle
PG&E	Pacific Gas and Electric Company
PV	Photovoltaic
RPS	Renewable Portfolio Standards
SCB	Shunt Capacitor Banks
SGIG	Smart Grid Investment Grant
TAC	Technical Advisory Committee
V	Volt
VAR	Volt-Ampere-Reactive
VR	Voltage Regulator
VVOC	Volt/VAR Optimization and Control

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