VOLT/VAR CONTROL FOR SMART GRID SOLUTIONS

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ABSTRACT

This paper presents integrated volt/var control solutions that include integrated control of capacitor banks, step-voltage regulators, load-tap changers, and reclosers. These systems include communications, a centralized automation platform, and software to optimize voltage control and reactive power flow.

INTRODUCTION

Traditionally, volt/var control in distribution systems has been performed locally by individual devices such as substation transformer load tap changers (LTCs), line step-voltage regulators (VRs), and switched capacitor banks based on the voltage and/or current data. Where volt/var corrections were required permanently, fixed capacitor banks were installed. Operational statuses of these devices were not continuously monitored. As a result, it was not possible to quickly respond to load condition changes in the distribution grid and no automatic reconfigurations were performed to adjust for the load condition changes. This resulted in non-optimal system conditions and feeder loading. In addition, it was difficult to override certain operating conditions during power system emergencies. With higher penetration of distributed generation (DG) that may cause reverse power flow in distribution feeders, the impact on protection and control devices designed for radial system became a serious issue since these devices may incorrectly operate or not operate at all (assuming, for example, that a feeder was reconfigured and no action was taken).

Integrated volt/var control (IVVC) solutions provide coordinated control of the system voltage and reactive power flow to achieve optimal distribution system operation. Economic benefits result from preventing voltage violations, optimizing the peak load requirements, and the system loss reduction. For example, the system voltages can be reduced to minimum values without violating equipment operating limits and other constraints set by the user. This action enables utilities to meet the load requirements during high-demand conditions with the existing resources. The IVVC system continuously analyzes and controls LTCs, VRs, capacitor banks, and reclosers, to optimize the system voltage and power factor. This allows flattening and lowering of average voltages on the distribution feeders, resulting in energy savings. During this process, near-unity power factor is maintained, which, in addition, results in loss reduction. The IVVC system analyzes (in real-time) feeder voltages obtained from VRs, LTCs, capacitors banks, voltage sensors located at various locations on the distribution system, and from customer meters. It also analyzes and incorporates historical data to determine the effect of each operation. The IVVC evaluates and controls capacitor bank states to manage feeder and substation VAR flows to maintain a power factor close to unity. As a result, the distribution system operates optimally with existing resources and investment in new installation can be deferred.

The IVVC solution presented here is designed to provide benefits such as:

- reduced generation requirements,
- reduced carbon footprint,
- continual (real-time) maintenance of unity power factor for all weather and load conditions,
- flat feeder voltage profile,
- Conservation Voltage Reduction (CVR) to reduce demand during peak hours,
- immediate notification of a capacitor or VR operation malfunction,
- remote switching/regulation of VRs and capacitor banks,
- remote access to control settings, and
- real-time alarms for voltage threshold violations.

DEVICES FOR VOLT/VAR CONTROL

Solutions for volt/var control in distribution systems may include devices such as voltage regulators, capacitor banks, transformers with load-tap changers, and reclosers.

Step Voltage Regulators

Distribution step-type voltage regulators (VR) are used to maintain constant voltage for individual customers. VRs hold line voltage within pre-determined limits and ensure consumer voltage magnitudes as specified by Standards. The VR is an auto-transformer with many taps, designed to regulate voltage in the range of ±10%, in 32 steps, with 5/8 percent voltage change per step (see Figure 1). Design and test of voltage regulators are defined by the C57.15-2009 standard from the Institute of Electrical and Electronic Engineers (IEEE). The VR short circuit impedance is small (less than 1%) and in many short-circuit studies is neglected.

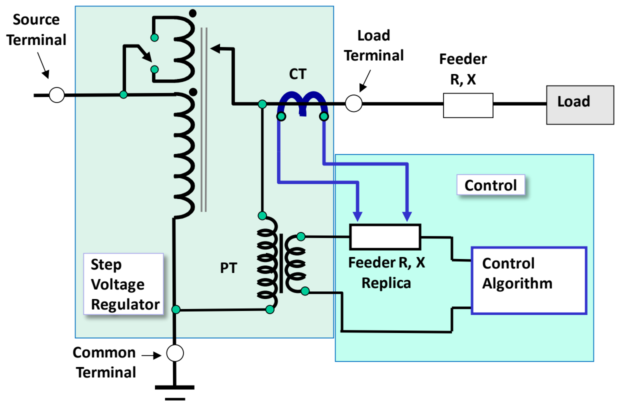

Figure 1 Step Voltage Regulator

Voltage regulators are equipped with an intelligent electronic device (IED) that monitors and controls the voltage regulating sequences. At greater distances from the VR location, due to the line voltage drop, voltage can be below a specified minimum level. To maintain the voltage magnitude at the remote end within a specified maximum and minimum limit, the VR can estimate the line voltage drop and regulate its load side voltage accordingly. This is effectively performed by the Line Drop Compensation (LDC) feature, which is an integral part of the voltage regulator control. With LDC, the line current is measured by the voltage regulator's internal current transformer (CT) in conjunction with the measured load-side voltage by the internal potential transformer (PT). Based on the secondary current of the CT, the secondary of the PT, and the line R and X parameters, the control derives the line voltage drop, active and reactive components, and makes "decisions" to correct the voltage magnitude.

During a reverse power flow, the LDC must have adequate control algorithms to properly perform voltage corrections. The reverse power flow may result from loop feed setups, switching operations that reconfigure the feeder, or it may be due to DG supplying power back to the substation. There are several Reverse Power Flow modes of operation presently available in modern VR controls. The impact of DG varies with each of them.

The VR controls are compatible with the DNP3.0 protocol. A fiber-optic/RS-232 communication module provides a flexible interface for SCADA applications. The fiber-optic port can be used in peer-to-peer or fiber-optic loop configurations. It incorporates an industry-standard ST fiber connector for installation into existing fiber-optic-based applications. The module also includes an RS-232 port for serial communication, or a direct connection to a radio. A RS-485 module supports multi-drop applications. Ethernet architecture utilizes open standards, providing seamless communication regardless of the manufacturer. An Ethernet module includes ST fiber and RJ-45 connections [1]. Alternate configurations are activated by way of programmable inputs and outputs in the voltage regulator control addressing the diverse load profiles on the power grid experienced during a day, month, or year.

Capacitor Banks

Switched capacitor banks are equipped with an intelligent electronic device (IED) that controls the capacitor bank switching sequences. Capacitor controls presented here support stand-alone functionality, as well as one-way and two-way communications. The controls are modular, universal devices capable of being deployed with a variety of communication configurations to meet different application needs. Capacitor controls are designed to operate with all major communications vendors' products such as two-way digital cellular communication. The DNP 3.0 Serial SelectComm module can be used with licensed and unlicensed radios. An Ethernet port offers two-way communications using industry-standard IP addresses and protocols; compatible with BPL, WiMax, and MDS INET networks [2].

Transformers with Load-Tap Changers

Transformers with LTCs are equipped with an IED that controls the LTC regulating sequences. The controls support stand-alone functionality, as well as one-way and two-way communications.

Reclosers

Reclosers are equipped with an IED that controls switching sequences. The controls support stand-alone functionality, as well as one-way and two-way communications [3].

OPTIMAL LOCATION OF DEVICES FOR VOLT/VAR CONTROL

Volt/var control in distribution systems can be performed using distributed or centralized methods as described later in the text. However, to optimize volt/var control, it is imperative that devices are properly located in the distribution system. This can be achieved by specially designed computer software.

The comprehensive analysis tool for industrial, distribution, and transmission power systems presented here is CYME [4]. This power engineering software is a suite of applications composed of a network editor, analysis modules, and user-customizable model libraries. The distribution analysis software (CYMDIST) is designed to assist engineers in distribution planning, operation, and optimization studies for radial or looped systems with multiple DG sources. User can graphically build their own distribution system or import data from other software using an efficient graphical user interface. Simulation results can be displayed directly on one-line diagrams or other options can be used to analyze results and prepare reports. The CYMDIST program is designed for planning studies and simulating the behavior of electrical distribution networks under different operating conditions and scenarios. The analysis functions such as load flow, short-circuit, and network optimizations are performed on balanced or unbalanced distribution networks that are built with any combination of phases and configurations. For integrated volt/var control, a function for optimal device placement and sizing is efficiently implemented in this software.

DISTRIBUTED VOLT/VAR CONTROL

The traditional method to improve volt/var conditions in distribution systems was to optimize placement of VRs and capacitor banks by computer software. In these arrangements, each device operates individually based on its local measurement data. Distributed volt/var control provides improvements such as reduced voltage violations, increased power factor, and reduced reactive power generation from the generators.

CENTRALIZED VOLT/VAR CONTROL

The centralized system presented in this paper is based on the Yukon advanced energy services platform (Yukon system) — a powerful software suite that is innovative, flexible, and scalable for applications [5]. The Yukon system automates the process of managing power factor, voltage magnitudes, and reactive power on the distribution system. The volt/var management may be implemented by encompassing hundreds of substations.

Centralized volt/var control provides improvements such as flattening feeder voltage profiles within the target limits; maintaining near-unity power factor (minimized losses); voltage change on demand (Demand response - conservation voltage reduction); prevents voltage limit violation; automated regulation coordination after feeder reconfiguration; and detection of voltage regulator and capacitor bank switching and operational problems.

For example, business cases for deployment of the Yukon system may be based on the fact that 1% voltage reduction results in 0.5% to 0.7% reduction in loading.

Principle of IVVC Operation

The Yukon system analyzes (in real-time) feeder voltages obtained from VRs, LTCs, capacitors banks, and voltage sensors positioned at various locations on the distribution system, and from customer meters (see Figure 2). Based on the assigned operational cost, the Yukon system sets a control period during which the measurement is performed. The operational cost is determined from the measurement data set compared against substation power factor and voltage magnitude targets. The objective is to minimize the operational cost by maintaining power factor and voltage magnitudes as close as possible to the target values.

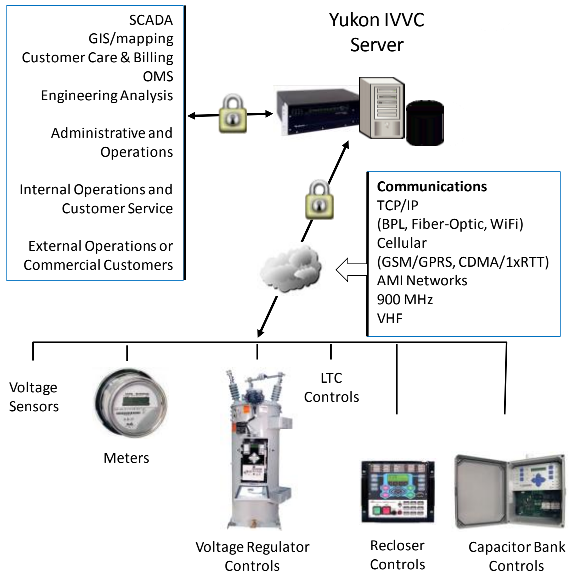

Figure 2 Example IVVC Network diagram

At the beginning of each control period, the Yukon system simulates different capacitor bank switching status changes using an iterative process to determine if the operational cost improves. Simulated changes in power factor and voltage magnitudes are compared to historical data archived by the Yukon system. If the operational cost is improved as desired by a particular capacitor bank status change, the system will issue a command for that capacitor bank to change its status. Successful status change is confirmed via a new set of measurements.

During each control period, if the Yukon system determines that no capacitor bank status change will improve the operational cost, the system will analyze the measured set of voltages to determine if an LTC or VR operation would improve the voltage magnitude. If yes, the Yukon system issues a raise/lower command to the LTC or VR. After completion of the LTC or VR analysis, the Yukon system will wait until a new control period starts and capacitor bank switching analysis is performed.

The power factor cost at the substation bus location is calculated from the difference between the measured power factor and the target power factor multiplied by the power factor weight. The voltage measurement cost is calculated based on the average and minimum voltage measurements multiplied by the voltage weight. Total calculated cost is the sum of the power factor cost and the voltage measurement cost. The Yukon system calculates the cost based on the real-time measurement data set and simulated status change of each capacitor bank, and compares the real-time cost with the estimated costs. If the lowest estimated cost associated with change in a capacitor bank status is less than the real-time cost, the system will issue command for status change of the capacitor bank.

Rate of Data Measurement. Real and reactive power, current, and voltage are required in each control period. Voltages, current, and real and reactive power are measured every 60 seconds. An LTC or VR tap position may change once every 15 minutes or a maximum of 50 times a day.

Loss of Communication. Controls support the identification of communication network failures and perform the transition to local automated control when a communication network failure has occurred. The Yukon system also supports loss of communications functionality. The state of communications is evaluated by validating device measurement data and device measurement data time stamps during each IVVC control period.

The IVVC supports a configurable percentage of stale data measurements. The Yukon system compares each device measurement date/time stamp to the present time. If the difference is greater than the specified configurable stale data time period, that particular measurement is marked as stale data. The Yukon system will tolerate a pre-defined number of stale device measurements based upon a utility specified configurable percentage. If for example, the 10% of the device measurements are stale, and the configurable percentage of stale device measurements is 20%, the Yukon system will continue to analyze and operate the devices to which it continues to communicate. However, if 30% of the device measurements are stale and the configurable percentage of stale device measurements is 20%, the Yukon system will disable automated control.

The Yukon system may be integrated with SCADA, DMS, or OMS systems to support the system reconfiguration. Also, less SCADA systems are required when the Yukon system is deployed.

Field Experience

This section summarizes field experience with the Yukon system implemented in a number of locations in the USA.

The system analyzes voltages at pre-defined locations (substations, capacitor banks, and other voltage monitoring points), then determines if any capacitor switching operations will flatten the voltage profile such as shown in Figure 3.

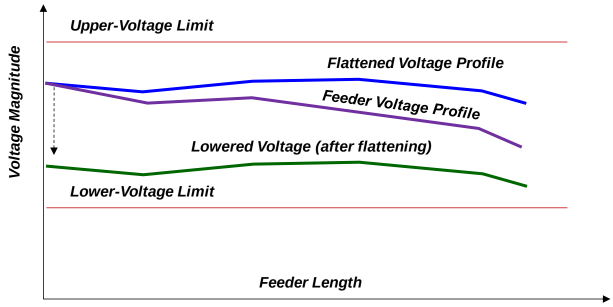

Figure 3 Flattening the Voltage Profile

If all voltages are between the target ranges, the substation voltage is lowered, but not below the lower voltage limit.

Simultaneously, near-unity power factor is also maintained as shown in Figure 4. The Voltage flattening solution may be overridden if the leading power factor would exceed the limits.

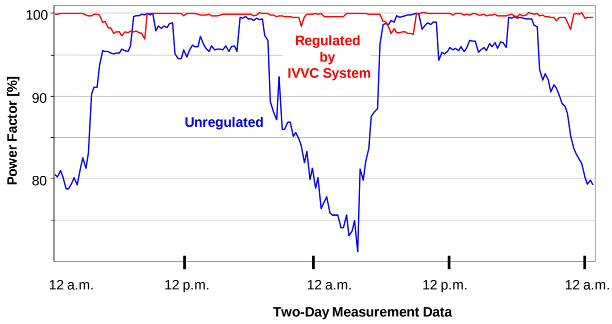

Figure 4 Effects of Yukon System Control to Maintain Near-Unity Power Factor

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