Time Series Simulation of Voltage Regulation Device Control Modes

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***Abstract* — The integration of photovoltaic systems (PV) on distribution feeders may result in unfavorable increases in the number of operations of voltage regulation devices, or may decrease the effectiveness of their settings, resulting in the need for mitigation. Voltage regulation devices commonly use controllers that have time delay settings and sample power system parameters at a high frequency. Quasi-static time series (QSTS) power flow simulation is necessary to properly analyze the impact of distributed PV integration on voltage regulation device operations. It is possible to properly simulate complex control algorithms through a COM interface program, resulting in more realistic and valuable results.**

***Index Terms* —distributed power generation, open source software, photovoltaic systems, power system interconnection, power system modeling, time series analysis, voltage control.**

I. INTRODUCTION

High penetration photovoltaic system (PV) integration into distribution systems is increasing. PV integration has the potential to cause several adverse effects. One concern is the increase in voltage regulation device operations, or a decrease in the effectiveness of control settings, requiring mitigation measures.

Interconnection studies are performed and designed to identify the impact(s) of integrating PV and assist in composing any necessary mitigation(s) [1-2]. Present modeling and analysis practices may be inadequate to fully reveal potential system impacts [3].

Common voltage regulation devices are substation transformer load tap changers (LTCs), substation and line voltage regulators (VREGs), and switched capacitors. These devices are operated by control units, which sample pertinent system parameters at a high frequency and usually incorporate time delay settings. Snapshot power flow software programs are still the most commonly used modeling tools, which are not capable of simulating the time-dependent aspects of the distribution system.

Quasi-static time series (QSTS) capable simulation tools have recently emerged to make time series modeling possible. QSTS simulations allow for proper modeling of control time delays and voltage regulation device operations. QSTS analysis introduces new challenges, including new model development, more profound system details, and more intense data inputs [3].

Voltage regulation device controls reference system parameters at sub-second frequencies to implement control settings with time delays. Control time delays are defined on the order of seconds, demanding higher resolution load demand data than has historically been collected. The demand for higher resolution time series data also applies to modeling PV systems that can change quickly on very short timescales. While, at least in the near future, shortcomings in available PV and load data resolutions will continue to be inevitable in many cases, improved simulation of voltage regulation control settings can be achieved with QSTS simulation.

Voltage regulation devices have evolved over time to provide increasingly complex and customized control modes for many different applications. It is unlikely to find QSTS capable software that offers the ability to simulate all existing control modes. However, if the QSTS software offers COM interface capability, it is possible to develop and implement control algorithms through an external program. Properly modeling control algorithms in QSTS simulations will improve accuracy and yield more valuable results.

II. VOLTAGE REGULATION DEVICE OPERATIONS

There are three types of voltage regulation devices commonly used on distribution systems: LTCs, switched capacitors, and VREGs [3]. The main purpose of voltage regulation devices is to keep the distribution system steady-state voltages within desired limits, such as ANSI C84.1 voltage limits [4], ultimately ensuring acceptable end-user voltage levels. This requires active monitoring and reaction due to the changing loads on a feeder and the direct impact they have on the voltage profile of a distribution substation and feeders [3]. Voltage regulation device are capable of changing the voltage on a feeder without interrupting service.

The addition of PV may affect how these devices operate, depending on their operational settings, location, and load level. The major concern is whether PV generation causes increases in the number of LTC or VREG tap changes, or capacitor switches, and how to mitigate excessive increases. An increase of tap or switching operations would require mitigation if the reliability or cost implications are deemed to be significant. Another concern is the need for updated control settings to accommodate for the changes resulting from PV interconnection.

The voltage regulation schemes on distribution systems can be complex with many factors to be considered including the devices deployed (LTCs, VREGs, and capacitors) and the location and control settings of each device. Coupling these

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factors with a unique deployment of PV, introducing its own factors of location, size, and variability, it becomes a difficult problem to identify a worst case period to study. In addition, the worst case period for one device may not coincide with the worst period for another. Identifying appropriate periods to study for the many possible scenarios is a complex process that will likely rely on engineering judgment. The longer the study period, the better the long term estimate of operations. For any study period shorter than one year, it may be desirable to make a conservative estimate based on a worst case period [3].

A. Device Descriptions and Operational Parameters

An LTC is a device attached to a substation transformer that allows for voltage regulation by changing the transformer turns ratio under load without interruption. The LTC typically has the ability to adjust the voltage ±10% with ±16 steps [3]. Voltage can be monitored on only one phase or by an averaging method using all three phases; however, the LTC is gang-operated and any tap-changing action affects all three phases on all feeders connected to the transformer. VREGs are capable of regulating voltage in essentially the same manner as LTCs, except they are single phase, independent devices that may be connected anywhere on the feeder and are usually set to control voltage on each phase individually.

LTCs and VREGs require control devices that regulate the voltage according to adjustable settings. All control devices operate at a lower voltage, so a potential transformer (PT) is used to convert the distribution system voltage to a control signal voltage. The most basic control devices include a voltage set point, a voltage bandwidth, and a time delay. Another common control setting may be the use of Line Drop Compensation (LDC). LDC allows for the setting of a voltage control point other than at the location of the LTC or VREG by programming estimated real and reactive impedances to the desired point and then monitoring the measured current in that direction to estimate voltage drop [3]. LDC settings are set in terms of R and X impedance in volts, and the line current is monitored though a current transformer (CT).

Switched capacitor banks may also be used for voltage support. Switched capacitor banks also require control devices that may offer many different control modes. A common control mode is to switch the capacitor directly according to the voltage at that capacitor location, with voltage setpoints defining when they are energized and de-energized and a switching time delay that pertains to each threshold. Switched capacitors set for voltage support are affected by the change in the voltage profile of the feeder resulting from the addition of PV. If the switched capacitors are set for PF support, they are also affected by the change in measured PF on the feeder caused by PV displacing active power from the source [3].

The time delay setting determines the amount of time a voltage deviation is allowed to occur outside of the specified thresholds before action is taken to bring the voltage back within range. The ability to simulate this time-dependent setting is critical to properly assess the device operations.

III. QSTS SIMULATION

Commercial circuit analysis tools have historically provided the capability to analyze the power system at specific snapshots in time. More recently, simulation platforms have been developed with the capability to perform QSTS simulations. Early QSTS tools like OpenDSS [5] have been developed for research and academia, and new commercial circuit analysis programs now offer this capability.

The main advantage of using QSTS simulation is its capability to properly assess and capture the time-dependent aspects of the distribution system. QSTS produces sequential steady state power flow solutions where the converged state of each time-step is used as the beginning state of the next. Examples of the time-dependent aspects of power flow include the interaction between the daily changes in load and PV output and the effect on voltage regulation device controls. Another advantage of QSTS is the ability to quantify both the magnitude of an impact as well as the frequency and duration of the impact [3].

A. QSTS Data

The application of QSTS simulation requires more data to represent the time-varying PV output coincident with time-varying load. The time series data is often difficult to obtain as the measurement equipment at the feeder and for the proposed PV plant will frequently not be available at the desired time resolution. It is common for utilities to record feeder level load data at 15-minute or 1-hour resolution, where interpolation may be the best option for obtaining higher resolution data [3]. The necessary data set can become very large depending on the resolution and length of simulation desired, causing simulation processing times to increase and become burdensome. Data can be interpolated to run a QSTS simulation, but 15-minute average data does not capture the variability necessary to accurately model voltage regulation equipment operations on a seconds timescale with respect to load variations. Future research could include methods using a load variability models to add a certain amount of high-resolution synthetic variability to the load data.

Details of voltage regulation controls, such as time delays, also need to be represented. If the simulation is performed in a simulation platform like OpenDSS [5] that is different from the platform in which the data is maintained, the data conversion effort between platforms can be substantial. Automated conversion tools have been developed for certain platforms, but they are not readily accessible or require a significant amount of expert supervision [3].

Solar plant output time series data is typically not available for the specific scenarios of interest. Estimated PV output profiles need to be synthesized from either irradiance or proxy data from similar plants. Ideally, proximate time-coincident data should be used to capture the correlation of load and PV plant output. If actual or simulated time-coincident data is unavailable, performing QSTS using a basic diurnal PV output pattern could still provide some valuable insights. As more PV systems are being monitored, high resolution plant output data is increasingly available [3].

IV. Implementing Control Algorithms

It is very important to properly model the correct control settings to get accurate results and to understand how the power flow software platform used for simulation implements control delays and the reset of delay counters. The time delay counter is triggered when an out-of-band voltage condition occurs. It is not likely to find every control mode built into a QSTS simulation platform. However, if COM interfacing is an option, it is possible to develop and implement control modes through external programming software.

A. Control Modes

Most modern LTC/VREG controls offer several modes of operation, such as sequential, time integrating, and voltage averaging [6]. There are also settings designed to offer flexibility of control during reverse power, such as bi-directional and cogeneration modes. These control options can make a difference in the way PV affects voltage regulation switching operations; therefore, it is important that the correct control settings be determined and properly implemented in the simulation software.

Sequential mode is common and is sometimes the default time delay control mode. During the time-out period in sequential mode, the voltage is continually sampled at a sub-second rate. If during the time-out the voltage returns to a level within the bandwidth, the timer is reset. If the voltage remains out of band for the duration of the time delay setting, an appropriate tap change is activated. After the first tap change, all subsequent tap changes, if necessary, will use a shorter inter-tap time delay of around a couple of seconds, allowing the sensing voltage to stabilize before continuing until the voltage returns to within band, resetting the timer [6].

A time-integrating mode may also be offered, where a voltage out of band initiates the timer, counting the time out of band up to the time delay setting. If the voltage goes back within band before reaching the time delay setting, the timer is decremented (i.e. subtracting from any time spent out of band), in some cases by an accelerating factor such as 1.1 seconds per second, potentially all the way down to zero, essentially resetting the timer. If a voltage excursion remains out of band for the duration of the time delay, it will operate the same as sequential mode [6].

A voltage averaging mode may also be offered. In this method, when the voltage has gone out of band, a microprocessor monitors and averages the voltage over the duration of the time delay setting. The microprocessor then computes the number of taps it would take to bring the average voltage value back to the voltage set point (middle of the bandwidth) and executes that number of taps with no delay, up to a maximum of five taps [6].

There are also a number of reverse operation modes that determine the behavior of the voltage regulation device during reverse power conditions. Most controls offer a separate set of control parameters for reverse operation. Some reverse power operation modes can be very simple, such as remaining locked on the last tap position reached in forward operation, or tapping to the neutral position and locking after a specified duration of reverse power [6].

Other more active modes for reverse power are also available, such as bi-directional and cogeneration modes. Bi-directional modes simply implement a separate set of control parameters when in reverse power. Cogeneration modes can offer the ability to focus the voltage regulation on a certain point, such as a cogeneration interconnection point, regardless of the power direction.

Switched capacitor controls can offer several different control modes. Some of the more common modes include time schedule, voltage, temperature, VAr/PF, and current. All of these modes require respective parameter thresholds defining the levels to switch the capacitor banks on and off, and can incorporate a time delay for each where appropriate [7].

B. Implementing Custom Control Modes in Simulation

Through the availability of a COM interface, it is possible to implement more realistic control modes using programmable software, such as MATLAB [8]. OpenDSS is open source software with COM interfacing capability that allows for customization of the existing control algorithms. The COM allows interface with OpenDSS solution results, changing of circuit parameters, and commanding OpenDSS to perform actions.

OpenDSS can be used to solve the power flow, and control logic can be implemented in MATLAB to monitor the voltages and currents and control devices according to a customized algorithm. All OpenDSS control blocks, such as regulator controls, should be disabled to ensure there is no interaction between the two algorithms trying to control the same object. Before disabling, MATLAB can automatically read OpenDSS control object settings such as voltage set point, bandwidth, PT ratio, CT rating, time delays, LDC X and R settings, and any other necessary settings.

An example of the interfacing process for controlling a substation LTC is shown in Fig. 1. For each time step in the OpenDSS time-series power flow solution, MATLAB reads the transformer voltages and currents by setting the OpenDSS active element to the monitored transformer by using the COM interface. MATLAB calculates the control voltage based on transformer voltage and the PT ratio, as well as the transformer current, CT rating, and LDC X and R settings if an LDC is present.

If the calculated control voltage is out of band, the custom control logic block is entered. The custom control logic block can be customized, from simple delays to more complex controls and secondary checks, such as remembering when the most recent tap change occurred. When all conditions are met, MATLAB commands the appropriate winding in OpenDSS to move to the new tap position.

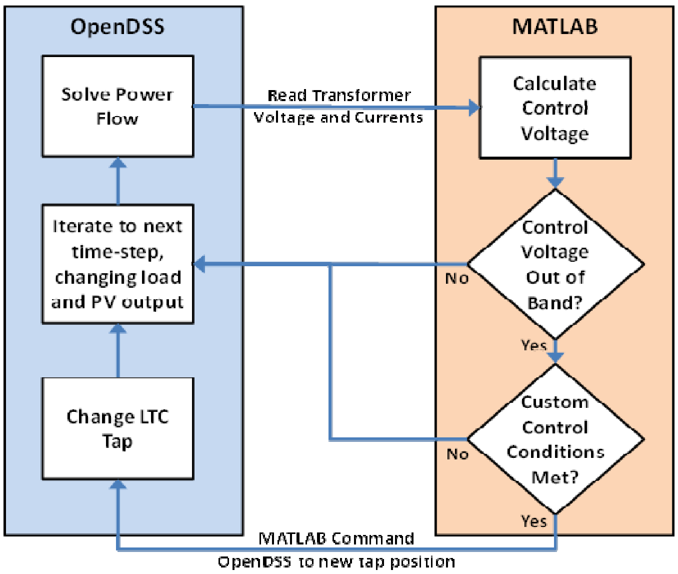

Fig. 1. MATLAB/OpenDSS interfacing for custom LTC control.

C. Custom Control Mode Simulation Example

The method of MATLAB controlling the LTC in an OpenDSS simulation was used to demonstrate the capability of implementing a customized control algorithm. A radial feeder model, Feeder A, was used. The topographic layout of Feeder A with major components highlighted is shown in Fig. 2.

OpenDSS offers a simple control algorithm for voltage regulators and LTCs that simply initiates the time delay with the first instance of an out of band voltage, then disregarding the voltage during the time delay, it simply checks the voltage at the end of the time delay and reacts according to whether the voltage is still out of band at that point. PV power output can be highly variable under cloudy sky conditions, potentially causing voltage variations that could be missed during the time delay in OpenDSS..

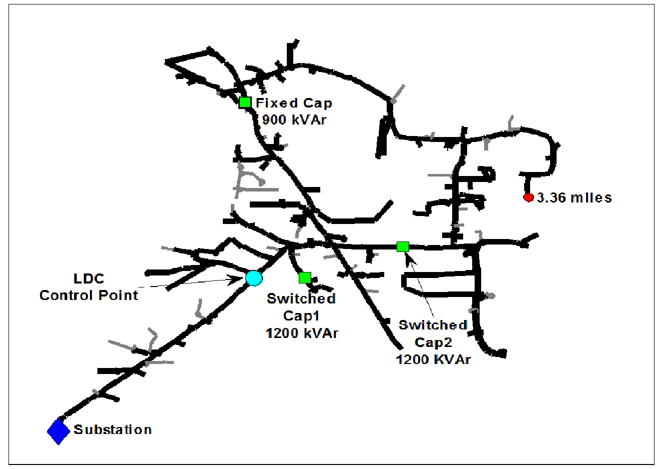

Fig. 2. Feeder A topographic layout.

Fig. 3 provides a visual example of the potential difference that can occur between a simple control algorithm and the sequential mode described in section IV.A, which properly simulates time resets when the voltage returns in band.

For both control modes shown, the voltage setpoint was 124V, the bandwidth was 2V, and the time delay was 60 seconds. The default control mode results in a tap change at 1:25:10 PM simply because the voltage is out of band when the initial counter expires. The sequential control mode does not result in a tap change here because the time delay was reset when the voltage surged back within band, resetting the delay. This illustrates a situation where properly modeling the actual control mode can make a difference.

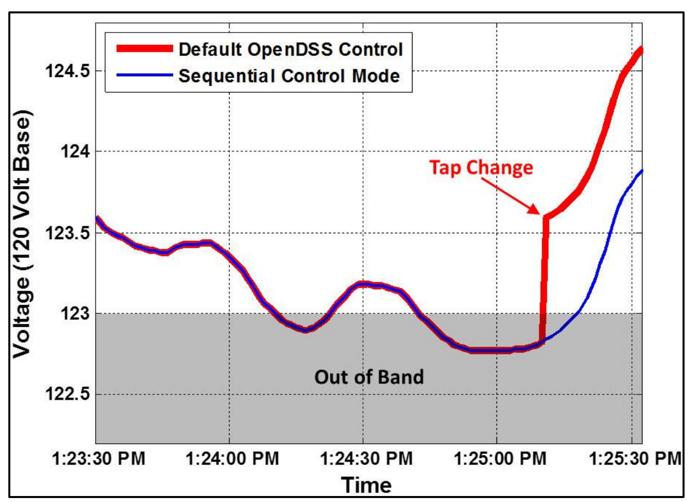

Fig. 3. Control mode simulation comparison.

Feeder A was used to run a 9-month simulation at one-second resolution using time coincident load and PV output data. A 7.5 MW PV system was simulated at the end of the feeder, representing 100% penetration of the feeder annual peak load. A base case without PV and the PV case were run utilizing both the default control mode in OpenDSS and the customized sequential mode using MATLAB. The use of external MATLAB control of the LTC was validated by implementing the default OpenDSS control algorithm through MATLAB. Identical results were obtained for the LTC taps and number of operations for the simulation period.

The load data was interpolated from the one-hour data points available. Load was allocated to the feeder based on transformer rated size and a 0.9 PF was assumed. The PV output data was estimated for this period using available one-second resolution irradiance data in the area. The PV output for a 7.5 MW PV system was estimated using the wavelet-based variability model [9].

The 9-month simulations at high resolution and detail take significant amounts of computer memory and simulation time. Future applications of methods like circuit reduction could be used to improve these simulations so that they only take a few minutes to run instead of 12 hours [10]. Fig. 4 shows a plot of the LTC activity for the 9-month simulation with PV using a sequential control mode algorithm through MATLAB.

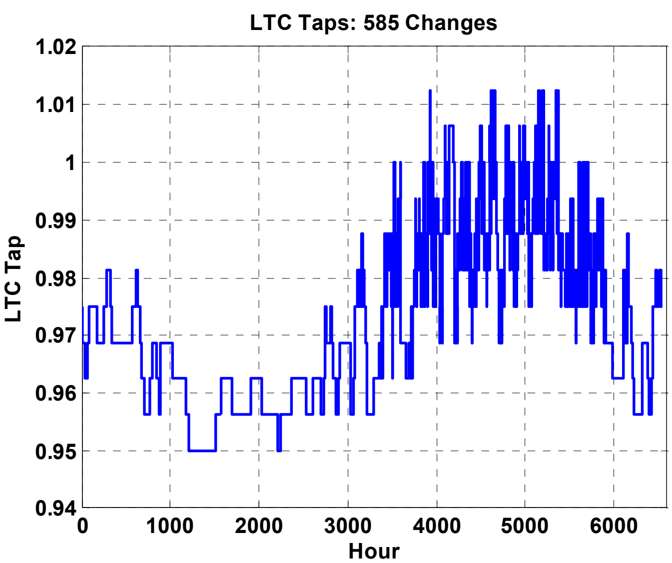

Fig. 4. LTC tap position controlled by MATLAB using sequential control mode during the 9-month simulation with 7.5 MW PV.

In this example, there were no differences in operation totals for the LTC found in either the base case or the case with PV when using the sequential control algorithm through MATLAB.

Conceptually, an LTC connected to a large transformer and stiff transmission source serving several feeders is less likely to be affected by PV and/or load variations during voltage regulation device time delay counters as a line voltage regulator or capacitor bank out on a feeder near a PV system, where voltage fluctuations are much greater. For the PV scenario, it was expected that the control mode would affect the number of operations during the simulation because of the high resolution variability. The results show that the control mode had no impact, mostly due to the fact that the PV penetration was 100% of the feeder load but less than 20% of the total substation load through the LTC.

Also, since the PV system was not large enough to ever exceed the substation load, an LTC such as the one in the example will not show the effects of properly modeling the reverse power control algorithms that may play a significant role in the number of operations observed for a line voltage regulator with a high penetration PV deployment downstream that causes frequent reverse power.

PV generation injects current into the system, resulting in a voltage rise at the PV location. The voltage change depends on both the current injection and impedance for the circuit path between the PV location and the nearest upstream voltage regulation device. The voltage difference between the voltage regulation device and the PV location is dependent on the direction and magnitude of the net current, the impedance and susceptance of the line, and the power factor. If the PV deployment level is high enough, a voltage rise will occur from the regulation point to the PV location. Fig. 5 illustrates the concept of voltage rise for PV at unity power factor for an overhead feeder with lagging load.

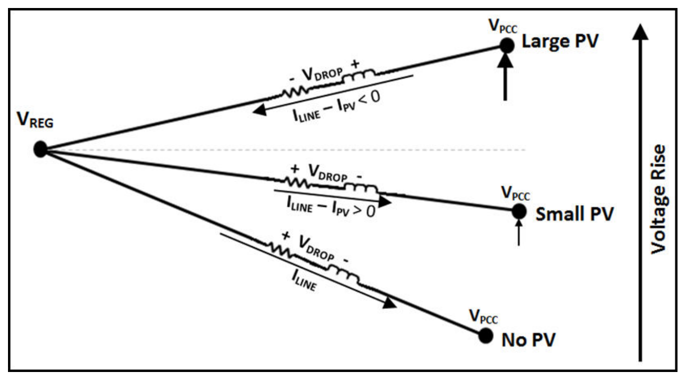

Fig. 5. PV Voltage Rise Concept.

V. Conclusions and Significance

There are many factors that need to be properly simulated in order to obtain valuable results from an interconnection study on voltage regulation device operations using QSTS simulation. While there are many aspects that will inevitably fall short of the desired simulation requirements, it is possible to correctly model control algorithms, which will increase the value of results. Proper modeling of control modes will increase confidence in results and mitigation measures, and in turn increase the actual effectiveness of the interconnection study.

While the example in section IV was chosen as a timely and accessible demonstration of the capability of properly modeling control algorithms, continued investigations could further demonstrate the value of proper control simulation, such as observing scenarios more sensitive to PV variability or scenarios with a high incidence of reverse power flow. An additional investigation angle for further validation would be to compare simple control algorithms and customized algorithms to field data.

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