MODELING THE EFFECTIVENESS OF POWER ELECTRONICS BASED VOLTAGE REGULATORS ON DISTRIBUTION VOLTAGE DISTURBANCES

James SIMONELLI
Gridco Systems – USA
jsimonelli@gridcosystems.com

Olivia LEITERMANN
Gridco Systems – USA
oleitermann@gridcosystems.com

Jing HUANG
Gridco Systems – USA
jhuang@gridcosystems.com

ABSTRACT

Utilities increasingly have access to new power electronic devices and controls to manage their networks, but these new tools must be evaluated to determine appropriate applications. Targeted, calibrated models can be used to evaluate whether a given device can be used to solve a particular problem, capturing the relevant aspects of large and complicated electrical networks. An example is provided of a system model developed in response to a customer power quality issue, and a power electronic device that was added to the model to determine whether its capabilities could successfully address the underlying problem.

INTRODUCTION

Induction motors can impose difficult current requirements on local electric grids, including large starting current surges and sudden increases due to mechanical load variation. These large and sudden currents can cause voltage disturbances for neighboring electric customers that may exceed the power quality (PQ) standards for the public network [1]. In addition, the power delivery from solar photovoltaic (PV) systems can also change the grid voltage rapidly. The resulting voltage variations can cause problems ranging from nuisance flicker to equipment failure.

To minimize the impact of these voltage variations, utilities tend to resort to grid reinforcements, lowering grid impedance by replacing conductors and transformers. Grid reinforcement is time consuming and expensive; thus it is prudent to evaluate alternative approaches. Traditional electromechanical control devices operate on time scales of minutes and are too slow to deal with these faster transients. Power electronic devices can offer active voltage control with the needed cycle level response [2][3][4]. The complexity of the electric grid system and of power electronic devices makes it challenging to gain confidence in the effectiveness of a solution without field deployment and measurement. Additionally, load flow modeling approaches [5] are effective at understanding the steady state characteristics, but are insufficient for studying motor start dynamics. We propose that dynamic simulation (in the time and phasor domains) and functional modeling calibrated with power quality measurements from the field can provide insight as to the effectiveness and limitations of a solution before field deployment begins.

GENERAL MODELING APPROACH

In order to evaluate the efficacy of the power electronic device for solving the power quality problems prior to installation and field testing, the following modeling was performed. First, the low voltage (LV) feeder structure was modeled, based on utility data, including PV and load sizes. To capture the dynamics of the observed motor start inrush, a motor size was selected which caused similar voltage changes in the model to the observed power quality problems. This calibration ensured that the model could provide relevant results. Next, the characteristics of the power electronic device under consideration were modeled and calibrated to the specific device performance. Finally, the power electronic device model was merged with the LV feeder model to measure effectiveness at different installation locations and perform limit testing.

MOTIVATION FROM CUSTOMER POWER QUALITY ISSUES

This approach was implemented in cooperation with a European utility experiencing dynamic voltage swings in a small village with an electric layout as represented in Figure 1. This is a 400 V LV line with a branch about 600 m long serving several customers. This type of extended secondary network is common in Europe but not typical in the US, and it complicates the placement of LV power electronic devices because of the larger secondary voltage drops. There is also a 24 kW PV generator connected at one of the customer sites, which is many times the estimated 1.1 kW minimum neighborhood load. The downstream motor loads were causing problems for the other customers on the secondary due to the voltage dip associated with motor transients. Power quality measurement equipment was installed by the utility near the distribution transformer and near the end of the line to investigate the causes of reported customer voltage problems. A sample voltage measurement from the power quality meter is provided in Figure 2. Examples of the substantial voltage dips which were causing problems for other customers can be seen in this figure. Figure 3 shows measurements from the power quality meter over about two weeks in April 2014, during which the voltage repeatedly falls below the -10% limit (207 V), and occasionally is as low as about 187 V (about 0.81 pu). These voltage excursions were causing problems with customer equipment. Given this scenario, a fast-acting power electronics based device was evaluated to determine whether it could serve to mitigate or reduce the poor voltage quality seen by the customer loads, or whether more costly and disruptive grid reinforcement or reconfiguration (running dedicated lines) would be required.

A new class of power electronics-based voltage regulator was considered to address this problem. This device provides a series voltage correction which affects only the downstream loads. The system and the device were both modeled to evaluate the efficacy of the device for solving this customer issue.

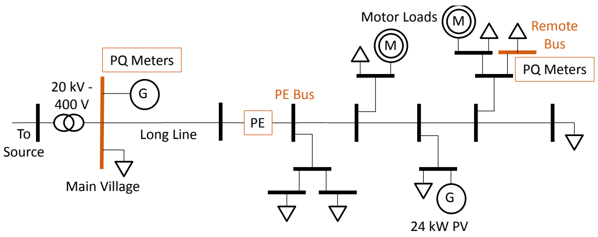

Figure 1. One-line diagram of feeder system under consideration.

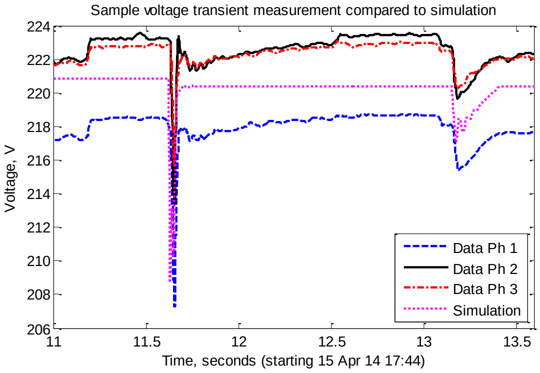

Figure 2. Short-term voltage transient measured at the remote bus of Figure 1, plotted alongside calibrated simulation data of a motor start and motor torque step event.

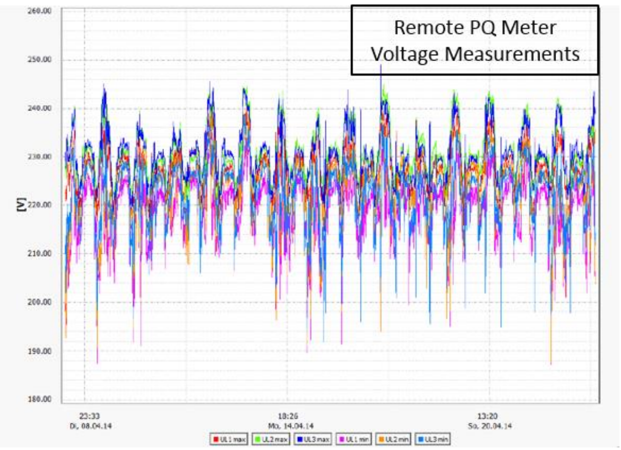

Figure 3. Sample voltage measurements from power quality (PQ) meters at the remote bus of Figure 1. Note that the voltage shows excursions lower than -10% from the 230 V nominal (207 V) and as low as about -19% from nominal (187 V).

SYSTEM MODEL CONSTRUCTION

The first step in this modeling approach is to make an applicable model of the distribution area. MATLAB Simulink SimPowerSystems [7] was used to develop this model as it is a relatively simple feeder and the tool can perform the load flow, phasor and time domain simulations that are necessary to validate motor start dynamics. MATLAB Simulink also provides the necessary building blocks to create a behavioral model (in the time and phasor domains) of the power electronics device which closely matches lab test performance. Other modeling tools could have been used for the actual simulation that would yield the same results

A system model was constructed based on the equipment data provided by the utility. This included conductor lengths, gauge, and interconnection, as well as approximate load. The attached nameplate PV generation and its location was also provided. A static load flow and electrical model corresponding to the known system state were developed. The results of a load flow model which confirmed the steady state characteristics of the feeder with utility data can be seen in Figure 4. To capture the measured motor start dynamics, the motor sizes were then approximated based on information from the utility as well as engineering judgement. Some reasonable induction motor configurations were explored, and it was determined that a 4 kW, 1430 rpm induction motor made an appropriate model choice. This was a standard motor selection from the MATLAB Simulink SimPowerSystems simulation package. The selected motor size caused voltage dips of approximately the same magnitude as those measured for both motor start (short deep voltage dip) and mechanical load change (torque step: longer, shallower voltage dip). Figure 2 shows the simulated three-phase voltage alongside the measured data and the similarity between model and measurement is clear. This lends confidence in the usefulness of the model for evaluating solutions to the power quality issue in question. The motor size can also be increased to make estimated currents more conservative.

To mimic the daily voltage variation which is recorded in Figure 3, a sequence of load changes, solar power changes, motor starts, and motor torque steps was synthesized and repeated for several days of simulation time using the on/off and magnitude profile shown in Figure 5. The objective was not to model the dozens for motor starts/stops and PV/Load fluctuations per day, but to capture the envelope of the worst case transients. The resulting simulated voltage profile is shown in Figure 6 (top waveform). The simulated voltage compares well with the voltage measurements of Figure 3 (in duration and magnitude as every transient was not modeled).

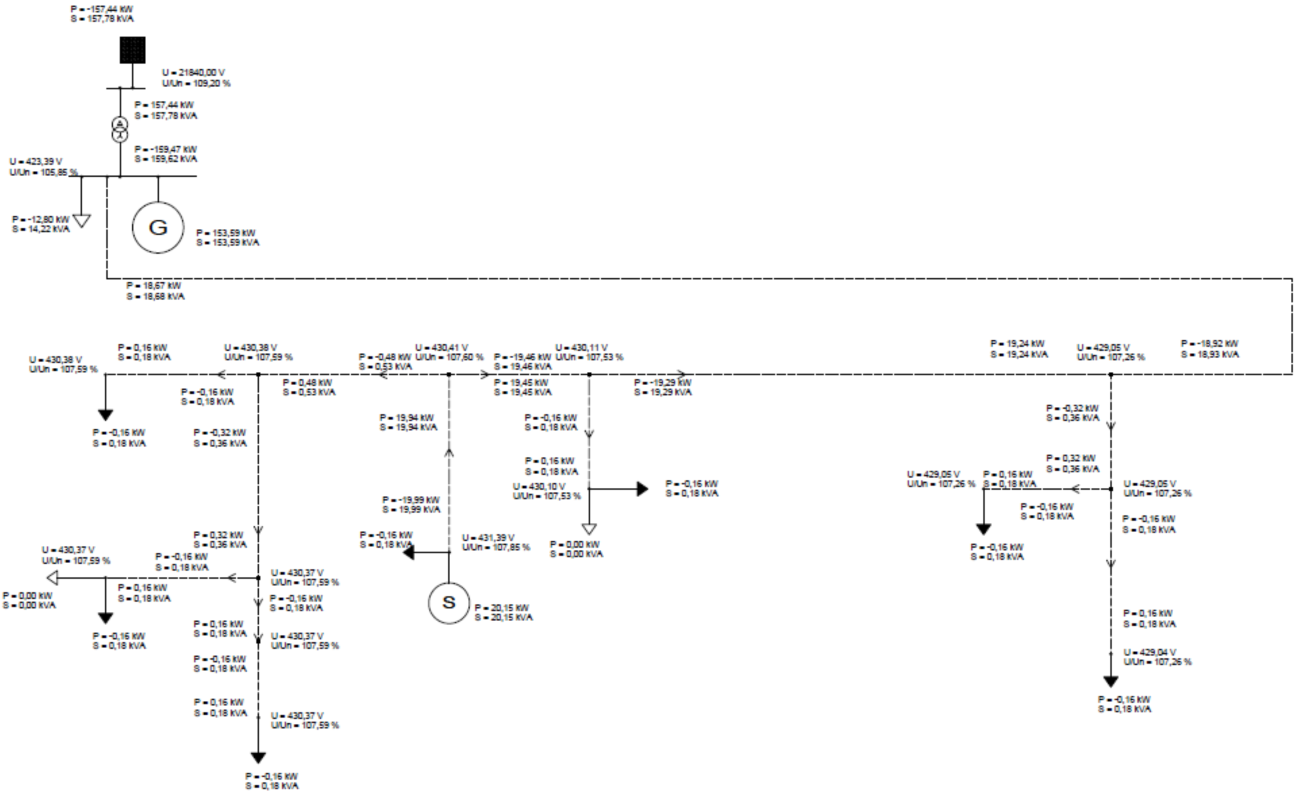

Figure 4 One-line diagram of circuit of interest, along with load flow results from a light-load case. The utility's own load flow results were replicated in the Simulink-based model.

.

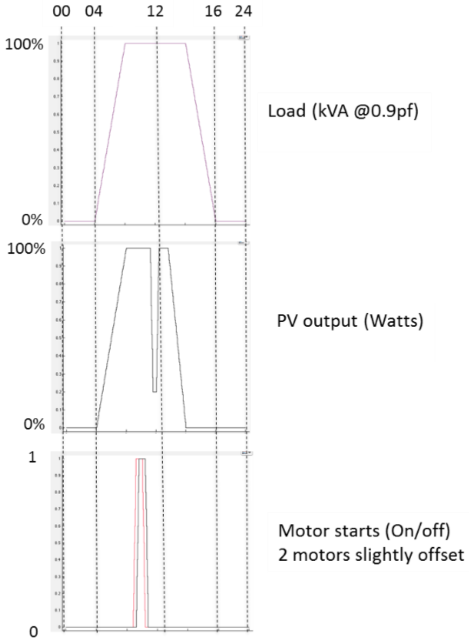

Figure 5 Representation of load and PV time of day profiles accompanied with motor start times. This profile was used to closely represent the worst case dynamics observed in the measured field power quality data

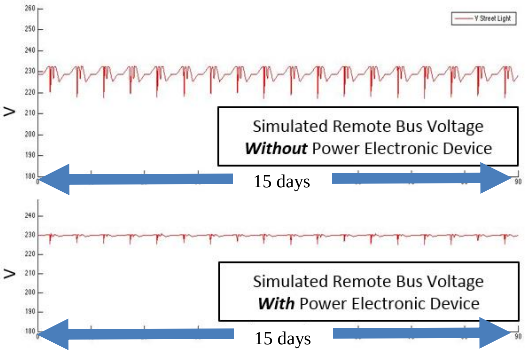

Figure 6. Comparison of simulated voltage at the remote bus with and without the addition of a power electronics based regulator over several days. The top portion shows the voltage before the addition of the power electronic regulator to the simulation, while the bottom portion shows the voltage after the regulator has been added. Compare the top portion to the measured data of Figure 3.

MODELING A NEW DEVICE

In order to draw conclusions about the effectiveness of a particular power electronics product in resolving the issues found, a model of the device was also created. The device comprises a shunt current source and a series voltage source. Both sources are implemented as power electronic converters with a shared dc bus. The series voltage source is used to regulate the downstream voltage to a fixed set point for input source voltage variations by as much as

±10% of nominal. The full device specifications can be found in [6]. The device model was organized in a very similar fashion, with a shunt current source and a series voltage source along with appropriate controls. A schematic representation of a portion of the device model is shown in Figure 7.

The behavior of the model was compared to the behavior of the device in question under several test cases to verify the model fidelity. A comparison of the device's modeled and lab test response to a 12 cycle 230V to 184V sag event is shown in Figure 8. The figure shows that the model provides a reasonable representation of the voltage control response of the device in approximately the same time frame as the voltage transients being addressed.

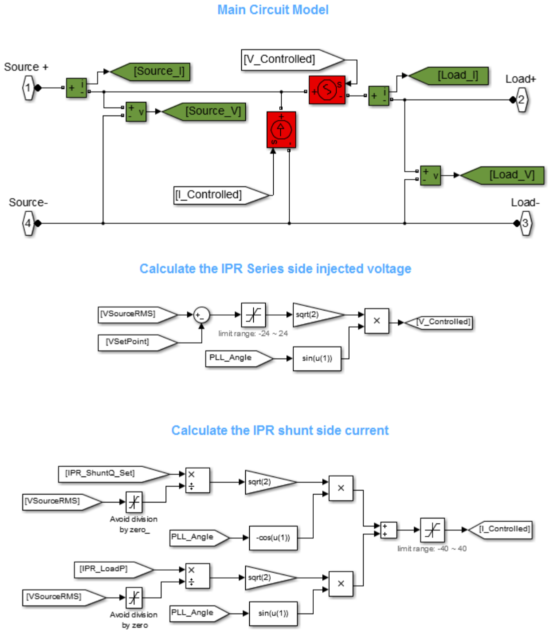

Figure 7. Simplified block diagram of the operation of the power electronic regulator model. Both the physical device and the model use a series voltage source and a shunt current source, along with appropriate controls.

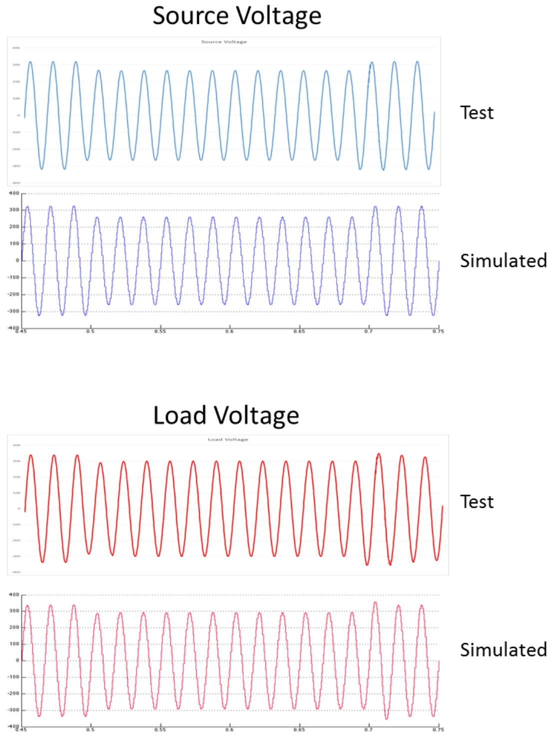

Figure 8 Comparison of lab test and simulation results for a 12 cycle sag event shows near identical dynamic behavior of modeled response to test data

MODELING RESULTS

The power electronic device was added to the system model to judge whether it would be able to solve the customer power quality problem. The effect of the added power electronic device on the modeled voltage is shown in Figure 6 (bottom waveform). It can be seen that the voltage at the output of the power electronic device, as well as at the customers, is improved from the initial case. This provides confidence that the power electronic device can solve the indicated power quality problem. In the base case (top), the voltage pattern seen by the remote bus of interest was largely replicated with the simulation of repeated motor starts and motor torque steps (compare Figure 3 and note discussion above about modeling transient magnitudes). The bottom plot shows the modeled result when the power electronic device is added. The voltage excursions seen by the distant customers are much smaller and they start from a higher nominal as the output of the power electronics device keeps out output fixed at 230V, mitigating the voltage drop across the 600m cable from the sub-station.

One finding from the analysis was the value in performing calibration and modeling in both the time domain and the phasor domain. The time domain model allows for greater depth of understanding of sub-cycle dynamics that would be observed in the real feeder. Once the cycle dynamics were understood, a simpler phasor model, which runs approximately 10x faster, proved better for running simulations of longer time durations and performing more limit testing with reasonable simulation times. An example of time domain response is shown in Figure 9. Similarly the top portion of Figure 6 shows a calibration response using phasor models, which may be compared to the measurements in Figure 3.

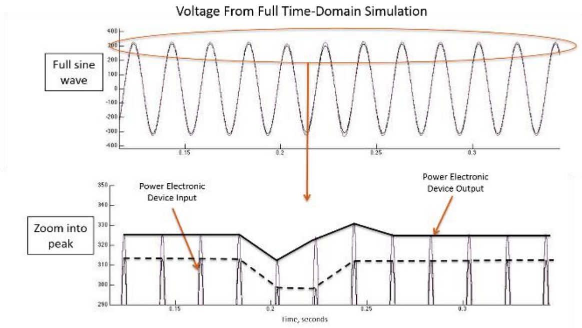

Figure 9. Voltage at output of power electronic device in full time-domain simulation in which the power electronic device is regulating voltage. Note the cycle-by-cycle voltage correction.

FIELD CONFIRMATION

Because of the positive results from the modeling process, the utility has elected to install this device on its network in this location to address the customer voltage problems. Figure 10 shows some preliminary results from the installation, including the voltage at the input and at the output of the power electronic device and the power through the device over several days. It should be noted that the data shown in Figure 10 only depicts RMS voltage snapshots at 30 second intervals as more granular PQ data was still being gathered at time of this writing. However, even with this more coarse data, the initial field impact looks much improved. As expected, the power electronic device is regulating its output voltage to a fixed setpoint, and so is reducing the voltage variation that may be expected at the remote bus from Figure 1. This is consistent with the modeled results.

The modeling of the system prior to installation ensured that the rating of the device was sufficient to address the current transients and voltage changes that would be expected. This has so far been the case. In this way, utility engineers have been able to address a challenging power quality problem.

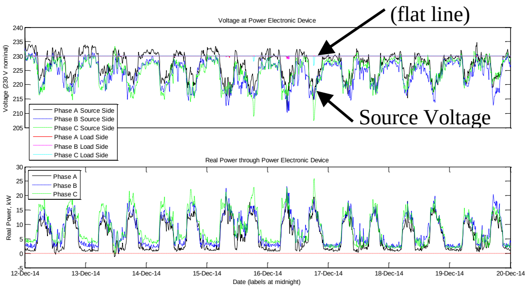

Figure 10. Preliminary voltage and power flow data from the power electronic regulator as installed to address the customer power quality issue. To date, the device is appropriately regulating its output voltage and has improved power quality at the site.

CONCLUSION

As utilities acquire new tools to manage their distribution grids, the ability to evaluate various options to resolve any issues becomes increasingly important. This is especially true in networks that are being pushed close to their limits and are integrating additional next-generation devices like distributed generation and electric vehicles. In-depth modeling of a problem may be required in order to evaluate a range of responses. A properly constructed model can determine whether a given device at a particular location can be successful prior to any hardware testing. It is important that models be calibrated at the time and voltage scales of interest to both the existing network and to any new devices to be added. This ensures that the problem can be reproduced and that the simulated solution will be representative. Once a solution has been fully modeled for the network, a utility may proceed to implementation with confidence. A successful modeling result can reduce overall costs by ensuring that a solution is appropriate prior to an expensive field trial.

REFERENCES

[1] Standard EN 50160, "Voltage characteristics of electricity supplied by public distribution systems," 2010.

[2] T. Gonen, 2008, Electric Power Distribution System Engineering 2nd Edition, CRC Press, Boca Raton FL USA, 444-475.

[3] J. M. Bloemink, T. C. Green, and S. Member, "Benefits of distribution-level power electronics for supporting distributed generation growth," IEEE Trans. Power Deliv., vol. 28, no. 2, pp. 911–919, 2013.

[4] A. K. Barnes, V. Martinelli, J. Simonelli, 2014, "A local voltage regulator that improves energy savings under advanced volt-var control," *2014 IEEE PES T&D Conf. and Expo.*

[5] A. K. Barnes, V. Martinelli, H. Wrede, A. Kam, J. Simonelli, 2014, "Load-Flow Modeling of a Three Phase Local Voltage Regulator," *Proceedings CIRED Workshop.*

[6] B. McMillan, P. Guido, O. Leiterman, A. Gonzaga, R. McFetridge , 2015, "Application of Power Electronics LV Power Regulators in a Utility Distribution System" *2015 IEEE Rural Electric Power Conference*.

[7] MATLAB Simulink and SimPowerSystems Toolbox Release 2013b, The MathWorks, Inc., Natick, MA, United States.