A COMPARISON OF FIELD RESULTS WITH MODELED BEHAVIOR FOR A POWER ELECTRONICS REGULATOR USED TO MANAGE DYNAMIC VOLTAGE VARIATION ON A FEEDER WITH HIGH PV CONTENT

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ABSTRACT

Electric utilities have an obligation to deliver power to their customers within set voltage tolerances. As distributed photovoltaic generation becomes increasingly prevalent, controlling the voltage at the customer becomes increasingly difficult. This paper describes the field trial of a power electronic device which regulates the voltage on the LV network to mitigate customer voltage issues. The device fixes the voltage partway down a long LV feeder and thereby improves the voltage profile for downstream customers.

INTRODUCTION

Key factors that have historically driven engineering design rules for Distribution Network Operators include unidirectional power flow and predictable customer load patterns. Both are changing dramatically with high penetration levels of distributed energy resources, in particular solar photovoltaic (PV) generation. Customer voltages rise during the lower load period midday when solar power generation is peaking locally, and fall at times with high load and little or no PV. Innovations in power electronics systems can help existing distribution systems be more flexible and resilient to these changing needs, for example by addressing this voltage variation over the course of the day. A new class of power electronics based in-line power regulator, scaled for low voltage (LV) secondary applications, offers dynamic voltage regulation, reactive power compensation, and harmonic cancellation, integrating into existing utility communications and operations systems.

OBSERVED POWER QUALITY ISSUES

Utilities have a responsibility to deliver power to customers within specified voltage, frequency, and waveform ranges. E.ON (of Germany), like many utilities, is handling increased customer installation of DG, including solar PV generators. This renewable generation, while promoting overall societal goals like clean energy, can cause voltage problems in the electric distribution system. These problems can include high customer voltage due to voltage rise from reverse power flow and interference with distribution protection schemes. At the same time, increasingly common power electronic and other nonlinear loads combine with inverter-based PV generation to increase the magnitude of harmonics on the grid, leading to higher losses and lower voltage quality for all customers.

In Germany, public utilities are subject to the EN-50160 voltage standard [1], which requires them to deliver voltage within ±10% of nominal (230 V) to their customers. While this is the absolute voltage limit, in practice, utilities are encouraged to take action when the voltage variations exceed +/- 5% of nominal. Given that it may take time to understand the causes for these variations and engineer an acceptable change, this protocol allows the utility to be proactive, minimizing the likelihood that the problem worsens and exceeds the ±10% limit.

The Bavaria region of Germany has a relatively large amount of distributed solar PV generation. On one circuit, a long LV feeder with small load and substantial PV generation was found through load flow modeling to be at risk of high voltages during light load, sunny days. When the PV was generating, reverse power flow was expected to lead to voltages at the customer meter that are far higher than at the distribution transformer, to the extent of exceeding the ±10% voltage limit at times.

Aside from the tested device, the mitigation options for voltage problems on this circuit are limited, and include reconductoring with larger-gauge wire and replacing the distribution transformer with a lower-impedance model. Both of these approaches are of limited efficacy. Altering the voltage at the medium voltage (MV) primary is limited by the requirements of neighboring circuits.

FIELD TEST SETUP

This paper describes the field trial of a new power electronics based LV inline power regulator (LV-IPR-150) added to the secondary network, about 250 m downstream of the distribution transformer. Further description of the site selection analysis for the field trial may be found in [2][3]. The secondary network extends about another 250 m past the device and serves six customer loads, as well as nearly 150 kW of distributed PV generation. A simplified one-line diagram of the placement of the regulator in the system is offered in Figure 1.

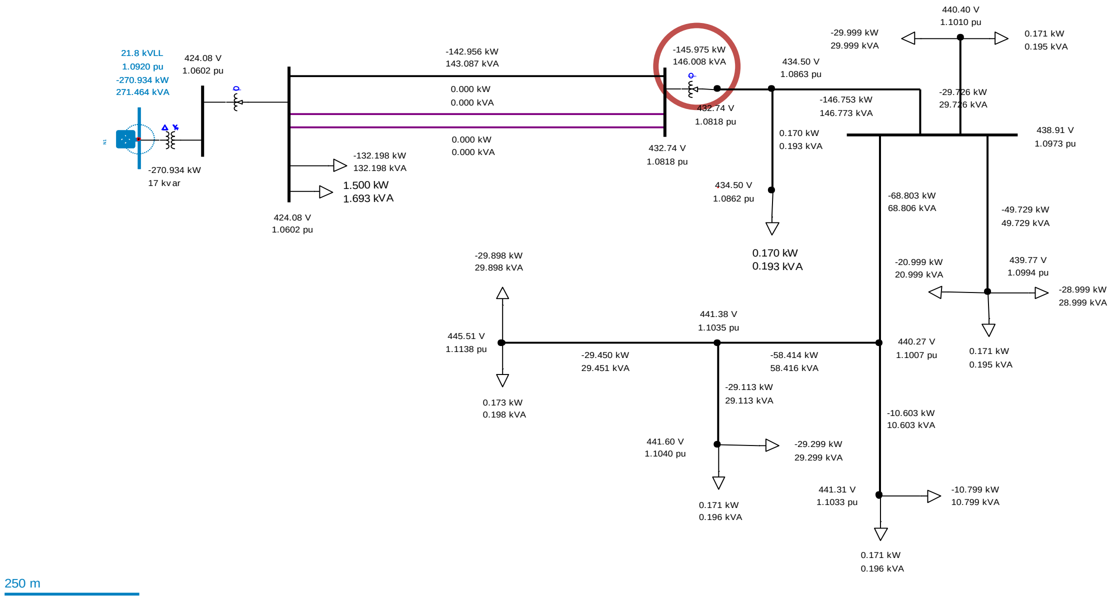

Figure 1.One-line diagram of the circuit where the LV-IPR-150 was installed. The regulator location is highlighted with a red circle.

The LV-IPR-150 uses a unified power flow controller (UPFC) architecture with a capability for shunt reactive current injection and series voltage control [4]. A photograph of the field test device installed on a pedestal is shown in Figure 2, where the LV-IPR-150 can be seen along with a power quality monitor and a third-party bypass switch. While the device itself includes a bypassed control mode, the third-party bypass switch allowed the utility independent control as a precaution.

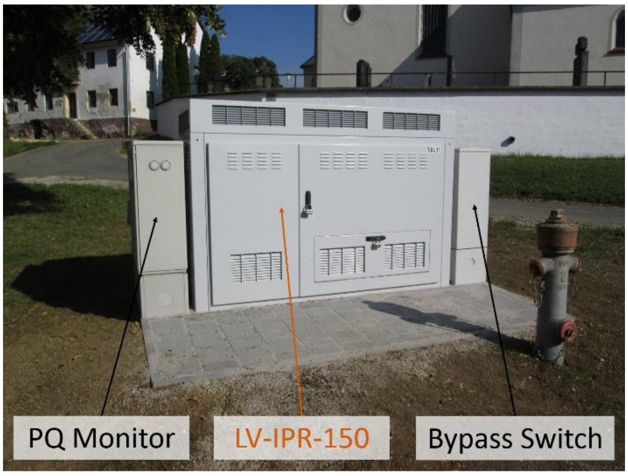

Figure 2. The power regulator, LV-IPR-150, as deployed in the field trial. The configuration includes a third-party power quality (PQ) monitor and a third-party bypass switch.

The specifications of the LV-IPR-150 are included in Table 1. The device can regulate load-side voltage and eliminate voltage harmonics directly by means of series voltage injection, and can inject reactive current (leading or lagging) and cancel source-side current harmonics. A simple one-line diagram illustrating the architecture of the LV-IPR-150 is shown in Figure 3. The device capabilities are available regardless of the direction of power flow, enabling use in systems with high DG penetration. The primary desired application at this site is voltage control, but the other capabilities of the device are also under test.

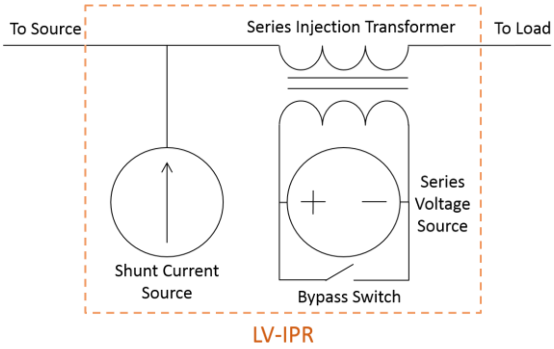

Figure 3.Illustration of the architecture of the LV-IPR-150. The series voltage source provides voltage regulation and harmonic voltage compensation, and the shunt current source provides reactive capability and harmonic current compensation. The two sources are implemented as power electronic converters with a shared dc bus, and the unit delivers no net real power.

TABLE I

SPECIFICATIONS OF LV INLINE POWER REGULATING DEVICE (LV-IPR-150)

Configuration	Three phase, wye-connected
Power Rating	50 kVA per phase, 150 kVA total, bidirectional
Form	Standalone pedestal-mount
Cooling	Passive, air-cooled
Frequency	50 Hz
Operating Temperature	-40 to +50 degrees C
Voltage	230 VAC (nominal)
Source Voltage Range	-30% to +25% from nominal
Load Voltage Control	Boost/buck ±10% of nominal, ±0.5% accuracy
Var Compensation	10% of rating, leading or lagging
Harmonic correction	3rd, 5th, and 7th order harmonics compensated for load voltage and source current
Harmonic distortion	Voltage THD < 3%, Current THD < 5%
Efficiency	>99% at full load

RESULTS

To demonstrate the regulation behavior of the LV-IPR-150, the source side and load side voltages it records are plotted in Figure 4. To date, the LV-IPR-150 has been found to effectively regulate its load-side voltage, thereby also improving the voltage quality at the downstream loads. The voltage at the output (load or downstream side) of the LV-IPR-150 is held steady at the device setpoint, and produces the flat line in the voltage plot. This is true even though the input voltage (source or upstream side) varies considerably over the interval. During this interval, the direction of power flow switches many times, with the PV unit exporting over 20 kW to the grid at times, and with loads drawing power overnight and on cloudy days while no PV generation is available. These large power flows over the long line had been causing even larger voltage deviations for customers far downstream than the fluctuations observed at the LV-IPR-150, and the downstream voltages have been brought closer to nominal by the device.

The load flow models for this circuit predicted voltages at the location of the LV-IPR-150 of up to +8% during lightest-load, full-PV times, based on an MV source voltage of about +6%. The models of the secondary also predicted a change in voltage magnitude of about ±3% from the MV source to the location of the regulating device [2]. The voltage as measured at the input (uncontrolled) terminals of the LV-IPR-150 has generally varied between approximately -5% and +3% from nominal. This magnitude of variation in voltage is in line with expectations based on power flow, where both the primary (MV) voltage and the secondary voltage drop changes over the course of a day. Additionally, the device has not yet been operational long enough to

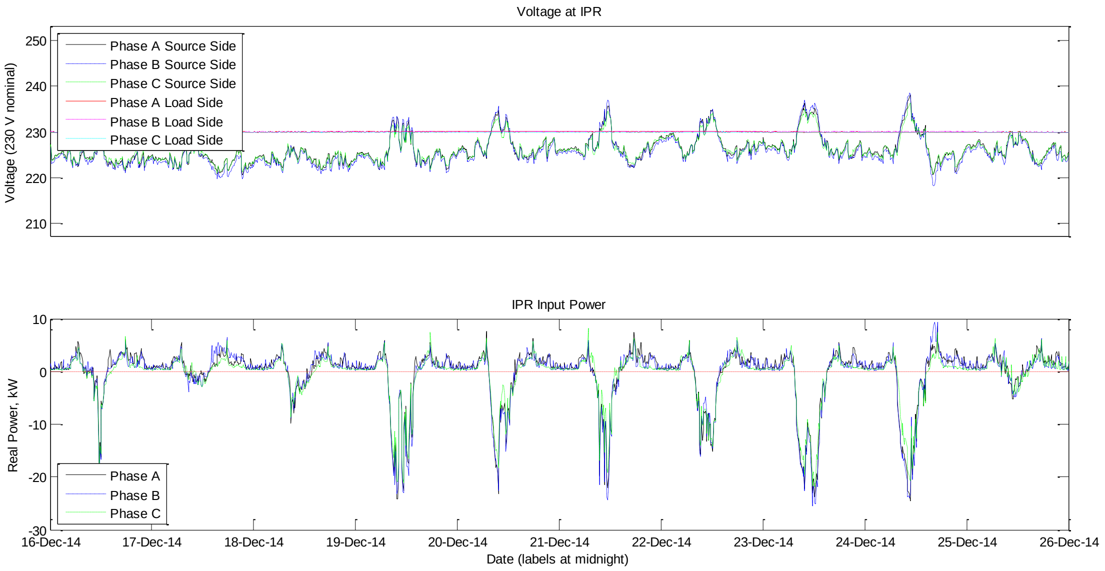

Figure 4. Sample results from field trial of LV-IPR-150. Input (source side) voltage, output (load side) voltage, and real power throughput as measured by the device are plotted for all three phases. Note the regulation of output voltage to the setpoint within ±0.5%. The device maintains voltage control under bidirectional power flow.

observe annual power flow and resulting voltage patterns, and the peak voltage at the input of the LV-IPR-150 may be larger at particularly light load, high PV times during the year.

Some sample data from the site as measured by the third-party power quality monitor is shown in Figure 5. The figure presents the source and load side voltages at the LV-IPR-150, as well as the real power flow through the device. The load voltage is regulated to within ±0.5% of the setpoint.

The LV-IPR-150 can also deliver harmonic compensation. Harmonic currents are mitigated by cancelling the current harmonics caused by nonlinear loads. Figure 6 shows the current THD on the load (uncompensated) and the source (compensated) side of the LV-IPR-150. The result is that the IPR significantly reduces the current harmonics transmitted from loads back to the grid.

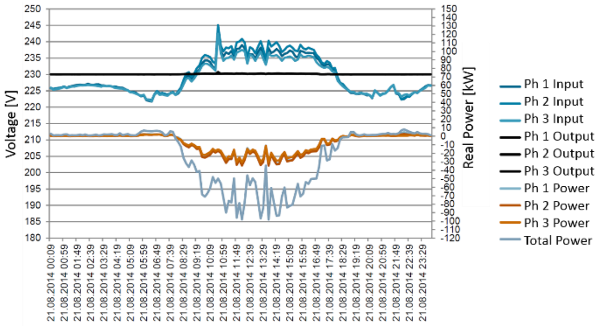

Figure 5. Three-phase voltage and real power data from the site of the LV-IPR-150 as measured by the third-party power quality monitor. The source (input, uncontrolled) and the load (output, controlled) voltage are plotted over the course of about a day, along with the real power flow during that time. The substantial reverse power flow from the PV generator can be seen.

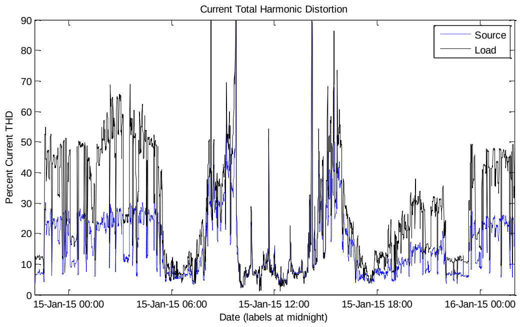

Figure 6. Total harmonic distortion in current waveform as measured at the source (compensated) and load (uncompensated) terminals of the LV-IPR-150. The current demand from the downstream loads has substantial harmonic components, but these are in part removed by the LV-IPR-150, which draws a cleaner current waveform from the source.

CONCLUSION

Due to the adoption of distributed PV generation by residential customers, some areas in this utility distribution system were beginning to experience high voltages. This effect is expected to become more serious in the future as DG installation continues. As part of its mitigation plan for these high voltages, E.ON is performing a field test of the LV-IPR-150, a new power electronics device which can regulate the voltage and improve the power quality on the LV secondary distribution network. The device is effectively regulating the voltage of customers who were experiencing high voltage due to PV, as well as generally improving power quality on the network. These initial results support the continued use of LV-IPRs for similar applications.

REFERENCES

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

[2] A. Kam, A. K. Barnes, V. Martinelli, H. Wrede, J. Simonelli, 2014, “Optimal placement of an inline voltage regulator on a secondary distribution system,” *Proceedings CIRED Workshop*

[3] A. Barnes, V. Martinelli, A. Kam, H. Wrede, J. Simonelli, 2014, “Load-flow modeling of a three-phase local voltage regulator,” *Proceedings CIRED Workshop*

[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.*