FAST LINE DROP COMPENSATION IN LOW VOLTAGE REGULATORS

Olivia LEITERMANN
Gridco Systems - USA
oleitermann@gridcosystems.com

Vince MARTINELLI
Gridco Systems - USA
vmartinelli@gridcosystems.com

Lars MOLSKE
Gridco Systems – Germany
lmolske@gridcosystems.com

James SIMONELLI
Gridco Systems – USA
jsimonelli@gridcosystems.com

ABSTRACT

New power electronic regulators with fast response capability are becoming available, and these can also perform fast line drop compensation. Such regulators are helpful in solving the challenges created by distributed generation and increasingly variable loads. A faster regulator response opens up new control options to address voltage fluctuations due to changes in load current, because a system operator can consider the tradeoff between steady voltage at the regulator output terminals and steady voltage at the remote reference point. Different rate control options are explored in this paper.

INTRODUCTION

Low voltage (LV) regulation with line drop compensation (LDC) can help address the increasing pressures that distributed generation and load growth are placing on distribution grids. With LDC, the controlled voltage is increased under heavy load and decreased under power backfeed. The amount of change in voltage is based on the impedance configuration specified by the system operator and on the current flowing through the regulator. LDC has long been used in HV-MV transformers with on-load tap changers (OLTCs) to better control feeder voltages [1].

Distributed generation can cause voltage rise on LV lines, and load growth increases the voltage drop during peak load. PV generation in particular results in fast changes in power flow, which can lead to rapidly changing voltage. Both rise and drop can occur on the same LV line at different times of day, or simultaneously on neighboring lines, making it potentially difficult to control customer voltage using MV devices. This widening voltage variation has led to increased adoption of LV voltage regulation to ensure delivery of acceptable voltage to customers. LDC can also be used in LV voltage regulators, providing design margin and addressing voltage problems which are otherwise difficult to remedy.

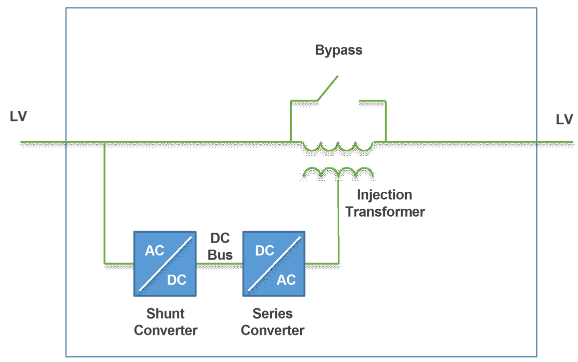

Figure 1. Illustration of UPFC architecture for a sample LV fast voltage regulator, as in [2].

VALUE OF LINE DROP COMPENSATION (LDC) IN LV

LV regulation is helpful in distribution networks for dealing with local areas that have unacceptable voltages due to MV conditions or due to excessive LV voltage drop or rise. In these contexts, LDC is helpful because it improves the flexibility of the regulator to handle large voltage drops and rises while keeping all customers at an acceptable voltage. LDC also eases regulator siting since the voltage drop and rise from the device to the end of the line need not always be within the allowed range. That is, the regulator can have a "virtual" regulation point downstream where voltage is held approximately constant, while being physically located somewhat upstream.

A voltage regulator with LDC generally uses a user-settable impedance with real and reactive components (R and X values) to calculate the adjustment of the output voltage based on real and reactive load current:

$$V_{reg} = V_{setpoint} + R\cdot I_{active} + X\cdot I_{reactive} \qquad \text{(Eq. 1)}$$

The regulator measures the active and reactive load current, and adjusts its output voltage accordingly. This has the effect of maintaining a nearly constant voltage at a remote (downstream) point which is separated from the regulator terminals by the specified impedance. When the load current increases, the regulator boosts its output voltage to keep the voltage at the remote point constant.

FAST LDC WITH POWER ELECTRONIC REGULATORS

In contrast to the majority of existing MV voltage regulators which use mechanically switched tap changers [1], LV voltage regulators may use power electronics to achieve much faster, more responsive regulation. For example, a unified power flow controller (UPFC) architecture, where a pair of inverters with a shared DC bus are connected, one in series and one in shunt, can perform this function [2]. Figure 1 illustrates this architecture. In this case, the inverters can regulate

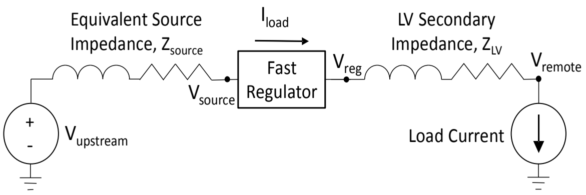

Figure 2. One-line diagram of the simulation system used to produce the results in this paper.

voltage by injecting a series voltage up to the rating of the series converter, operating at the bandwidth of the series converter. For power electronic inverters, this bandwidth can be very fast, even compared to a line cycle.

It is important to distinguish between speed of response to input voltage fluctuations and speed of response to load current fluctuations as part of LDC. When the input voltage to a regulator changes, it affects all the customers connected to that regulator equally, as the voltage fluctuation will be reflected in the voltage observed at all customers. In contrast, when the load current changes, the voltage drop downstream of the regulator, determined by the current and by the impedance of the downstream conductor, varies as well, meaning that customers at different downstream locations experience different voltage fluctuations. A regulator cannot change the downstream voltage drop; it can only control the voltage at a single location. LDC offers some flexibility in which point on an LV network has controlled voltage, and the tradeoff between steady voltage at the regulator output terminals and steady voltage at a downstream remote point is the new design choice that is offered by regulators with fast LDC. If properly configured, this should allow an overall improvement in voltage quality at customer meters.

SIMULATING FAST LDC AND CONTROL OPTIONS

A simulation model of a regulator like that illustrated in Figure 1 was created to illustrate the effects of fast LDC. The simulation model combines an equivalent source, a fast regulator, a secondary (downstream) impedance, and a load, and is illustrated in the one-line diagram of Figure 2. The equivalent voltage source, at 230 V nominal, supplies a fixed 220 V with an impedance Z_{source} of 9.6 + j9.6 mΩ. The impedance for the downstream wiring, Z_{LV}, is 38.5 + j9.6 mΩ, which could represent roughly 100 meters of LV wiring. The simulation was performed at 60 Hz, but the result is equally applicable to a 50 Hz system. Figure 3 shows the output of a simulation where the load (current, I_{load}) is stepped from about 40 A to about 203 A at time 0. In order to hold the LDC virtual remote regulation point at the setpoint, the regulator output voltage immediately increases to account for the voltage drop in the line.

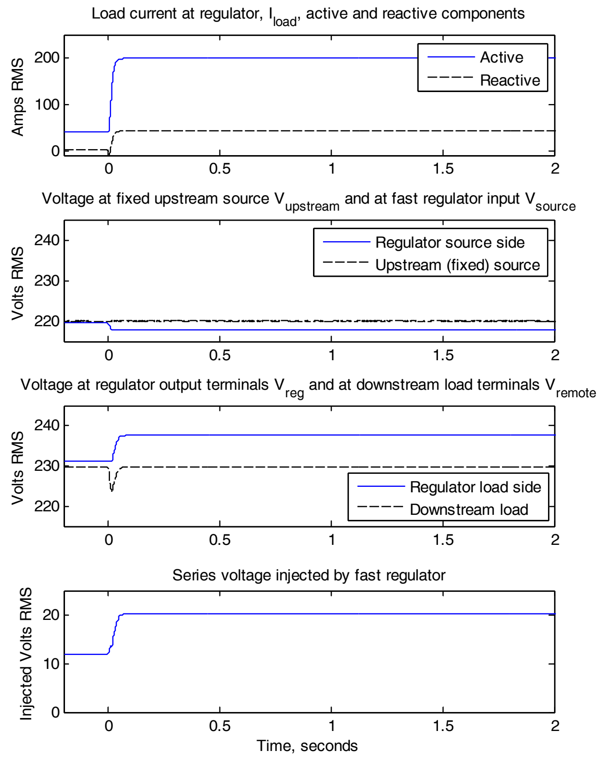

Figure 3. Simulated response of fast voltage regulator to load (current) step. Note that the regulator output voltage quickly increases to account for the increased load drop, and the voltage at the remote load returns to near its setpoint in about three line cycles.

The voltage at the remote load is almost constant because the LDC settings are calibrated to the line impedance between the regulator and the load.

The tradeoffs of this rapid regulation based on load current are more evident in the case of a motor start transient. Instead of a simple load step, a current spike modeled after a motor startup current is drawn by the load. The current spike ramps up over ¼ line cycle to 350 A at 71% power factor, then persists for 15 line cycles, then ramps back down to zero over an additional 3 line cycles. Figure 4 shows the resulting voltages at the regulator output V_{reg} and at the remote load point V_{remote}. The fast regulator senses the current boost and reacts almost instantly to adjust the output voltage so that the remote load point experiences minimal change in voltage. This means that the voltage at the output of the regulator increases sharply when the current increases, and drops again when the current drops.

Whether this voltage change at the regulator output terminals V_{reg} is desirable is a design choice for the network operator. The operator may trade steady voltage at the regulator terminals for steady voltage at the remote point V_{remote}. If there is substantial voltage drop due to current flowing through line impedance Z_{LV} on the load side of the regulator, these goals are mutually exclusive

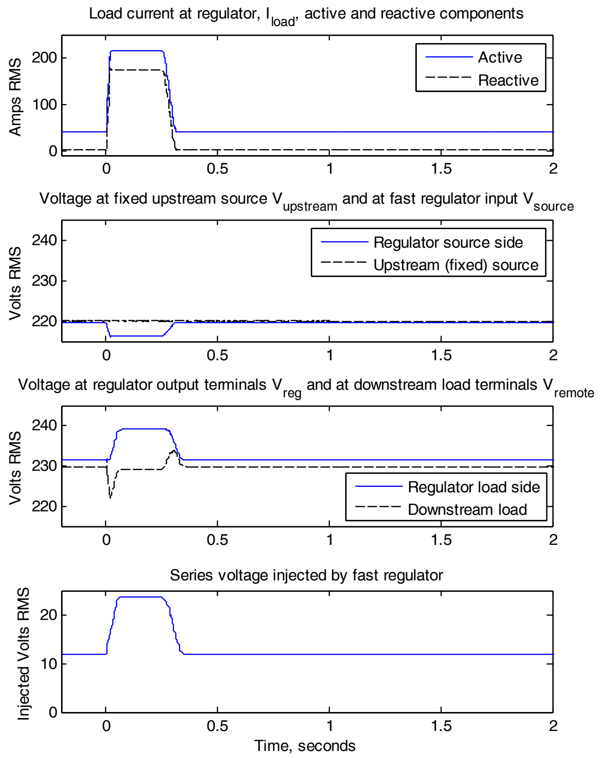

Figure 4. Simulated response of fast voltage regulator to a current spike chosen to mimic a motor start. Without any ramp rate control, the regulator output is quickly raised during the motor start to maintain the remote point voltage near its setpoint, then dropped again after the motor current has returned to lower levels. This voltage "spike" at the regulator output may or may not be desirable.

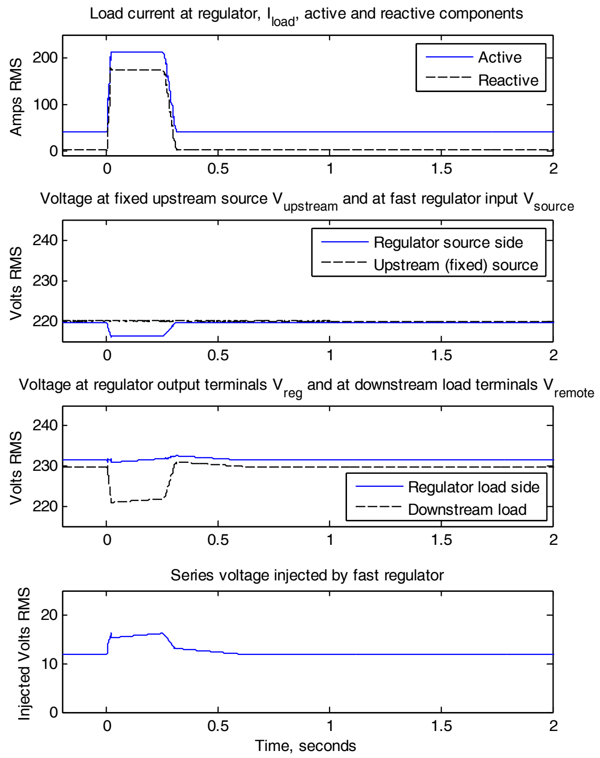

Figure 5. Simulated response of fast voltage regulator with a ramp rate control of 4 V/sec to a current spike chosen to mimic a motor start. Because of the ramp rate control, the regulator output voltage has increased very little by the time the current spike has ended, resulting in a smoother voltage profile at the regulator terminals in exchange for a voltage dip at the remote load point.

under unsteady current conditions. However, if steadier output voltage is desired at the regulator output, the regulator control may be adjusted to react to voltage changes more slowly, and so not to respond to fast current changes such as would be expected with motor starts.

Figure 5 shows a similar situation to Figure 4, but a ramp rate controller has been implemented on the LDC feature. The regulator still responds basically instantly to input voltage changes, for example to the change in source voltage caused by the increased load current, but it responds to changes in current only at the rate of 4 V/sec. That is, the $R{\cdot}I_{active} + X{\cdot}I_{reactive}$ component of the voltage setpoint is allowed to change no faster than the 4 V/sec ramp rate setting. This means that the output voltage V_{reg} of the regulator moves no faster than the specified rate, although the injected voltage may change faster if the input voltage V_{source} changes fast. On the other hand, the voltage at the controlled remote V_{remote} point dips with the motor current. The 4 V/sec ramp rate has been selected to result in minimal voltage change during the motor start current transient while allowing the remote point voltage V_{remote} to return to the setpoint within about 2 seconds in the case of the (sustained) load step. This may or may not be preferable to the non-ramp-rate-limited control version, where the voltage dip at the load is replaced by a voltage spike at the regulator output. Note that in either case, the regulator has compensated for the dip in source voltage V_{source} which is caused by the load current flowing through the upstream impedance Z_{source} : this voltage dip does not appear at the output terminals V_{reg}.

The performance of the ramp-rate-limited LDC on a load step may be seen in Figure 6. For this case where the change in load current is sustained, the resulting voltage at the regulator terminals V_{reg} is a smooth ramp to the new value, and at the remote load point V_{remote}, the voltage jumps based on the voltage drop across the line impedance, then ramps back to its initial value at the same rate. Again, the dip in source voltage V_{source} is compensated much faster than the LDC acts, and the dip does not appear at the regulator terminals V_{reg}.

Besides ramp rate control, filtering or averaging of the current or other methods may be used to intentionally slow the LDC response rate and achieve smoother voltage at the regulator output terminals at the expense of increased voltage variation at the remote load point. It is

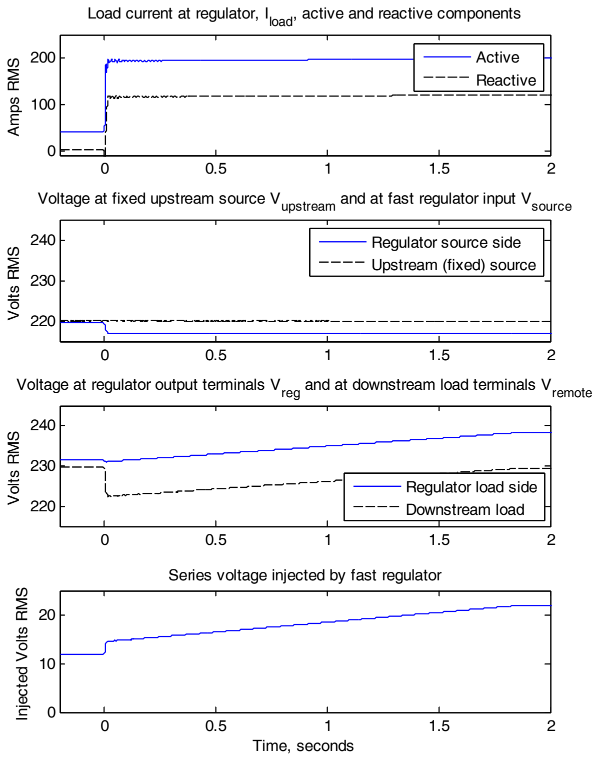

Figure 6. Simulated response to load current step of fast voltage regulator with a 4 V/sec. ramp rate control. Note that the regulator output terminal voltage changes only slowly in response to the current. The remote point voltage has returned to near its setpoint within about 2 seconds of the load step.

important to note that no filtering, averaging, or rate limit at the regulator can achieve steady voltage at both the regulator output terminals and the remote point under changing current conditions. These features serve to exchange voltage fluctuation at one point for voltage fluctuation at the other point.

CONCLUSIONS

Fast voltage regulators react quickly to changes in input voltage which would otherwise affect all downstream customers. Fast voltage regulators also enable the use of fast LDC, which opens up new design choices that had not been available with previous equipment. One of these choices is how to respond to fast current spikes. Whereas older-style mechanically-switched regulators necessarily responded only to sustained changes in current, new fast voltage regulators offer the design choice to respond to fast changes in current or not as the system operator chooses. For example, it may be desirable to ignore the current spike associated with a motor start, or it may be preferable to respond as quickly as possible to prevent downstream voltage fluctuation.

This feature lets system operators determine how voltage transients resulting from current spikes from loads like motor starts are experienced (and mitigated) for their customers. The speed settings for individual regulators on a network may each be determined separately, or a general policy selecting for constant voltage at regulator terminals (like V_{reg}) or alternatively at remote load locations (like V_{remote}) may be implemented across larger areas. In such a case, the effects of fast LDC in a particular territory may be evaluated once and not revisited with each individual regulator installation. The system operator may then achieve improved voltage control for its customers while limiting the additional design complexity required for network improvements.

REFERENCES

[1] W. H. Kersting, 2002, *Distribution System Modeling and Analysis,* CRC Press, Boca Raton, FL, USA, pp. 152-174.

[2] A. K. Barnes, V. Martinelli, and J. Simonelli, “A local voltage regulator that improves energy savings under advanced volt-var control,” in T&D Conference and Exposition, 2014 IEEE PES, (Chicago, IL, USA), Apr 2014.