LOAD-FLOW MODELING OF A THREE-PHASE LOCAL VOLTAGE REGULATOR

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ABSTRACT

Distributed power electronics are proposed as a solution for mitigating voltage regulation issues caused by photovoltaic generation. However, few commercial and open-source software packages for distribution system analysis support the modeling of such devices. A steady-state model for load-flow analysis of a three-phase voltage regulator is described. The model is multi-faceted and covers not just power flows and voltage regulation, but also design behaviours such as bypass. The model is implemented in Gridlab-D, but is suitable for implementation in other distribution analysis software packages. Results are demonstrated to be comparable to those obtained with an approximate model in a commercial package.

INTRODUCTION

Rapid reductions in the purchased cost of PV panels combined with attractive feed-in tariff programs are driving a rapid increase in the penetration of customer-owned PV installations. High penetration of PV on distribution feeders can cause voltage regulation problems in actual field installations, especially given the high variability in real power output from PV panels on a partly cloudy day [1]. Existing equipment, such as load tap-changers, operate in coarse increments and with slow time constants on the order of tens of seconds to minutes, preventing them from effectively regulating voltage. Coincident with the drop in cost of PV panels is the drop in cost of power electronics, which has now become a viable solution for low-voltage distribution system equipment. However, few tools for analysis and design of distribution feeders with such devices exist. This work presents the development of a steady-state model for a three-phase local voltage regulator (LVR) to be used in the distribution feeder. The model is multi-faceted and covers not just power flows and voltage regulation, but also design behaviours such as bypass. The model is implemented in the Gridlab-D simulation environment to assist distribution system engineers in deploying such devices. However, the modeling approach described can be applied to any extensible load flow analysis tool.

MODEL & GRIDLAB-D IMPLEMENTATION

The LVR topology we studied in this paper is based on a shunt-series UPFC architecture [2] (Fig. 1). This can be modeled with the series and shunt converters represented as voltage and current sources respectively (Fig. 2), which in turn can be modeled by its Norton equivalent (Fig. 3).

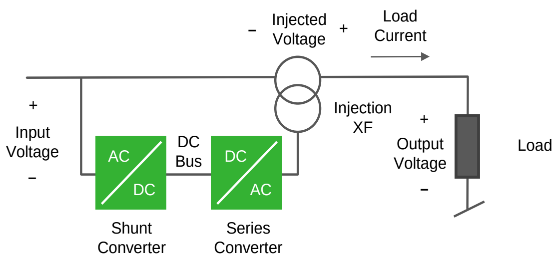

Figure 1: UPFC architecture of an LVR

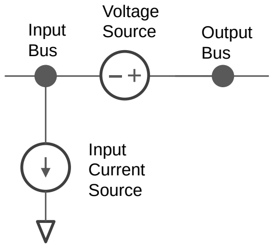

Figure 2: static model of an LVR

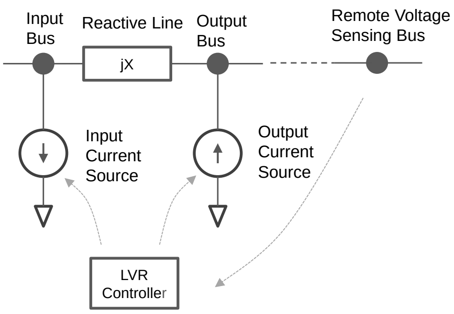

Figure 3: Norton equivalent of the static model

We have implemented the Norton equivalent model in a custom build of Gridlab-D [3]. Gridlab-D is an open-source distribution system modeling tool developed by Pacific Northwest National Laboratory in Washington State, USA. The LVR is implemented as a new device (object) type, with its own controller logic. Some of the LVR controller pseudocode is shown in Table 1. Similar modeling technique can be applied to any extensible tool (e.g. CYMDIST via its COM interface or Python scripting module).

Init: set count = 0
At each step:
1. *If 200% overload: transition to bypass and start 30 s counter*
2. *If 150% overload: start 1s delay timer. If counter has expired, transition to bypass and start 30 s counter*
3. *If not overloaded and counter has expired: switch back to active*
4. *If 0.7 pu undervoltage: transition to bypass and start 30 s counter*
5. *If 1.25 pu overoltage: transition to bypass and start 30 s counter*
6. *If input voltage – setpoint voltage > regulation range: adjust setpoint voltage to input voltage – regulation range*
7. *If setpoint voltage – input voltage > regulation range: adjust setpoint voltage to regulation range + regulation range*
8. *If bypassed: set voltage setpoint to input voltage*
9. *If count = 0: set injected (purely reactive) current to a small initial value*
   Else If count = 1: set injected (purely reactive) current to another small initial value and measure output voltage
   Otherwise: calculate slope of change in output voltage vs. change in current as
   slope = (previous output voltage –output voltage)/(previous injected current – injected current).
   Calculate new injected current = injected current – injected voltage/slope
10. *Calculate shunt converter power = series converter real power × (change in voltage)/(nominal voltage)*
11. *Calculate losses = fixed losses + series loss coefficient × series converter power + shunt loss coefficient × shunt converter*

Table 1: (partial) pseudocode for LVR controller in Gridlab-D model

While the static model (or its Norton equivalent model) is necessary for implementation in many load flow solvers [4-9], to represent a more realistic device behaviour additional functions should be implemented. The LVR model we implemented within Gridlab-D supports the following capabilities:

- Reactive power injection / absorption via the shunt converter.
- A linear loss model. Losses are a function of the load power and the injected voltage.
- Automatic bypass when an over-current condition or a severe over- or under-voltage condition occurs.
- Three different voltage regulation modes.

We have tested all these capabilities of the LVR model in various simulations. In this paper, we concentrate on the voltage regulation function. The three different voltage regulation modes implemented are:

- Output terminal: the voltage at the LVR output terminal is regulated.
- Line drop-compensation (LDC): The LVR estimates the voltage at a remote node to regulate it.
- Remote: The LVR measures the exact voltage at a remote node to regulate it.

In all three modes, the LVR control parameters, i.e. injected currents in the Norton equivalent model, are iteratively updated. More precisely, Gridlab-D starts with an initial solution (e.g. obtained via the Newton-Ralphson method) and then the LVR controller observes relevant voltage and current values from that solution. The exact values (inputs) being observed by the LVR controller depends on its user-defined voltage regulation mode. Based on these inputs, the LVR controller updates its injected currents, and Gridlab-D modifies its solution based on the new LVR currents (e.g. by using the Newton-Ralphson method again). Then the LVR controller observes the new voltages and currents from the new solution, and might change its injected currents, which causes Gridlab-D to modify its solution, etc. This loop is repeated until a convergence criterion is met. In our implementation, the LVR controller updates its injected currents based on the secant method.

Some of the model's parameters are summarized in Table 2. Coefficients for the loss model are calculated based on a linear least-squares fit with estimated LVR behaviour.

Parameter	Value
Fixed loss coefficient	*123 W*
Series converter loss coefficient	*3.61 W/kVA*
Shunt converter loss coefficient	*99.10 W/kW*
Norton impedance	*5 mΩ*
Rated power	*25 kVA/phase*

Table 2: LVR model parameters

CASE STUDY

The LVR model is applied to test its performance on a generic 400 VLL German secondary distribution feeder, shown in Fig. 4. This feeder has a peak load of about 100 kW and a peak solar photovoltaic (PV) power output of about 110 kW. The PV generation sources are distributed across the feeder (as opposed to having one large PV installation).

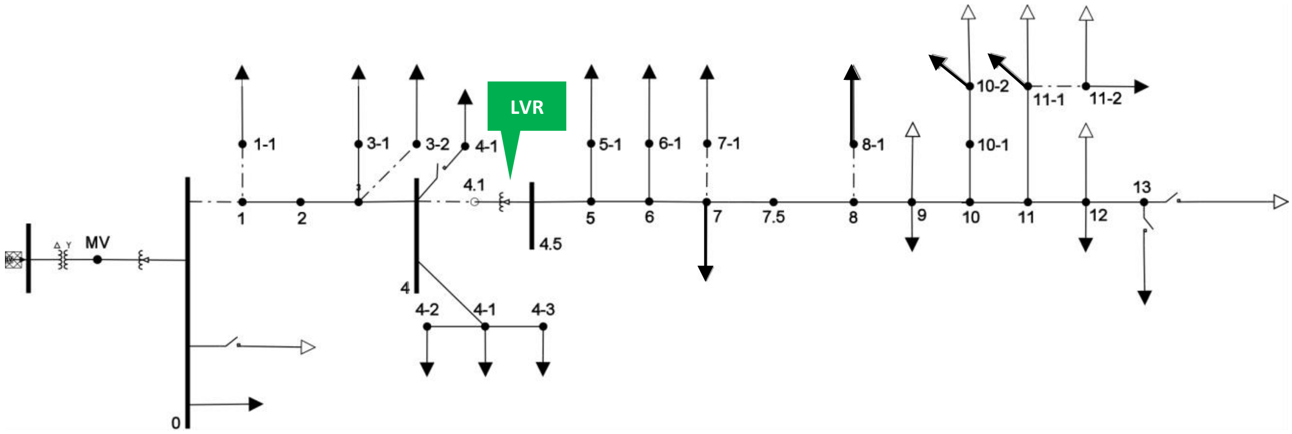

Figure 4: Generic secondary distribution network with LVR located between nodes 4.1 and 4.5. Loads are indicated by black arrows; PV systems are indicated by white arrows.

In our simulations, the LVR is placed between node (bus) 4 and node (bus) 5, and it is configured for Remote Voltage Regulation. Specifically, it attempts to regulate the voltage at node (bus) 7 to 1.0 pu.

We studied the LVR's performance under 3 different scenarios – (i) a static scenario with maximum voltage drop, (ii) a static scenario with maximum voltage rise, and finally, (iii) a quasi-dynamic scenario where both the load and the PV output varies throughout a typical cloudy day.

Fig. 5 shows the voltage profile in the high load / no PV static scenario. This represents the worst-case voltage drop scenario that might happen e.g. on a cloudy afternoon or evening after sunset.

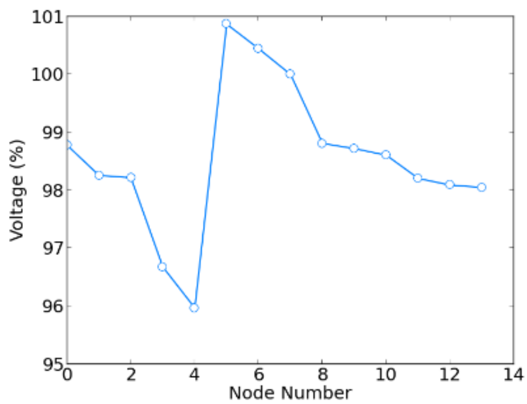

Figure 5: Voltage profile for high load / no PV scenario. Voltage at node 7 is regulated to 100%.

As can be seen from Fig. 5, the LVR raises its output voltage (node 5) to ≈ 101%, in order to regulate the (remote) voltage at node 7 to 100%. This demonstrates correct functioning of our Norton-equivalent-based LVR model, integrated with the Gridlab-D simulation environment. In this example, the lowest voltage with LVR ≈ 96%, whereas without LVR (voltage profile not shown) the lowest voltage would have been ≈ 93%.

Fig. 6 shows the voltage profile in the low load / maximum PV static scenario. This represents the worst-case voltage rise scenario that might happen e.g. on an early afternoon on a sunny day. In this scenario, the LVR lowers its output voltage (node 5) to ≈ 99%, in order to regulate the (remote) voltage at node 7 to 100%, demonstrating correct functionality of the LVR model even in case of reverse real power flow. In this example, the highest voltage with LVR ≈ 103.5%, whereas without LVR (voltage profile not shown) the highest voltage would have been ≈ 104.5%.

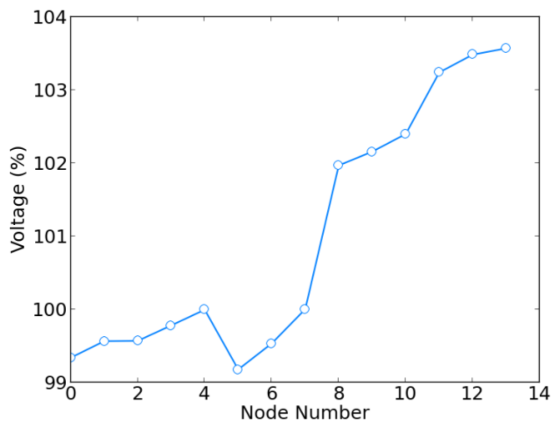

Figure 6: Voltage profile for low load / max PV scenario. Voltage at node 7 is regulated to 100%.

Note that, in this feeder, the voltage at node 0 is less than 100% due to voltage drop across the distribution transformer. Obviously both voltage profiles could have been raised (or lowered) with a higher (or lower) source voltage on the LV bus out of the distribution transformer. However, this would have been a tradeoff between maximum voltage drop (96%) versus maximum voltage rise (103.5%) – changing the source voltage can only improve one while worsening the other. We have chosen the location of the LVR (between nodes 4 and 5) and the remote regulation point (node 7) partly to balance the maximum voltage drop (−4%) and rise (+3.5%), i.e., minimize worst case excursion from nominal voltage, and partly based on physical reality on the actual feeder.

Besides the two static cases, we also simulated a quasi-dynamic scenario with time-varying load and time-varying PV on a cloudy day. Quasi-dynamic refers to chaining together a set of load flow simulations (as opposed to a true dynamic simulation which represents the system as a set of coupled differential equations). Fig. 7 shows the time-varying power output at the feeder source. In this example, the real power curve clearly shows intermittent reverse real power flow (i.e. real power output < 0) during daylight hours, when the sun is out and total PV output exceeds total load. These are the maximum voltage rise scenarios. Also, the peak load happens around hour 21 (late evening) – the maximum voltage drop scenario.

The time-variation curves for load and PV output are both based on actual measurements, albeit from a different distribution feeder than the one studied here.

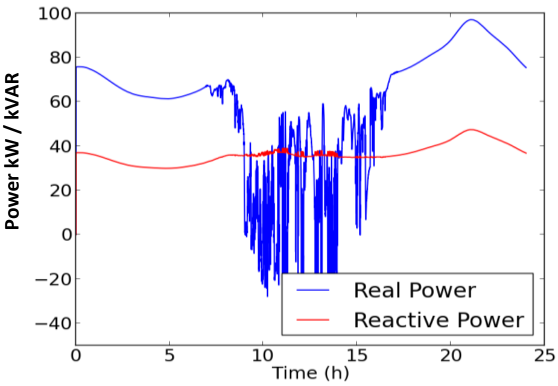

Figure 7: Time-varying power output at feeder source.

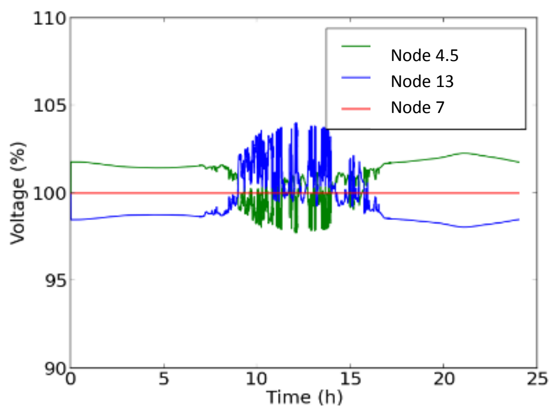

Figure 8: Time-varying voltage at 3 points in the feeder.

Fig. 8 shows the time-varying voltage at 3 different points in the feeder. The regulated voltage (node 7) stays constant at 100%, demonstrating correct functionality of our LVR model in quasi-dynamic simulations. The end-of-feeder voltage (node 13) reaches peaks during sunny moments in the daylight hours, and reaches its lowest value during the peak load / no PV moment around hour 21. Finally, the LVR output voltage (node 4.5) shows the exact opposite behaviour. I.e., the LVR raises its output voltage during maximum voltage drop and lowers its output voltage during maximum voltage rise.

COMPARISON WITH CYMDIST MODEL

We also compared the voltage regulation only characteristics of the Gridlab-D LVR model with a different approximate model in the commercial load-flow solver CYMDIST. Instead of adding a new device type to CYMDIST or using its scripting capability, we approximated the LVR by a load tap-changer (LTC) with a large number of taps (800 taps) over its regulation range (± 10%). A constant-power load and a purely resistive line are also added to model the LVR's no-load and load-dependent losses respectively. Other aspects of the Gridlab-D LVR model are not represented in the CYMDIST LTC approximation – the automatic bypass action, and the reactive power injection/absorption capability.

Fig. 9 and 10 show the CYMDIST output for voltage profiles during the same two static scenarios, for maximum voltage drop and rise respectively. These figures are labelled by distance from the source (meter). The LTC (LVR) is at ≈ 275m where the vertical jumps occur. The regulation point (node 7) is at ≈ 550m where voltage is regulated to 100%.

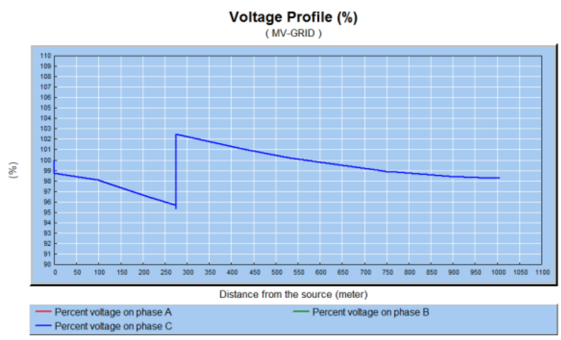

Figure 9: Voltage profile for high load / no PV scenario, from CYMDIST using LTC as an approximation for LVR.

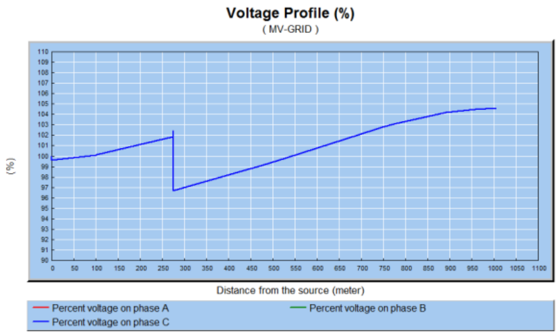

Figure 10: Voltage profile for low load / max PV scenario, from CYMDIST using LTC as an approximation for LVR.

For the purpose of studying voltage regulation, we find that the LTC (with a large number of taps) is a good approximation of the LVR. The LTC has a small discretization error because it operates in discrete tap positions, whereas the LVR can regulate its output voltage in a continuous range. However, in our example, the LTC's 20% regulation range / 800 taps = 0.025% per tap, which is often comparable to (or only slightly worse than) the convergence tolerance of the Gridlab-D iteration loop. In any case this is well within the measurement error of the feeder characteristics (kW and kVAR consumed by the loads, conductor impedance values, etc).

For the quasi-dynamic study, the CYMDIST LTC should be specified in such a way that it can jump to any tap position at any time, with zero actuation delay. Otherwise, it would not be a good approximation to the instantaneous reaction of the LVR, and the time-varying voltage plots would be inaccurate.

CONCLUSION

With increasing adoption of PV generation (and other variable generation sources such as wind power), voltage fluctuations are expected to become an increasingly important issue. Power electronics devices, with their fast response speed, fine-granular control, unlimited number of lifetime actuations, and decreasing cost, represent a viable solution for voltage and other power quality problems. However, few tools for analysis and design of distribution feeders with such devices exist.

In this paper, we presented a model for a power-electronics-based (UPFC-based) Local Voltage Regulator, and implemented the model as a new device type in Gridlab-D. Our model incorporates multiple functions of the LVR – several modes of voltage regulation, reactive power injection/absorption, bypass action, and a realistic loss model. Similar modelling techniques can be adapted to other extensible load flow analysis tools.

Through static and quasi-dynamic simulations, we demonstrated the correct functioning of the model. We also compared the voltage regulation function of the model to an approximation based on LTC. We find the model to be accurate, easy-to-implement and flexible, and envision it to be a useful tool for planners and engineers of distribution feeders.

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