Technical University of Denmark

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Douglass, Philip James; Han, Xue; You, Shi

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Comparison of Algorithms for Control of Loads for Voltage Regulation

Philip J. Douglass, Xue Han, and Shi You
Center for Electric Power and Energy, Technical University of Denmark
Elektrovej-Building 325, 2800 Kgs. Lyngby, Denmark
email:{pjdo, xueh, sy}@elektro.dtu.dk

Abstract

Autonomous flexible loads can be utilized to regulate voltage on low voltage feeders. This paper compares two algorithms for controlling loads: a simple voltage droop, where load power consumption is a varied in proportion to RMS voltage; and a normalized relative voltage droop, which modifies the simple voltage droop by subtracting the mean voltage value at the bus and dividing by the standard deviation. These two controllers are applied to hot water heaters simulated in a simple residential feeder. The simulation results show that both controllers reduce the frequency of undervoltage events. The simple droop controller delivers a widely different response depending on where the load is located on the feeder. In contrast, all of the loads with the normalized relative droop controller have a similar response.

I Introduction

The capacity of electric power distribution systems is often limited by voltage constraints. Overvoltages can occur when energy production from photovoltaic (PV) generators is high, and undervoltage conditions indicate excessive load. PV inverters can control their active and reactive power output to avoid violating voltage constraints, however, using PV inverters to regulate voltage has high costs: Curtailing active power spills energy, and reducing the power factor increases line losses [1]. Flexible loads, which have the ability to adjust the timing of their energy consumption without compromising the delivery of energy services, can also be utilized to regulate voltage levels.

In the literature, several methods have been proposed for using loads to regulate voltage and optimize the utilization of fluctuating energy sources [2–4]. One method to control loads is to use a centralized controller with global knowledge of the system state to create an optimal schedule for power consumption [2]. The focus of this work is simple autonomous controllers which lack the communication capabilities needed for centralized optimization. In these autonomous systems, control decisions are made using only local measurements of RMS voltage. Autonomous load controllers can quickly react to voltage deviations, such as those that occur during cloud transients.

Autonomous load control algorithms for voltage regulation are based on a proportional droop controller, where the load power consumption is a linear function of input voltage [3]. The algorithm described in [4] modifies the droop response to use normalized voltage values, rather than absolute RMS voltage values. This paper seeks to compare the normalized droop response to the absolute droop response to illuminate the relative advantages and disadvantages of the two algorithms.

II Voltage Drop in Distribution Systems

Distribution system operators in Europe are required to deliver voltage within $\pm 10\%$ of nominal voltage U_{nom} [5]. The voltage drop (ΔU) through a conductor is approximated by:

$$\Delta U \cong PR + QX \tag{1}$$

where P is the active power, Q is the reactive power, R is line resistance, and X is line reactance. Fluctuations in ΔU can be reduced by reducing fluctuations in P. In a system where PV generators produce power P_{pv}, uncontrolled loads consume P_{ul}, and flexible load consume P_{fl}, the net power P is the sum of the three components: $P = (P_{\text{pv}} - P_{\text{ul}} - P_{\text{fl}})$. The quantities P_{pv} and P_{ul} are assumed to be given, the only controlled variable is P_{fl}. The purpose of the load control algorithms is to modulate P_{fl} to compensate for fluctuations in P_{pv} and P_{ul} and thereby stabilize P and ΔU.

III Description of Load Control Algorithms

This section briefly describes the two load control algorithms evaluated in this paper.

III.1 Simple Voltage Droop Load Controller

The simple droop control method seeks to make flexible load power consumption proportional to voltage deviations:

$$\hat{P}_{\text{fl}} = (U - U_{\text{nom}}) \cdot K_{\text{droop}}$$

where U is the measured RMS voltage, and K_{droop} is chosen such that $\hat{P}_{\text{fl}}$ lies in the interval [-1,1] under normal operating voltages. In this work, the actual power consumption of the flexible load will not exactly track the ideal response because of constraints on the load to provide a given quality-of-service. Specifically, this work investigates loads providing thermal energy services because these represent a large and flexible load class. The quality-of-service constraints on the thermal loads are given as a temperature band that they are required to always lie within. To provide the droop response, a conventional hysteresis thermostat is modified so that the temperature setpoint (T_{s}) is offset from the user-given setpoint (T_{o}) by the formula: $T_{\mathrm{s}} = (T_{\mathrm{o}} + \hat{P}_{\mathrm{fl}} \cdot T_{\mathrm{ol}})$, where T_{ol} is the maximum tolerated temperature offset. Note that for heating applications $(T_{\mathrm{ol}} > 0)$ because more power is consumed by raising the temperature setpoint; in cooling applications, $(T_{\mathrm{ol}} < 0)$.

III.2 Normalized Relative Droop

The voltage droop load controller has a number of drawbacks in practical operation. One drawback is that the voltage reference U_{nom} is fixed, while in practice the mean voltage will differ from bus to bus. Similarly, K_{droop} must be chosen based on the typical level of voltage variation, but the magnitude of voltage variation also differs from bus to bus. Finally, activating the loads changes the voltage that they measure. Without compensating for the voltage drop caused by the load itself, laboratory tests have shown that the loads may oscillate between ON and OFF states as the voltage drop caused by turning ON lowers voltage so much that they immediately turn OFF again.

To compensate for the drawbacks of a pure voltage droop response, a modified algorithm has been developed, the full details of which are described in [4]. The modified algorithm uses normalized voltage measurements, rather than absolute voltage measurements, as input to a proportional controller. The voltage is normalized in the statistical sense of subtracting the mean, and dividing by the standard deviation. The mean voltage is found for each state of load operation (i.e. ON and OFF), to compensate for the effect of the load itself on the voltage measurements.

IV Simulation Results

An 11-bus single-phase low voltage radial feeder was simulated in the GribLAB-D software simulator [6]. Ten houses were placed in the feeder, where 6 of the houses had an electric water heater whose thermostat setpoint was offset by a voltage-regulating load controller. The maximum allowed temperature offset was T_{ol} = 3 °C . The last 4 houses on the feeder had PV generators with a rated capacity of 6 kW each. The system was simulated over 10 days using typical residential electrical and hot water load profiles. For the entire 10 day period, the average water heater load was 4.5 kW, the average PV production was 3.3 kW, and the average residual load was 16.7 kW.

The system was simulated in 3 scenarios: a base case scenario where the water heaters did not receive temperature setpoint offsets, a scenario where the water heaters

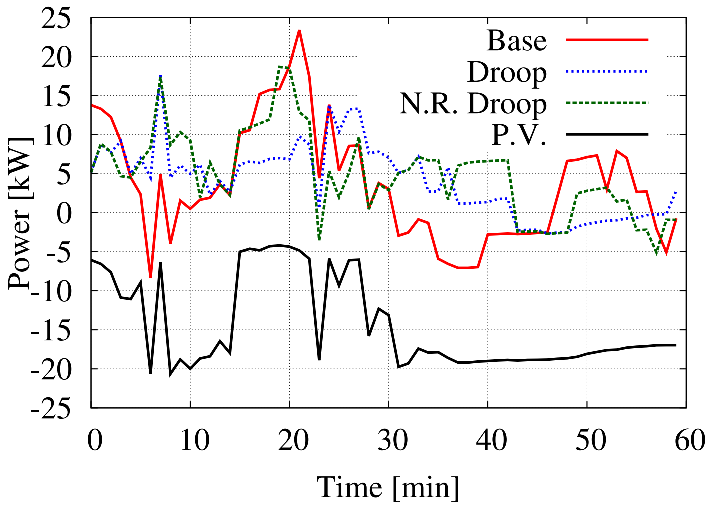

Figure 1: Time series of net load and aggregate PV production for all three scenarios.

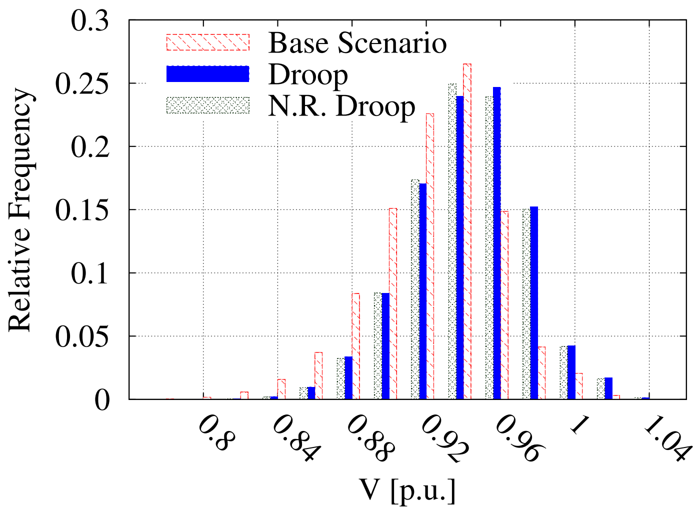

Figure 2: Distribution of voltages seen at all busses for each scenario.

temperature offsets were controlled by a simple voltage droop, and a scenario where the temperature offsets were controlled by a normalized relative droop controller.

A representative time series showing the net load in all three scenarios, as well as the aggregate PV production, is shown in Fig. 1. In the base case, the fluctuations in PV production (caused by cloud transients) show up as large fluctuations in the net load. In the two scenarios with the voltage-regulating load controllers, the fluctuations in net load are smaller because the water heater load smooths out the variations caused by the fluctuating PV production.

The distribution of voltage measurements taken from all busses in the three scenarios is shown in Fig. 2. Comparing the distributions shows that both the load control algorithms reduced the frequency of low voltage values. While the effectiveness of the two

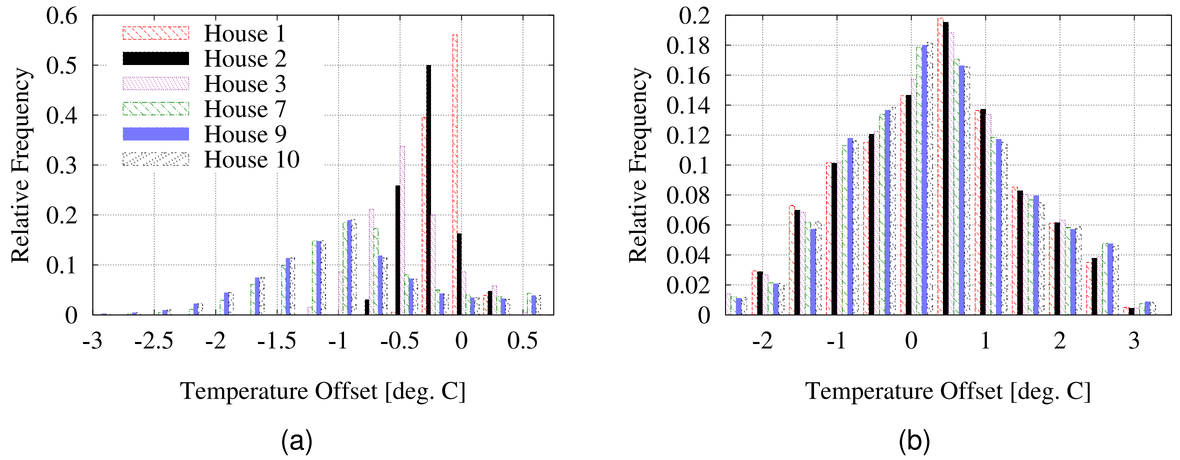

Figure 3: Distribution of Temperature Setpoint Offsets with Simple Droop Controller (a) and Normalized Relative Droop Controller (b)

load control algorithms in avoiding undervoltage conditions was comparable, they way they achieved that result varied significantly. The relative frequency of temperature offsets for each water heater with the droop controller is shown in Fig. 3a. The loads close to the end of the feeder have lower temperatures, and a wider distribution, compared to those located close to the transformer. In contrast, Fig. 3b shows relative frequency of temperature offsets for the normalized relative droop controller. The distribution of temperature offsets utilizes the entire range of temperature offsets, and is approximately the same for all loads.

Statistics gathered from the simulations are shown in table 1. The water heaters controlled by a simple voltage droop reduced the maximum net load by 12 % compared to the base case, while the normalized relative voltage droop controller only reduced the maximum net load by 7 %. Looking at the minimum load levels confirms that the droop controller had the greatest effect in reducing load extremes. The frequency of undervoltage events was measured by counting the total number of 1-minute samples below 0.9 p.u. By this metric, the normalized relative droop controller outperformed the simple droop controller, though both were a significant improvement over the base case. The minimum voltage observed varied slightly from case to case, with the normalized relative controller showing the lowest voltage. Closer examination of the system state at the lowest voltage revealed that the all the water heaters were turned off, indicating that the load controller had correctly delivered its full response.

V Conclusion

This paper has described two alternative methods for controlling autonomous loads to provide voltage regulation service. The simple voltage droop seeks to control load

Table 1: Performance of Metrics for Base Case, Droop Controller, and N.R. Droop Controller

Parameter	Base	Droop	N.R. Droop
Max. Net Load	57 kW	50 kW	53 kW
Min. Net Load	-8.4 kW	-7.5 kW	-8.2 kW
Nr. V samples $<$ 0.90 p.u.	6440	4450	4180
Min. Voltage	0.81 p.u.	0.82 p.u.	0.80 p.u.
Max. Voltage	1.06 p.u.	1.05 p.u.	1.06 p.u.

power to be proportional to absolute RMS voltage values. The normalized relative droop load controller modifies the droop response to compensate for different voltage profiles observed at different busses in a feeder. Both load controllers were implemented in a simulation environment where they controlled an electric hot water heater.

The simulation results showed that both controllers were successful at reducing the frequency of undervoltage events. Both controllers reduced the maximum and minimum net loads seen in the simulated feeder, though the simple droop was more effective at moderating load extremes. The response of the individual water heaters was evenly spread with the normalized relative droop, while the simple droop response was concentrated among the customers at the end of the line.

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