ETH zürich

Experimental Validation of Feedback Optimization in Power Distribution Grids

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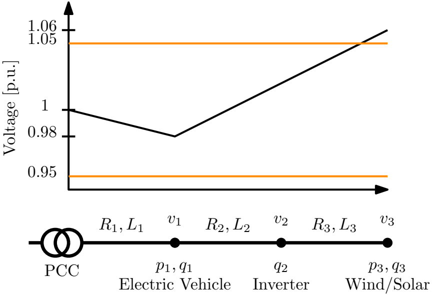
Congestion Leading to Overvoltage



Volt/VAR Problem

$$\begin{aligned} \text{find} \quad q_h \min_{q} \quad & \frac{1}{2} q^T M q \\ \text{subject to} \quad & v_{\text{min}} \leq v_h(q, w) \leq v_{\text{max}} \\ & q_{\text{min,h}} \leq q_h \leq q_{\text{max,h}} \end{aligned}$$

Example:

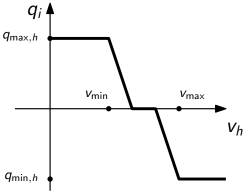
- Long distribution grid line
- Wind/Solar inject p_3 leads to overvoltage
- Power consumption of EV p_1 is higher than Wind/Solar production p_3

Local Feedback Control

Local Strategies

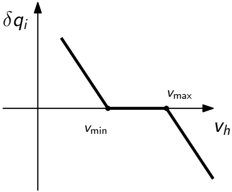
$$q_h(t+1) = g_h(q_h(t), v_h(t))$$

where $g_h(q, v)$ only uses local information



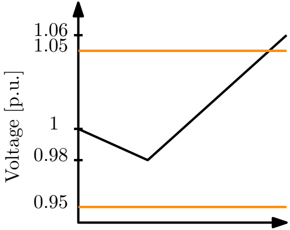
$q_h(t+1) = f_h(v_h(t))$

Droop control
IEEE 1547



$q_h(t+1) = q_h(t) + \delta q_h(v_h(t))$

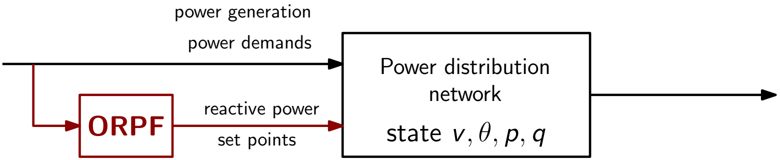
Integral control



Local control strategies cannot solve this problem

Mathematically proven in "On the need for communication for voltage regulation of power distribution grids"

A Feedforward Approach



Optimal Reactive Power Flow (ORPF)

- Similar to power transmission grid ORPF
- Motivated by encouraging results on **ORPF convexification**
  Lavaei (2012), Farivar (2013), ...
- Requires **load knowledge** - **full communication**
- Heavily **model based**

The Optimization Problem

$$\min_q \quad \frac{1}{2} q^T M q$$
$$\text{subject to} \quad v_{\text{min}} \leq v_h(q, w) \leq v_{\text{max}}$$
$$q_{\text{min,h}} \leq q_h \leq q_{\text{max,h}}$$

Without model for $v_h(q, w)$ and knowledge of w

How to design a feedback controller that steers grid to the solution?

Lagrangian $\mathcal{L}(q, \lambda) = \frac{1}{2} q^T M q + \lambda_{\text{max}}^T (v(q, w) - v_{\text{max}}) + \lambda_{\text{min}}^T (v_{\text{min}} - v(q, w))$

Optimization Algorithm

- **Dual update** $\lambda(t+1) = \left[\lambda(t) + \alpha \frac{\partial \mathcal{L}}{\partial \lambda}\right]_{\geq 0}$
- **Primal update** $q(t+1) = \arg\min_{q \in Q} \mathcal{L}(q, \lambda(t+1))$

Feedback Optimization Control

Lagrangian $\mathcal{L}(q,\lambda) = \frac{1}{2}q^T M q + \lambda_{\max}^T(v(q,w) - v_{\max}) + \lambda_{\min}^T(v_{\min} - v(q,w))$

Dual update

$$\lambda(t+1) = \left[\lambda(t) + \alpha \frac{\partial \mathcal{L}}{\partial \lambda}\right]_{\geq 0}$$

$$\lambda_{\max}(t+1) = [\lambda_{\max}(t) + \alpha(v(q,w) - v_{\max})]_{\geq 0}$$

$$\lambda_{\min}(t+1) = [\lambda_{\min}(t) + \alpha(v_{\min} - v(q,w))]_{\geq 0} \qquad (\lambda\text{-Update})$$

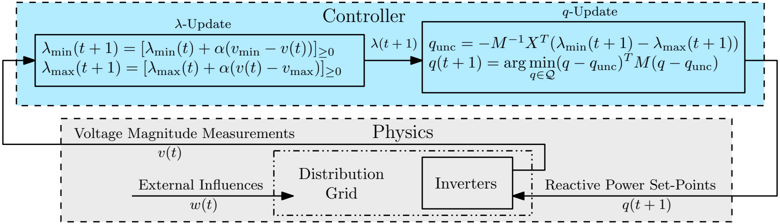
Locally integrate the voltage violation

Primal update $q(t+1) = \arg\min_{q \in Q} \mathcal{L}(q, \lambda(t+1))$

$$\frac{\partial \mathcal{L}}{\partial q} = 0 \quad \Rightarrow \quad Mq + \underbrace{\frac{\partial v}{\partial q}}_{X}(\lambda_{\max} - \lambda_{\min}) = 0 \;\Rightarrow\; q_{\text{unc}} = -M^{-1}X(\lambda_{\max} - \lambda_{\min})$$

$$q(t+1) = \arg\min_{q \in Q} \|q - q_{\text{unc}}\|_M \qquad (q\text{-Update})$$

Block Diagram



- Inverters take local voltage magnitude measurements
- Central control unit calculates set-points
- Set-points are send to the inverters

Needed Model Information

Linear Model Approximation

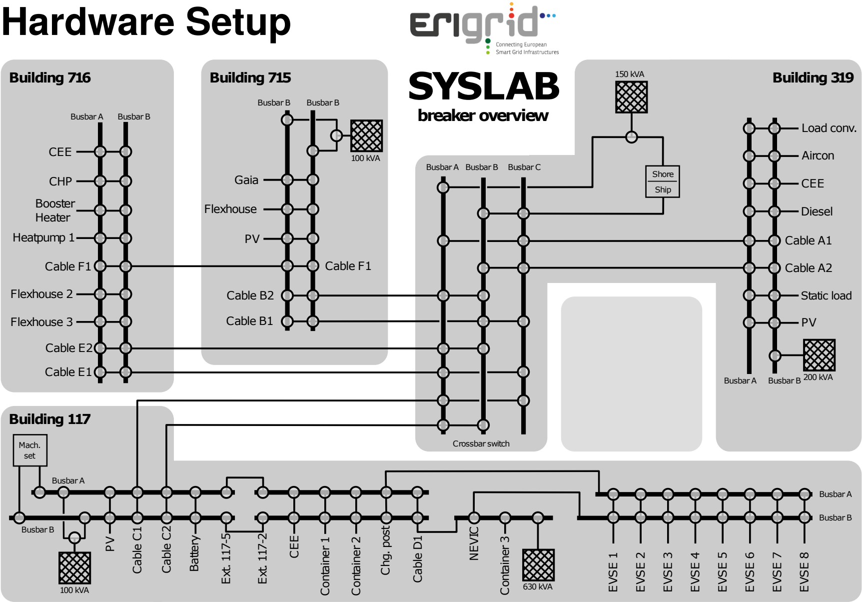
- The derivative $\frac{\partial v(q,w)}{\partial q}$ can be approximated by a constant X
- X models the sensitivity of v with respect to q
- Can be calculated using topology and cable data
- Similar to Power Transfer Distribution Factors

Model-free Approximation

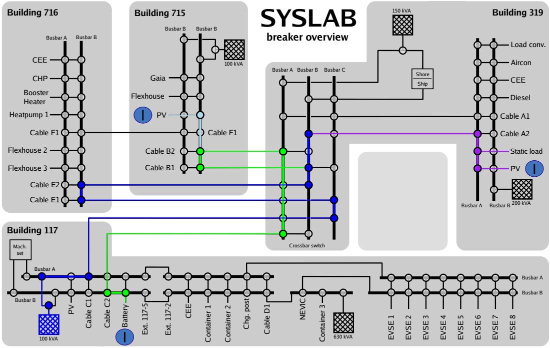
All entries of X are positive

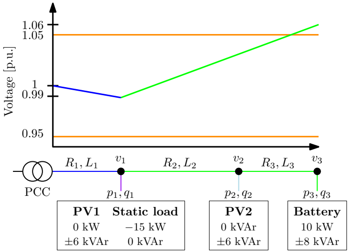
$$\Rightarrow X = \begin{bmatrix} 1 & \cdots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \cdots & 1 \end{bmatrix}$$

Hardware Setup



Hardware Setup

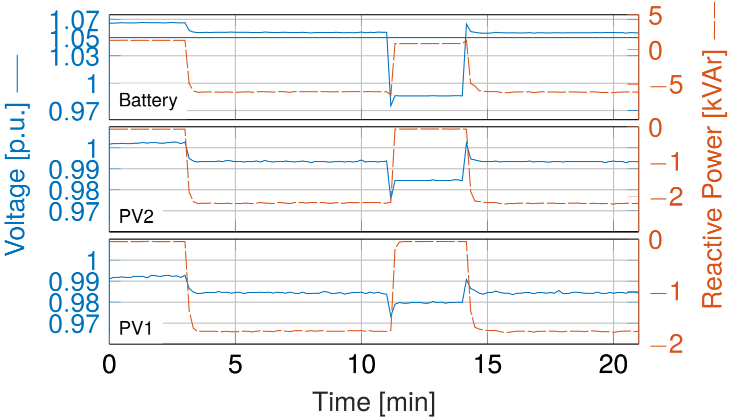




Active Power and Reactive Power Capabilities

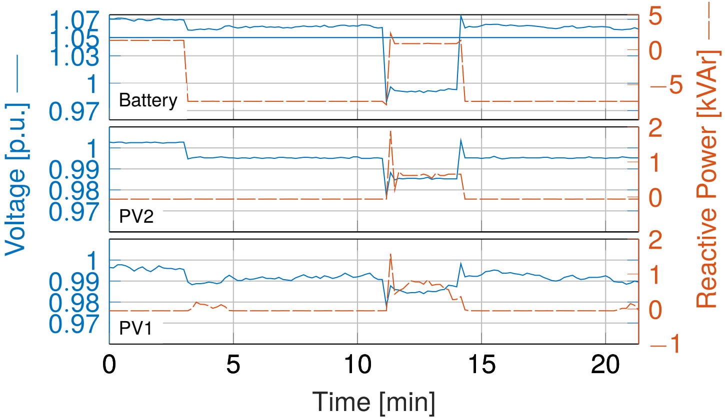
Battery:	P=10 kW	Q=±8 kVAr
Static Load:	P=15 kW	Q=0 kVAr
PV Inverter:	P=0 kW	Q=±6 kVAr

Experimental Results - ORPF



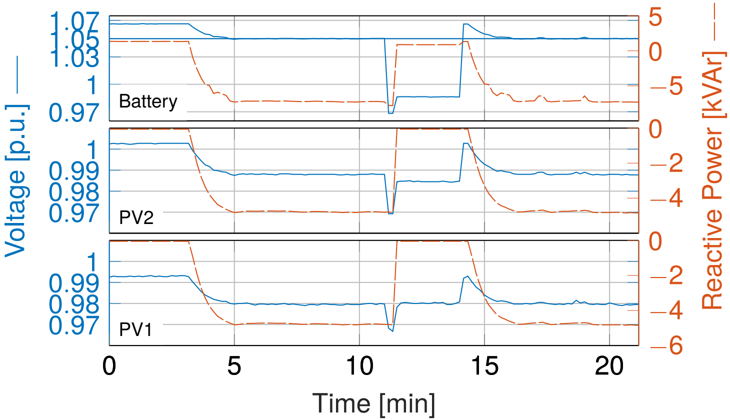
Steady-state error with voltage violation

Experimental Results - Droop Control



Reactive power of PVs not used ⇒ persistant overvoltage

Exp. Results - Feedback Optimization



Convergence to the allowed voltage band

This is the model-free version

Conclusions

Take-Away Messages

- All local control strategies can make over/undervoltages worse
- Feedback Optimization can solve the problem
- Feedback Optimization has great potential for power grid applications
- Feedback Optimization is very robust

People Involved

Lukas Ortmann

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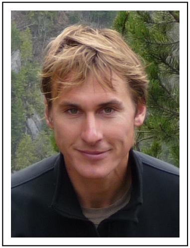

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Acknowledgement

European Commission | Horizon 2020
European Union funding
for Research & Innovation

DTU Technical University of Denmark

ERIGrid
Connecting European
Smart Grid Infrastructures