Combining Local and Centralized Voltage Control Schemes in Active Distribution Networks

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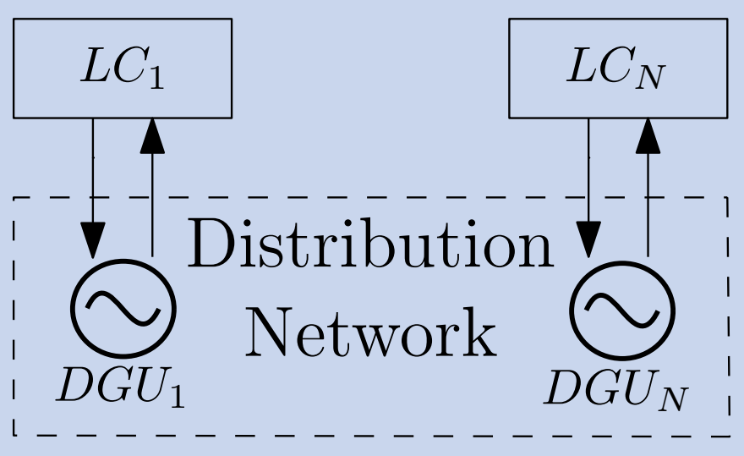
Voltage control architectures

Different control schemes can be contemplated in a distribution system taking into account practical needs, technical limitations of the Distributed Generation Units (DGU), and regulatory policies.

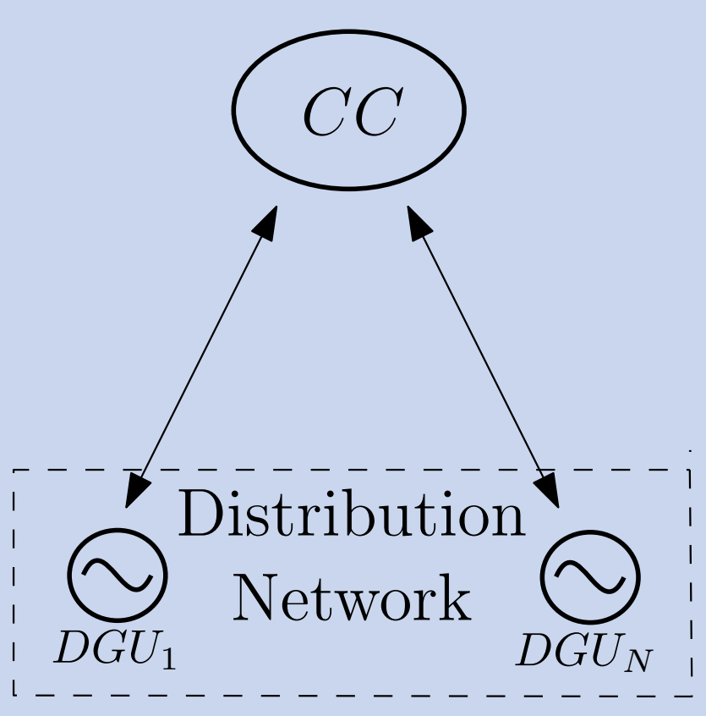
Local Control (LC)

- DGUs may quickly adjust their power outputs based on voltage (and active power) measured at their terminals
- control embedded in the equipment
- no communication infrastructure needed.



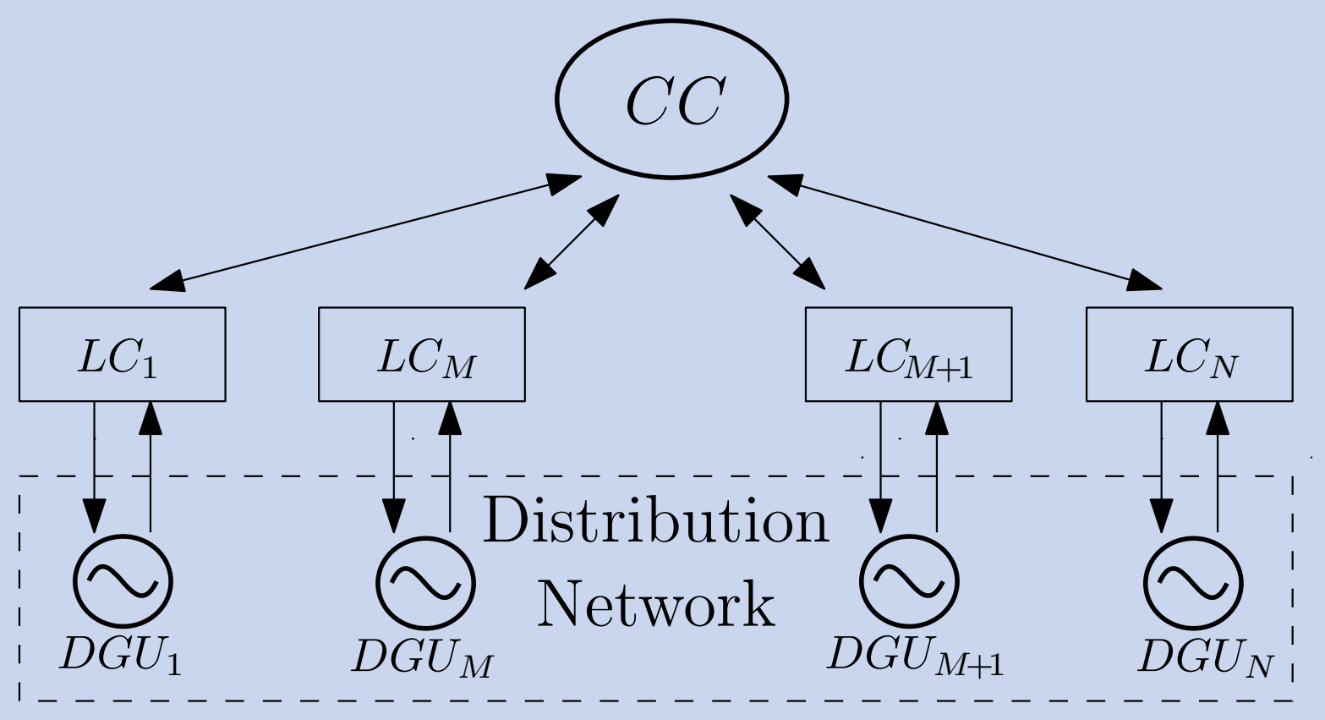
Centralized Control (CC)

- periodically gathers measurements and sends set-point corrections to the DGUs
- shares the corrective efforts over multiple DGUs
- communication infrastructure needed.



Combined Local and Centralized

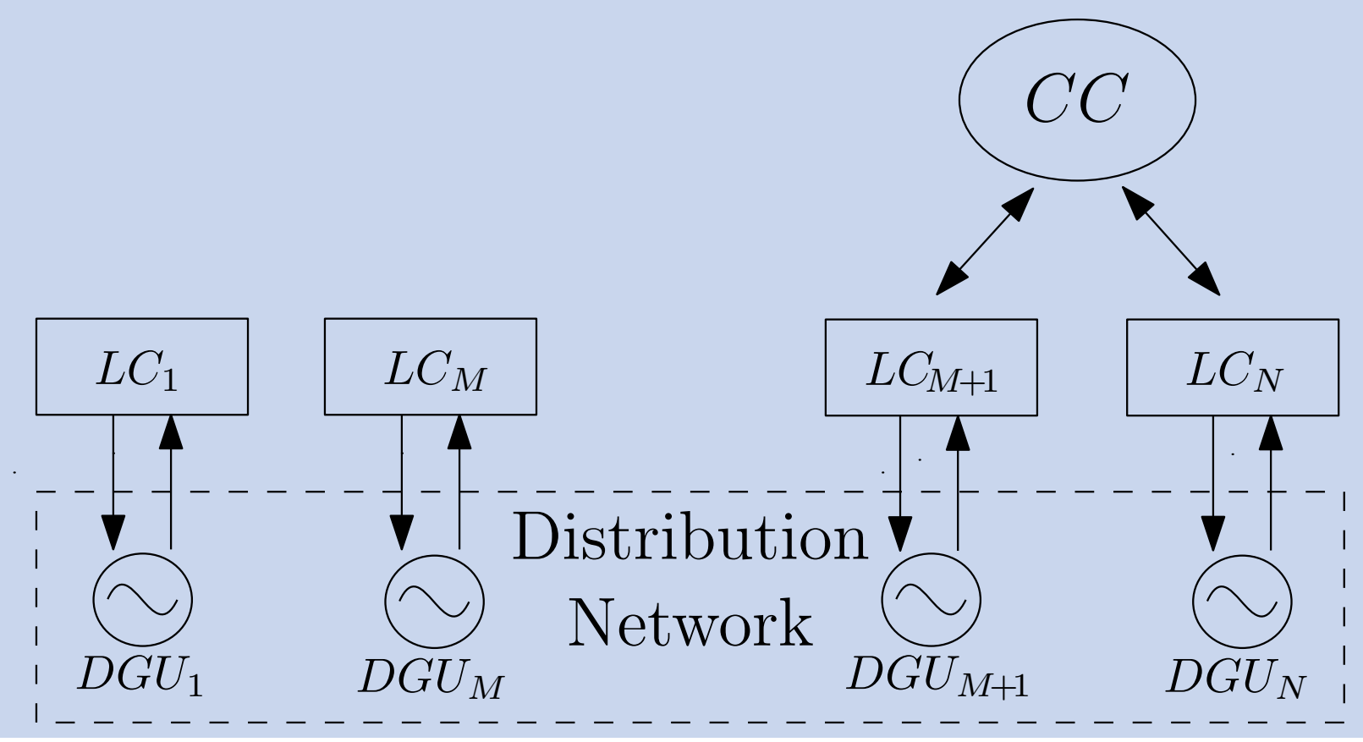
- fast reactions from LCs after any disturbance
- followed by slower, but coordinated adjustment of DGUs at upper level, to refine the local corrections
- enhanced control possibilities



Hybrid control

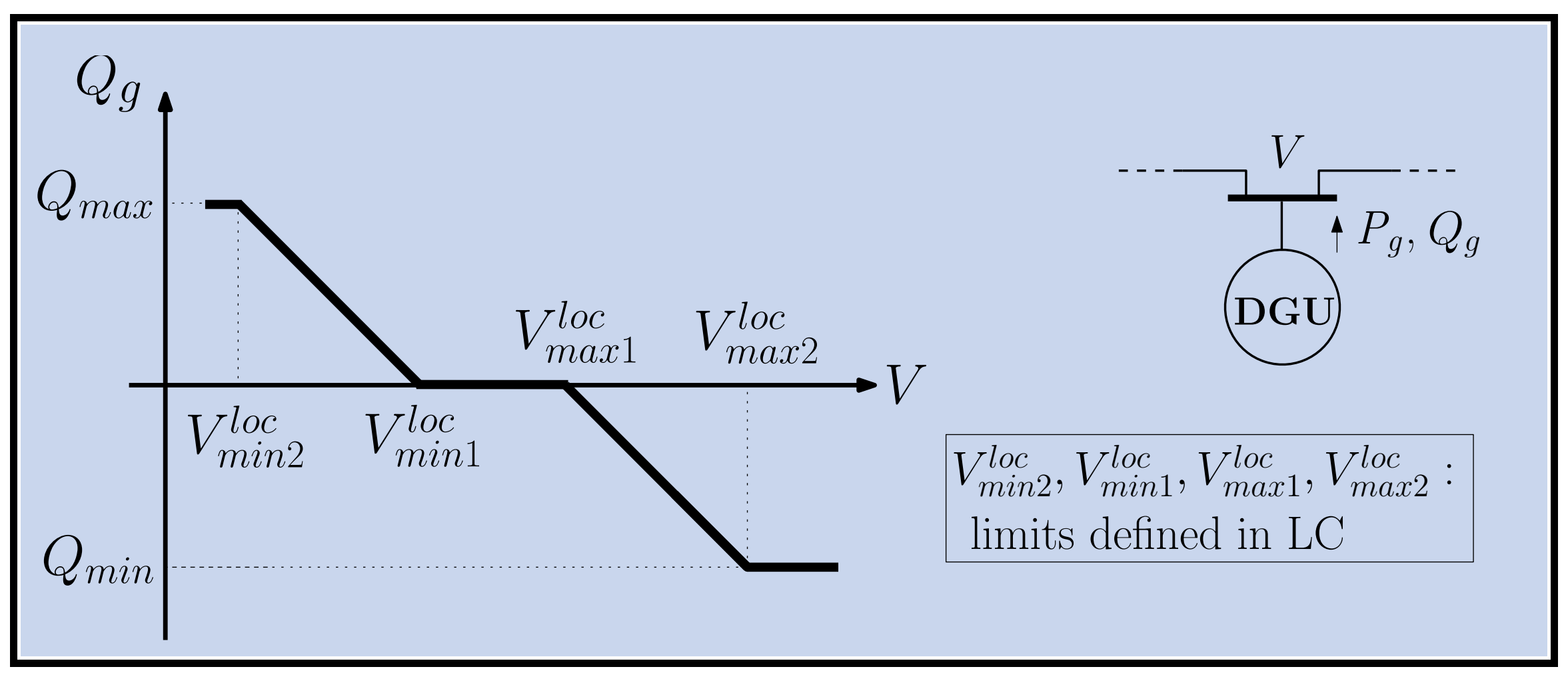
The deployment of the CC and its communication infrastructure may not be feasible or affordable over all DGUs, for instance on small DGUs or DGUs with older technology.

In the hybrid control scheme, some DGUs are under LC mode only, while others are in CLC mode, accounting for the effect of the former.



Lower level : local, fast control

The reactive power output of a DGU varies according to the piecewise linear VQ characteristic shown below.

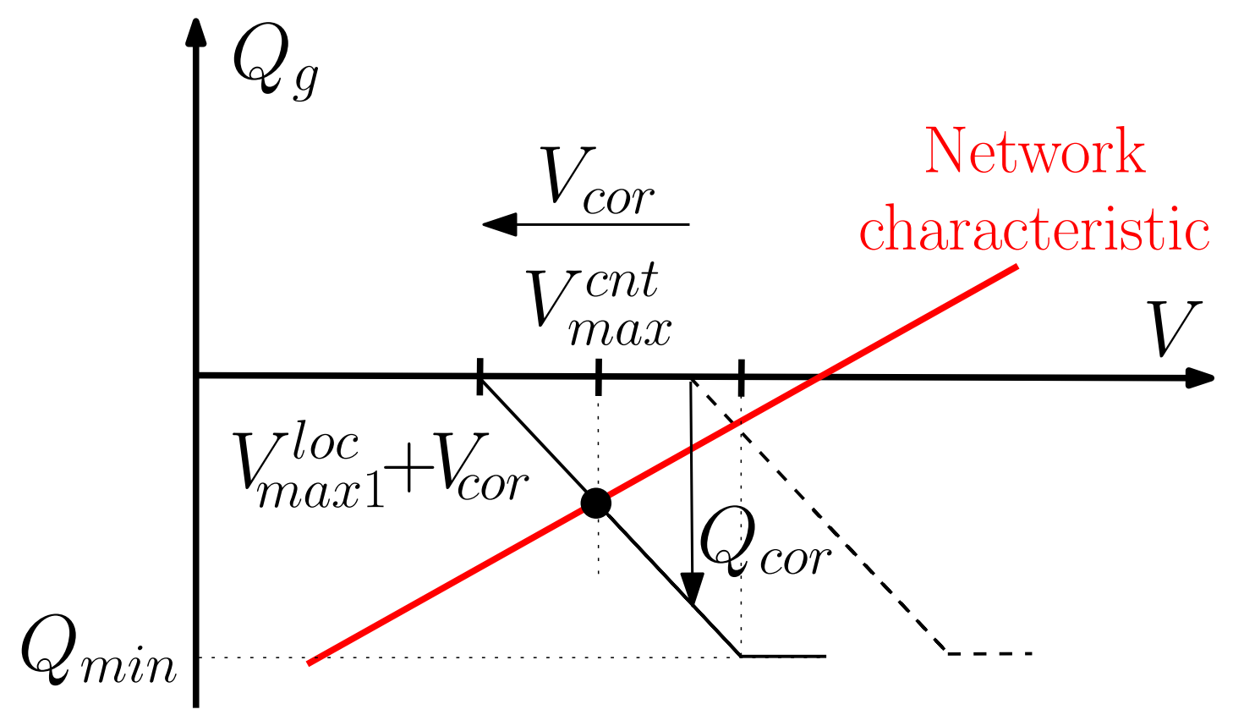


As long as the measured terminal voltage lies the dead-band $[V^{loc}_{min1}, V^{loc}_{max1}]$, the produced reactive power Qg is kept at zero to minimize the DGU internal losses.

Correction from upper level

The cumulated correction $\boldsymbol{Q}_{cor}$ received from the upper level shifts the VQ characteristic of the DGU under control.

only high voltage part of VQ characteristic shown here, for clarity



Upper level : slow, centralized control

A Model Predictive Control scheme is used, which involves solving at each discrete time, the multi-step constrained optimization problem detailed below.

$$\min_{\Delta \boldsymbol{Q}_g, \boldsymbol{\varepsilon}} \sum_{i=0}^{N_c-1} \|\Delta \boldsymbol{Q}_g(k+i)\|^2_{\boldsymbol{W}} + \|\boldsymbol{\varepsilon}\|^2_{\boldsymbol{S}}$$

where $(i = 1, \dots, N_c)$:

$$\Delta \boldsymbol{Q}_g(k+i) = \boldsymbol{Q}_g(k+i) - \boldsymbol{Q}^m_g(k)$$
$$\Delta \boldsymbol{Q}_g(k+i) = \boldsymbol{S}_Q \, \Delta \boldsymbol{Q}_{cor}(k+i)$$

$\Delta \boldsymbol{Q}_g$: DGU reactive power change

$\boldsymbol{\varepsilon} = [\varepsilon_1, \varepsilon_2]^T$: slack variables to relax the inequality constraints in case of infeasibility

$\boldsymbol{Q}^m_g$: last measured values of DGU reactive power

$\boldsymbol{W}$, $\boldsymbol{S}$: weighting and penalizing matrices

$\Delta \boldsymbol{Q}_{cor}$: DGU reactive power correction by controller

$\boldsymbol{S}_Q$: sensitivity matrix of DGU reactive power to requested reactive power correction

for $i = 1, \dots, N_p$:

$$\boldsymbol{V}(k+i \mid k) = \boldsymbol{V}(k \mid k) + \boldsymbol{S}_V \, \Delta \boldsymbol{Q}_g(k+i-1)$$

$\boldsymbol{V}(k+i|k)$: bus voltages predicted at time $k+i$ given the measurements at time k

$\boldsymbol{V}(k \mid k)$: last measured values of voltages

$\boldsymbol{S}_V$: sensitivity matrix of voltages to reactive power changes

for $i = 1, \dots, N_p$:

$$(-\varepsilon_1 + V^{cnt}_{min}) \, \mathbf{1} \leq \boldsymbol{V}(k+i \mid k) \leq (V^{cnt}_{max} + \varepsilon_2) \, \mathbf{1}$$

for $i = 0, \dots, N_c - 1$:

$$\boldsymbol{Q}^{min}_g(k) \leq \boldsymbol{Q}_g(k+i) \leq \boldsymbol{Q}^{max}_g(k)$$
$$\Delta \boldsymbol{Q}^{min}_g(k+i) \leq \Delta \boldsymbol{Q}_g(k+i) \leq \Delta \boldsymbol{Q}^{max}_g(k+i)$$

$\boldsymbol{Q}^{min}_g$, $\boldsymbol{Q}^{max}_g$,$\Delta \boldsymbol{Q}^{min}_g$ and $\Delta \boldsymbol{Q}^{max}_g$: lower and upper limits on the DGU outputs and on their rates of change

$\mathbf{1}$: unit vector

$\boldsymbol{V}^{cnt}_{min}$, $\boldsymbol{V}^{cnt}_{max}$: voltage limits considered at upper level

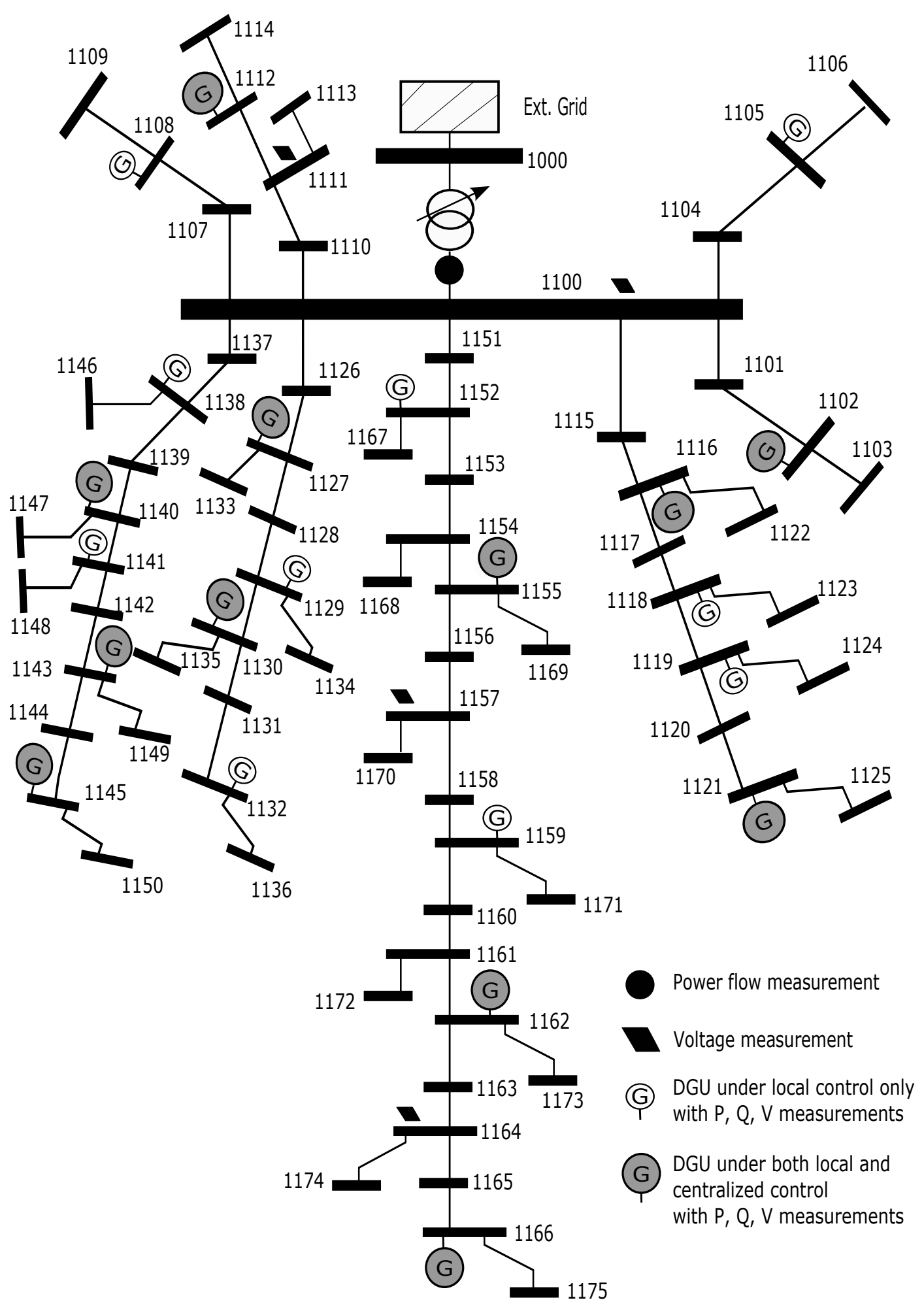
Non-updated sensitivity matrices

- to minimize information exchanges, the optimization is performed under the assumption that all DGUs operate on the sloping part of their VQ characteristics
- however, those DGUs operating in the dead-band of their VQ characteristic do not respond to a correction $\Delta \boldsymbol{Q}_{cor}$ with the expected additional reactive power
- this is corrected by the closed-loop model predictive control scheme (other DGUs compensate for the non responding ones)
- by not updating the sensitivities, the voltage correction takes some more time.

On the control of transformer ratios

- Increasing the number of tap changes reduces the lifetime of the transformer Load Tap Changer (LTC)
- hence, the latter has not been considered (assuming there is enough controllability from DGUs)
- but the formulation can be easily extended to include the LTC voltage set-point of as a control variable with proper associated "cost".

Simulation results using hybrid scheme



75-bus, 11-kV distribution network

38 static and 15 dynamic loads

Upper level :

$N_c = N_p = 3$

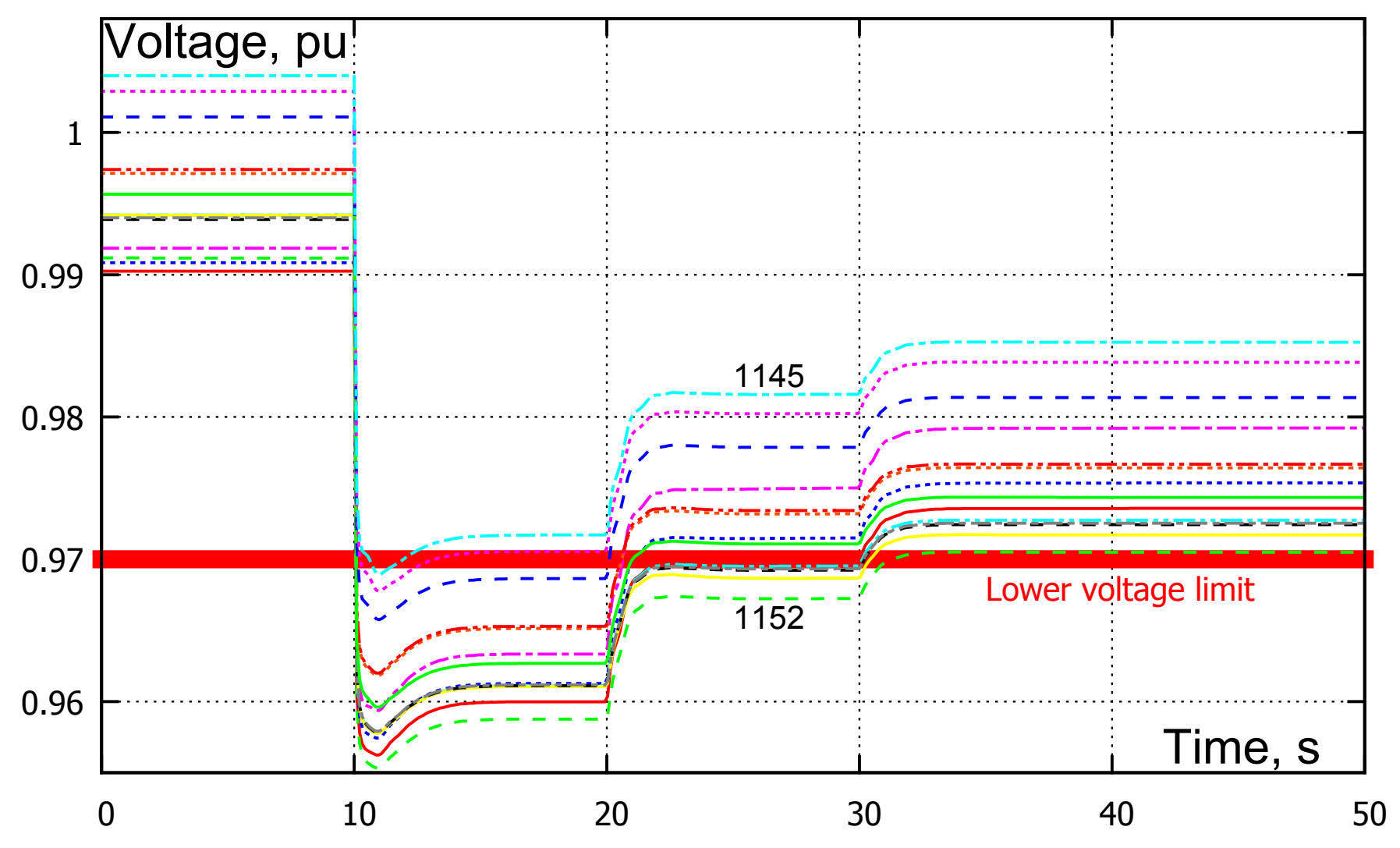
measurements received every 10 s : (P, Q, V) on 11-kV side of transformer, (P, Q, V) at the terminal of each DGU, V at 4 non-DGU buses.

reactive power corrections sent every 10 s

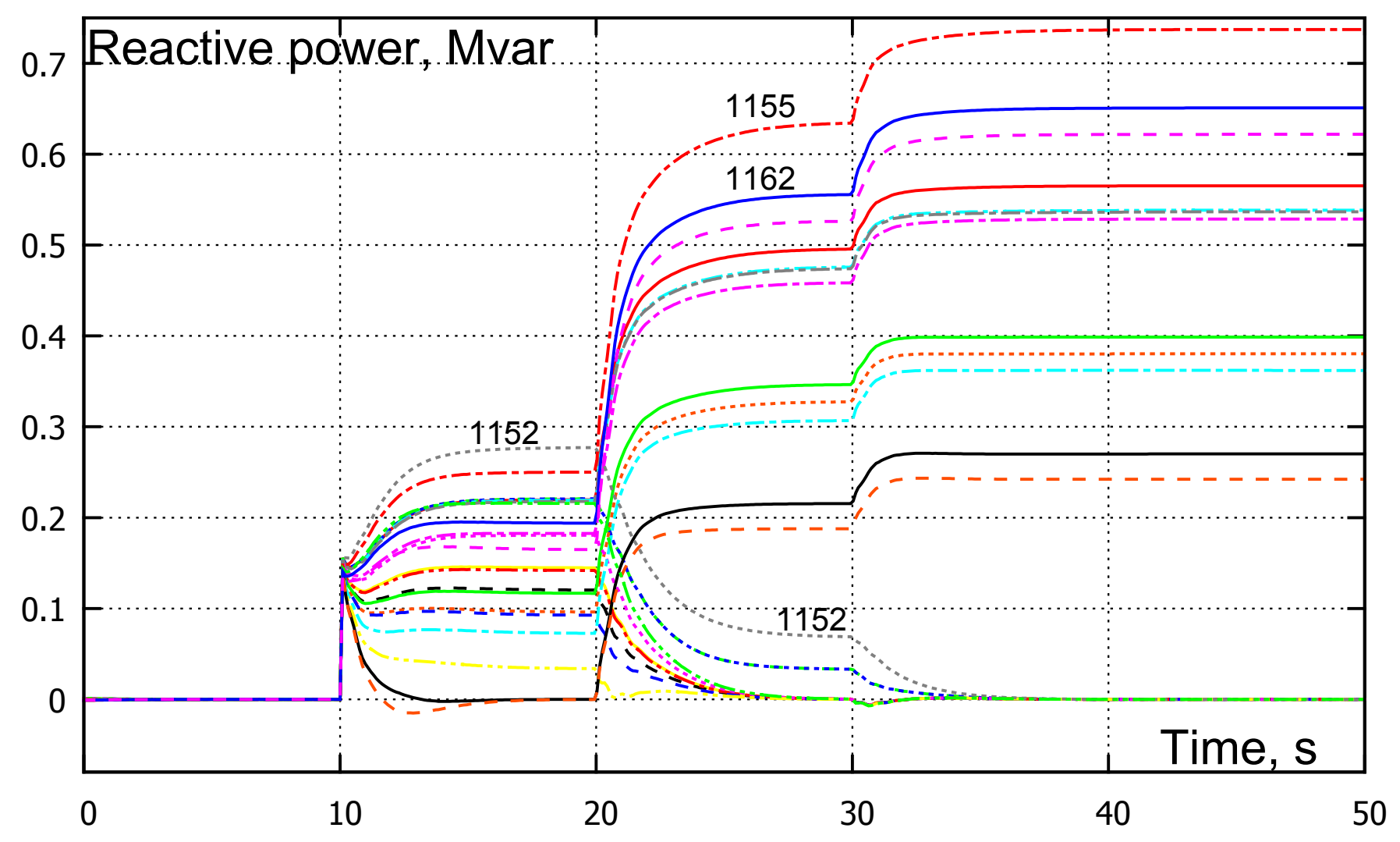
22 DGUs : 3.3-MVA doubly fed induction generators driven by wind turbines and 3-MVA synchronous geners.
10 DGUs under local control only;
12 DGUs under both local and centralized control.

Correction of voltages after a 0.05 pu voltage drop taking place in the external grid, at t = 10 s.

Under the effect of local control, DGUs with terminal voltage outside the dead-band inject reactive power right after the disturbance. The voltages are rapidly but partly corrected, leading to fewer buses in low voltage situation.



At t = 20 s, the upper level, coordinated controller has sensed the unsatisfactory voltages and applies the corrective actions ΔQ_{cor} on the 12 DGUs under its control. The remaining voltage violation is cleared in two steps.



The 10 DGUs under local control only participate in the initial correction of the voltages. They are reset to their initial reactive power after the upper level has acted.

Related publications and acknowledgement

- H. Soleimani Bidgoli and T. Van Cutsem. "Voltage Profile Correction in Distribution Grids Combining Single- and Two-level Controllers", to be presented at the IEEE PES PowerTech Conferencc, Manchester, June 2017
- H. Soleimani Bidgoli and T. Van Cutsem. "Combined Local and Centralized Voltage Control in Active Distribution Networks", submitted for publication in IEEE Trans. on Power Systems, 2017 (manuscript under second review)

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