Model Predictive Control for Reference Tracking in Distribution Networks Hosting Dispersed Generation

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A real-time, centralized control system is presented which is acting on the active and reactive powers of distributed generators when the network experiences voltage and/or thermal limits violation. The control resorts to multi-step receding horizon optimization. The objective is to minimize the deviations of Dispersed Generation Units (DGU) active and reactive powers from reference values. Furthermore, the formulation is such that DGU powers are restored to their desired schedule as soon as operating conditions allow doing so. Three modes of operation of the proposed controller are presented, involving dispatchable units as well as DGUs operated to collect maximum power.

Motivation

- The number of renewable energy sources connected to distribution systems is progressively increasing
- temporary voltage problems and/or thermal overload are expected to occur more frequently.

Controller main features

- Centralized controller receives the near future schedules of DGUs and:
  - in normal situation, steers the DGUs to follow the schedule or, capture maximum available power
  - in undesired situation, keeps the production level as close as possible to their reference values while solving the voltage or thermal violation
  - restores DGU outputs to the schedule as soon as system conditions improve (resetting effect).

Model Predictive Control (MPC) approach

At time k, the controller:

- collects measurements
- uses an internal model and the measurements to predict the system response over an interval of N_p steps
- computes an optimal sequence of N_c future control changes $\Delta \boldsymbol{P}_{cor}(k+i)$ and $\Delta \boldsymbol{Q}_{cor}(k+i), i = 0 \dots N_c - 1$
- applies only the first component ($i = 0$).

At time $k+1$, the whole procedure is repeated.

Constraint multi-step optimization

$$\min_{\boldsymbol{P}_g, \boldsymbol{Q}_g, \boldsymbol{\varepsilon}} \sum_{i=0}^{N_c-1} \|\boldsymbol{P}_g(k+i) - \boldsymbol{P}_{ref}(k+i)\|^2_{\boldsymbol{R}_1} + \\ + \sum_{i=0}^{N_c-1} \|\boldsymbol{Q}_g(k+i) - \boldsymbol{Q}_{ref}(k+i)\|^2_{\boldsymbol{R}_2} + \|\boldsymbol{\varepsilon}\|^2_{\boldsymbol{S}}$$

$\boldsymbol{u}(k) = [\boldsymbol{P}_g^T(k), \boldsymbol{Q}_g^T(k)]^T$: control variables

$\boldsymbol{u}_{ref}(k) = [\boldsymbol{P}_{ref}^T(k), \boldsymbol{Q}_{ref}^T(k)]^T$: control reference values

$\boldsymbol{R}_1$, $\boldsymbol{R}_2$: weighting matrices to prioritize the controls

$\boldsymbol{\epsilon} = [\epsilon_1, \epsilon_2, \epsilon_3]$: slack variables to relax the inequality constraints in case of infeasibility

$\boldsymbol{S}$: weighting matrix heavily penalizing nonzero $\boldsymbol{\varepsilon}$

Linearized system evolution

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

$$\begin{aligned} \boldsymbol{V}(k+i \mid k) &= \boldsymbol{V}(k+i-1 \mid k) + \\ &\quad + \boldsymbol{S}_V \left[\boldsymbol{u}(k+i-1) - \boldsymbol{u}(k+i-2)\right] \\ \boldsymbol{I}(k+i \mid k) &= \boldsymbol{I}(k+i-1 \mid k) + \\ &\quad + \boldsymbol{S}_I \left[\boldsymbol{u}(k+i-1) - \boldsymbol{u}(k+i-2)\right] \end{aligned}$$

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

$\boldsymbol{V}(k \mid k)$, $\boldsymbol{I}(k \mid k)$: last received measurements

$\boldsymbol{S}_V$, $\boldsymbol{S}_I$: sensitivity matrices of voltages and currents respect to control changes

Inequality constraints

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

$$-\epsilon_1 \mathbf{1} + \boldsymbol{V}^{low}(k+i) \le \boldsymbol{V}(k+i \mid k) \le \boldsymbol{V}^{up}(k+i) + \epsilon_2 \mathbf{1}$$
$$\boldsymbol{I}(k+i \mid k) \le \boldsymbol{I}^{up}(k+i) + \epsilon_3 \mathbf{1}$$

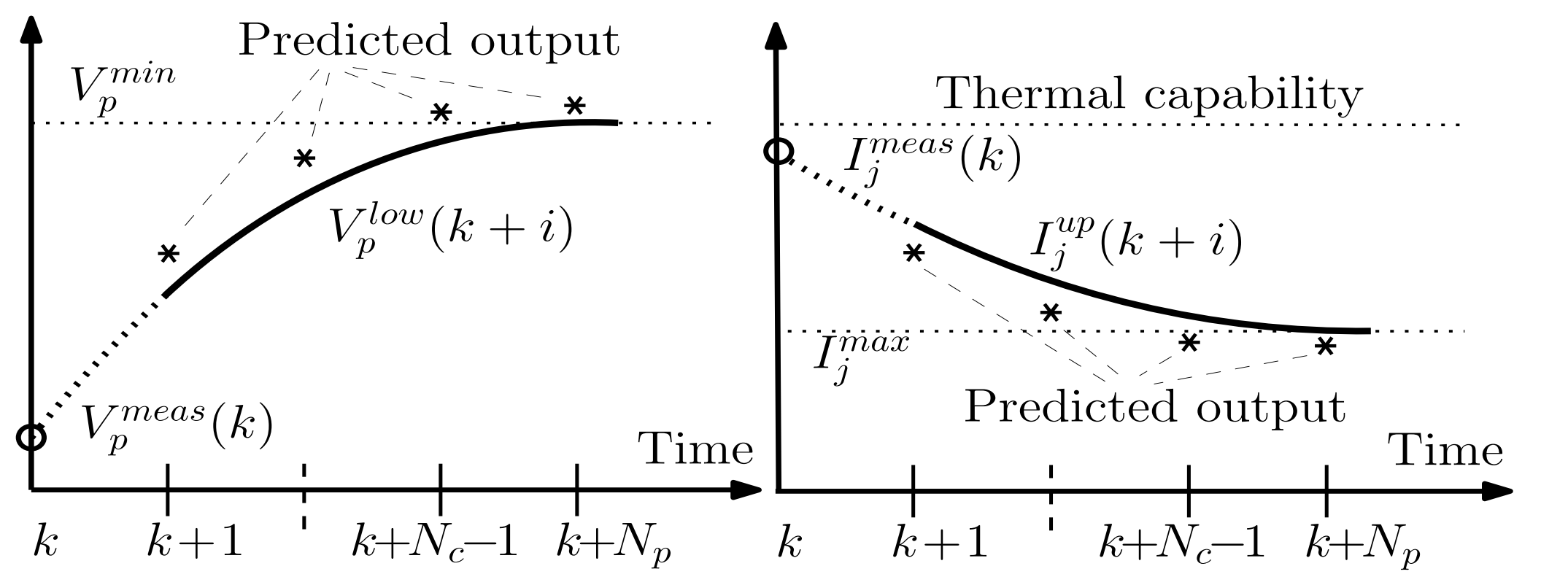
for $i = 0, \dots, N_c - 1$:

$$\boldsymbol{u}^{min} \le \boldsymbol{u}(k+i \mid k) \le \boldsymbol{u}^{max}$$
$$\Delta \boldsymbol{u}^{min} \le \boldsymbol{u}(k+i \mid k) - \boldsymbol{u}(k+i-1 \mid k) \le \Delta \boldsymbol{u}^{max}$$

$\boldsymbol{u}^{min}$, $\boldsymbol{u}^{max}$,$\Delta \boldsymbol{u}^{min}$and $\Delta \boldsymbol{u}^{max}$: lower and upper limits on DGU outputs and their rate of change

$\mathbf{1}$: unit vector

$\boldsymbol{V}^{low}(k+i)$, $\boldsymbol{V}^{up}(k+i)$ and $\boldsymbol{I}^{up}(k+i)$: progressive tightening bounds on predicted voltages and currents



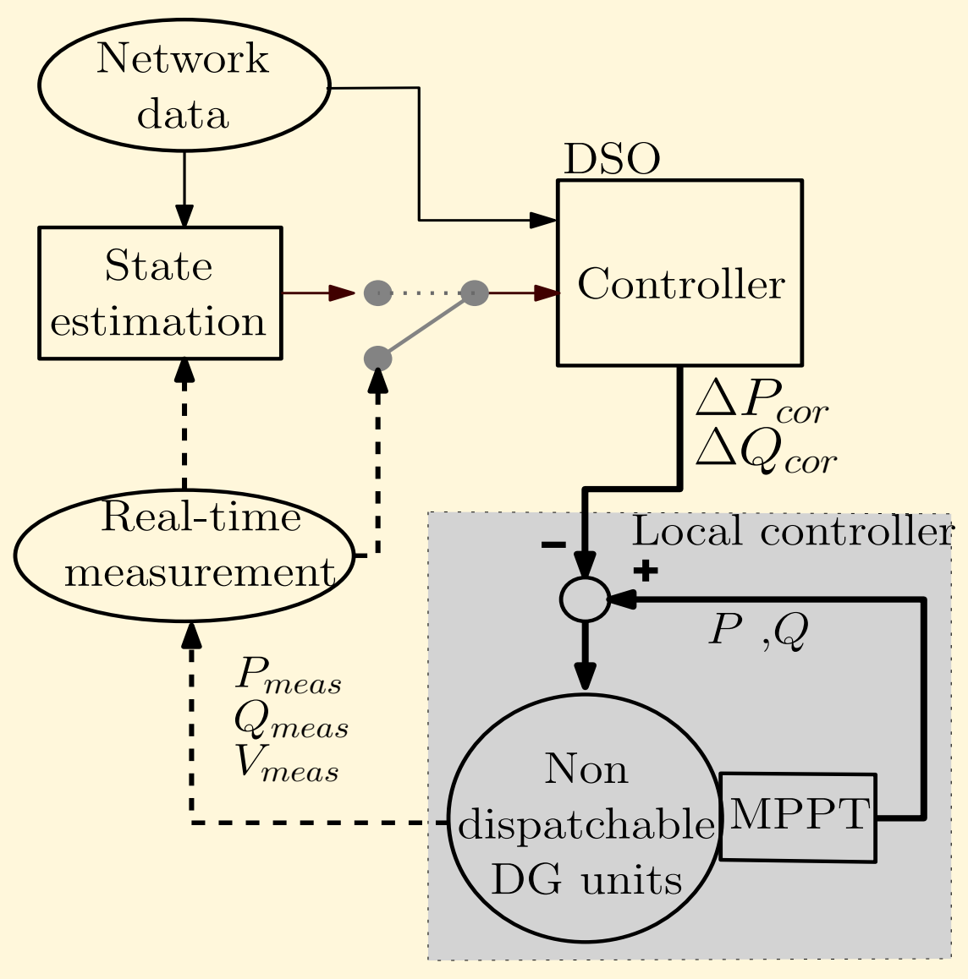
The voltages and currents are brought within the limits $\boldsymbol{V}^{low}$, $\boldsymbol{V}^{up}$ and $\boldsymbol{I}^{up}$ at the end of prediction horizon.

Contexts of application

The above MPC formulation can accommodate various contexts of application and regulatory policies, depending on the interactions and information transfers between Distribution System Operator (DSO) and the entities acting on the DGUs.

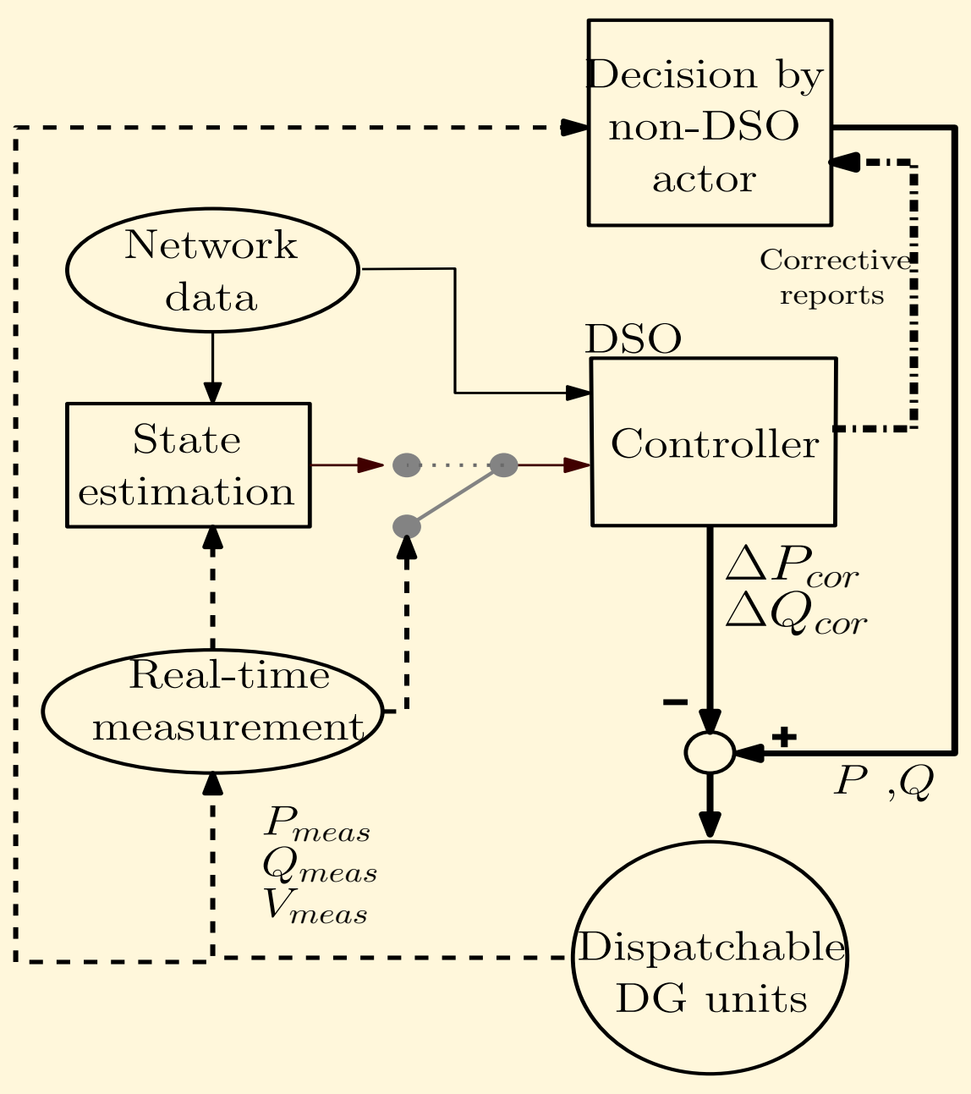
Mode 1

- applies to *non-dispatchable* units tracking maximum available power
- once a limit has been exceeded, the controller sends power corrections to the units of concern.



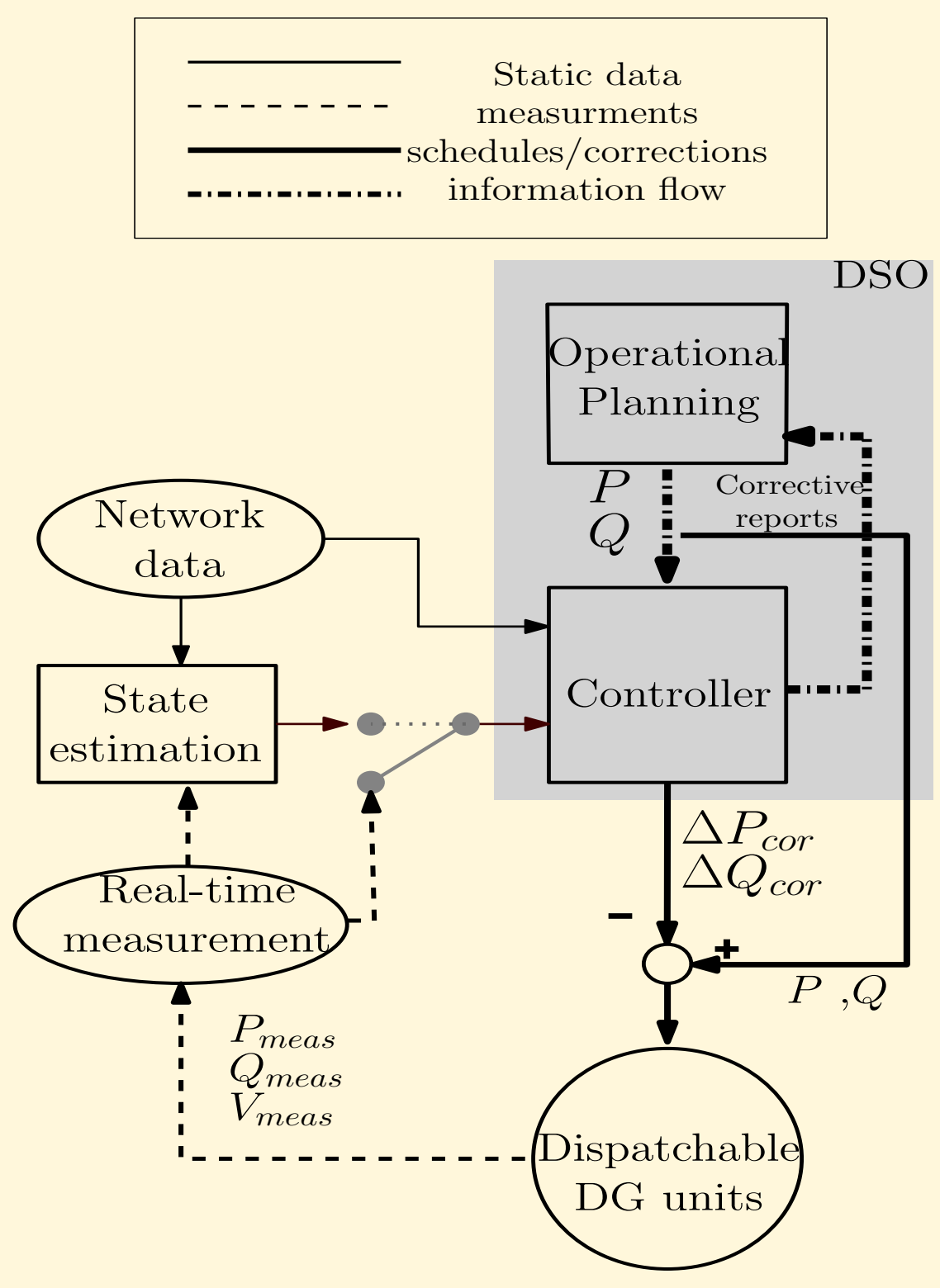
Mode 2

- applies to dispatchable DG units under the control of another entity than the DSO
- thus, the latter does not know the schedule followed by the units of concern
- power corrections are sent as in mode 1.



Mode 3

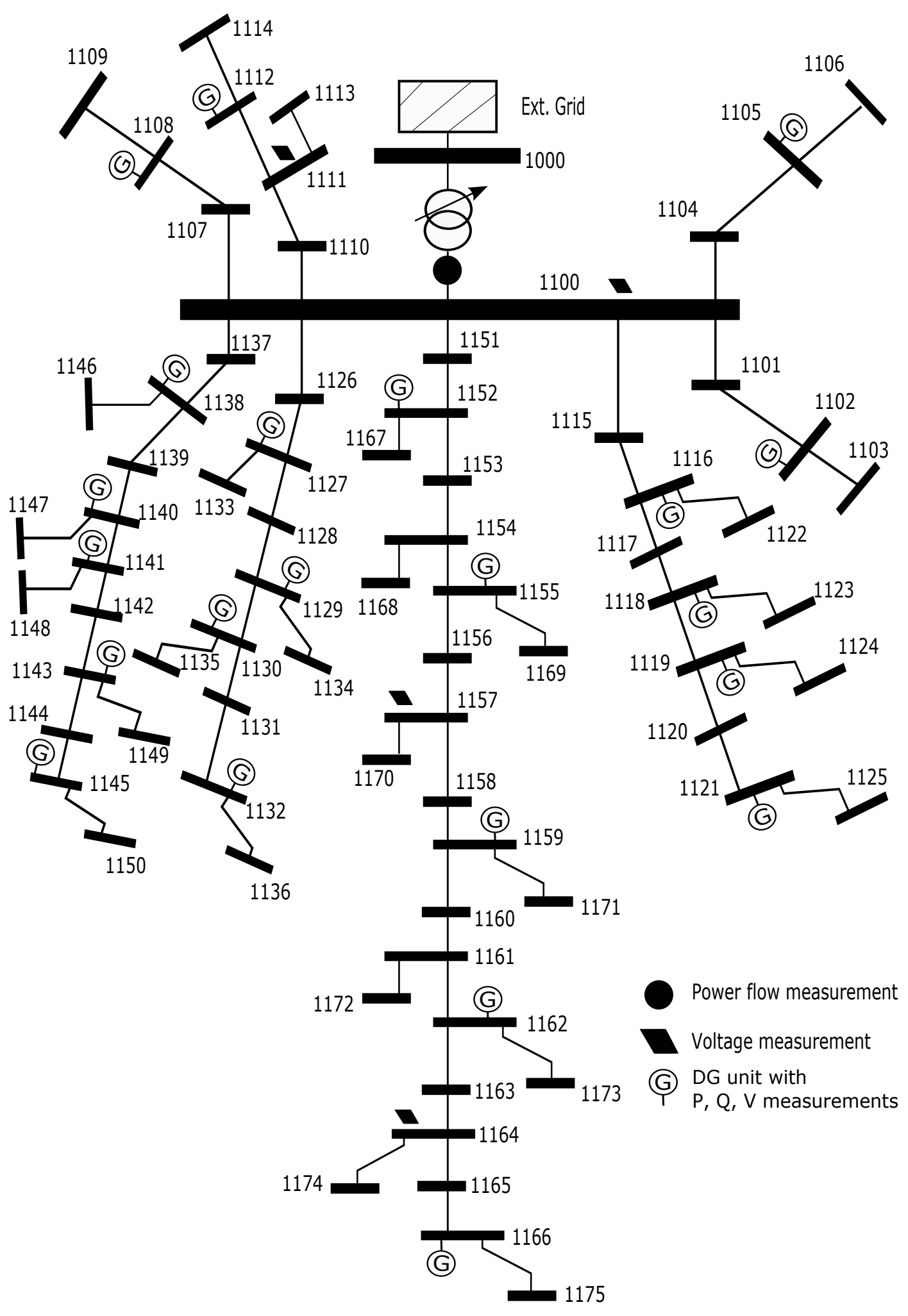
- applies to dispatchable DG units under the control of the DSO itself
- unlike in Mode 2, the schedule imposed to the units is known by the DSO
- DSO controller anticipates most violations, which allows keeping the system within limits.



In all modes the controller sends the corrections:

$$\Delta \boldsymbol{P}_{cor}(k) = \boldsymbol{P}_{ref}(k) - \boldsymbol{P}_g(k)$$
$$\Delta \boldsymbol{Q}_{cor}(k) = \boldsymbol{Q}_{ref}(k) - \boldsymbol{Q}_g(k)$$

Simulation results



75-bus, 11-kV distribution network

connected to upper grid through a 33kV/11kV transformer

38 static and 15 dynamic loads

$N_c = N_p = 3$

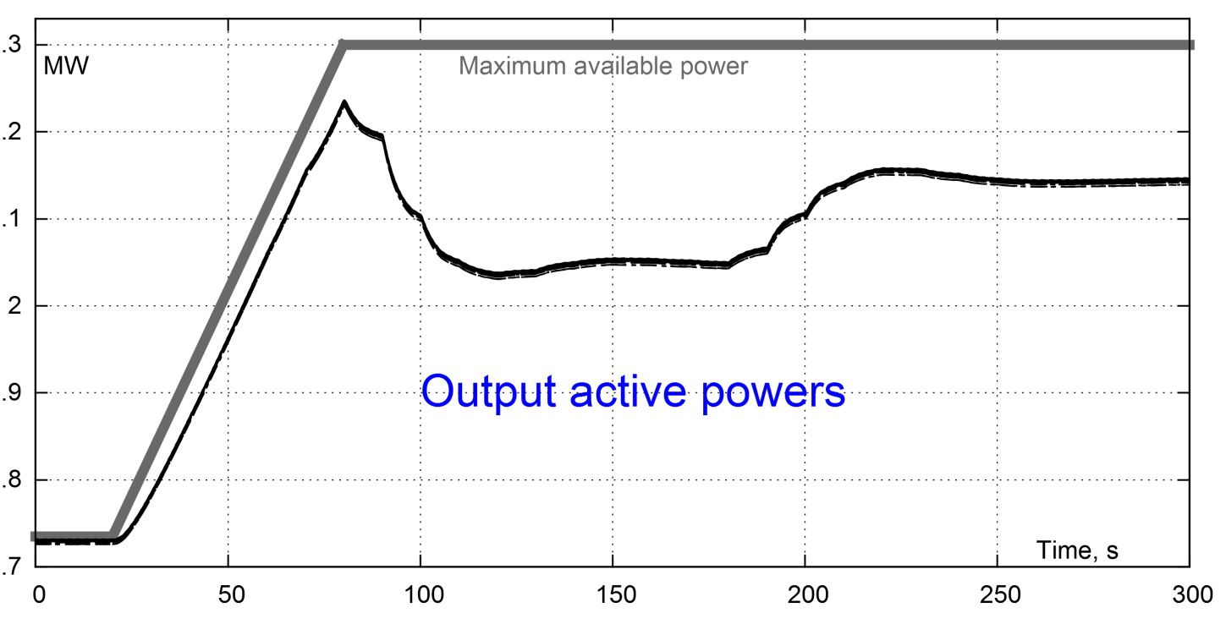
controls adjusted every 10 s after receiving measurements

(P, Q, V) measured on each DGU and V at 4 non-DGU buses

22 DGUs, consist of 3.3-MVA doubly fed induction generators driven by wind turbine and 3-MVA synchronous generators.

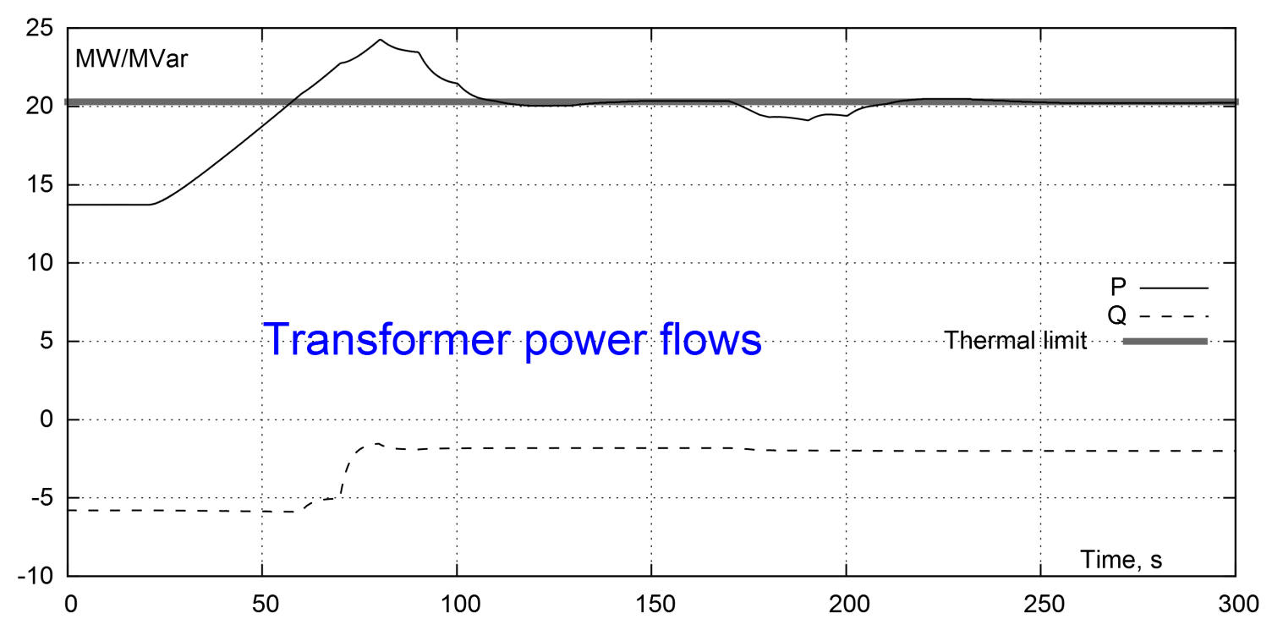
Correction of thermal overload and DGUs resetting effect–Mode 1

All DGUs are assumed to be driven by wind turbines.



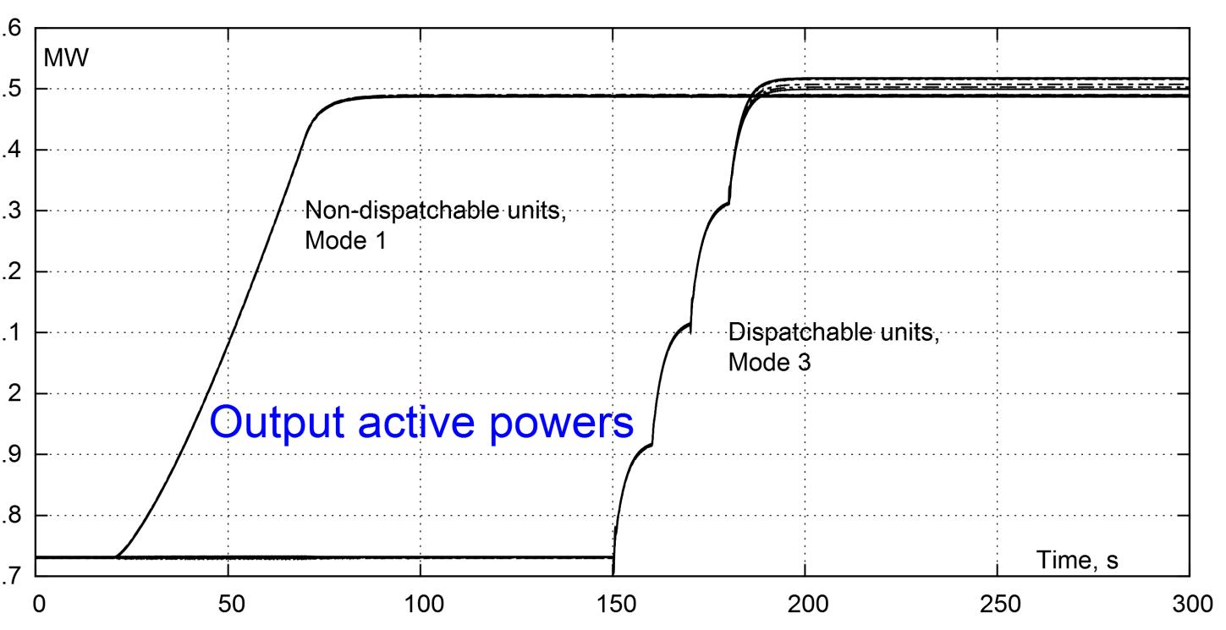
DGUs curtailment after violation observation under the impact of wind increase from t=20s to t=80s.

Part of the curtailed DGU active powers are restored as soon as operating condition improves.



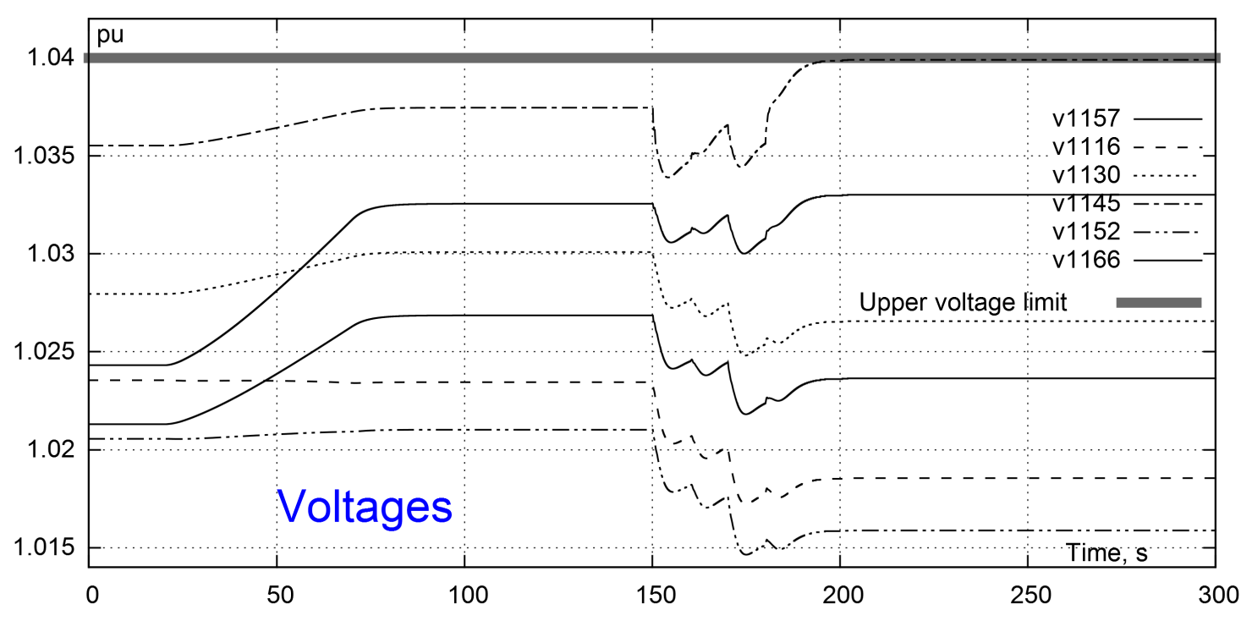
Capability of anticipating violation–Modes 1 and 3

13 DGUs are synchronous generators operating in mode 3, and the rest wind units running in mode 1.



Unforeseen wind increase before the schedule change makes voltages approach their limit.

The controller anticipatively adjusts the DGU reactive powers; as a result no voltage exceeds the limit.



Related publications and acknowledgement

- H. Soleimani Bidgoli, M. Glavic and T. Van Cutsem, “Model predictive control of congestion and voltage problems in active distribution networks“, *Proc. CIRED conference*, 2014.
- G. Valverde, T. Van Cutsem, “Model Predictive Control of Voltage in Active Distribution Networks”, *IEEE Trans. on Smart Grid*, Special issue on *Optimization Methods and Algorithms Applied to Smart Grid*, 2013

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