Real-time Corrective Control of Active Distribution Networks

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Motivation

- The number of renewable energy sources connected to distribution grids is increasing significantly
- (over- or under-)voltage and/or thermal overload problems are expected to occur more frequently, although for limited periods of time
- acting on Dispersed Generation Units (DGU) and Load Tap Changers (LTC) is more attractive (cheaper) than reinforcing the network ("fit-and-forget" attitude).

Controller main features

Centralized scheme monitoring the grid and controlling the DGUs and the LTC.

- In normal operating conditions : steers DGUs to either follow schedules or let them operate in maximum power tracking mode
- when the grid operates outside specified limits : computes and sends corrections of the DGU active and reactive powers, and possibly the LTC voltage set-point
- minimizes the deviations of DGU powers with respect to schedules and/or maximum power tracking
- resets DGU powers to desired values as soon as operating conditions allow doing so.

Model Predictive Control (MPC) approach

At time k, the controller:

- collects measurements
- uses them and an internal model to predict the system response over the next N_p discrete times
- 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 $\Delta \boldsymbol{P}_{cor}(k)$ and $\Delta \boldsymbol{Q}_{cor}(k)$.

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

Constrained multi-step optimization

Control variables : $\boldsymbol{u}(k) = [\boldsymbol{P}_g^T(k)\ \boldsymbol{Q}_g^T(k)]^T$
Corresponding reference values : $[\boldsymbol{P}_{ref}^T(k)\ \boldsymbol{Q}_{ref}^T(k)]^T$

Note: The formulation is easily extended to include the voltage set-point of the LTC as a control variable.

Objective function

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

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

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

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

Equality constraints : linearized system evolution

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

$$\boldsymbol{V}(k+i \mid k) = \boldsymbol{V}(k+i-1 \mid k) + \boldsymbol{S}_V\, [\boldsymbol{u}(k+i-1) - \boldsymbol{u}(k+i-2)]$$

$$\boldsymbol{I}(k+i \mid k) = \boldsymbol{I}(k+i-1 \mid k) + \boldsymbol{S}_I\, [\boldsymbol{u}(k+i-1) - \boldsymbol{u}(k+i-2)]$$

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

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

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

Inequality constraints : limits on bus voltages, branch currents, and their rate of changes

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

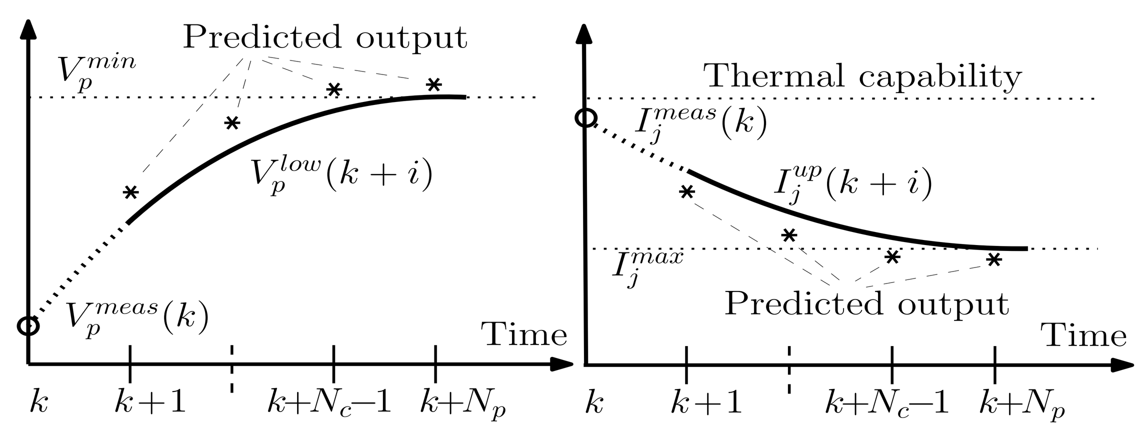
$$\boldsymbol{u}^{min} \le \boldsymbol{u}(k+i) \le \boldsymbol{u}^{max}$$

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

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

$\mathbf{1}$: unit vector

$\boldsymbol{V}^{low}(k+i)$, $\boldsymbol{V}^{up}(k+i)$ and $\boldsymbol{I}^{up}(k+i)$: tightening bounds bringing voltages and currents within the limits $\boldsymbol{V}^{low}$, $\boldsymbol{V}^{up}$ and $\boldsymbol{I}^{up}$ at the end of prediction horizon.



Corrections sent to the DGUs

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

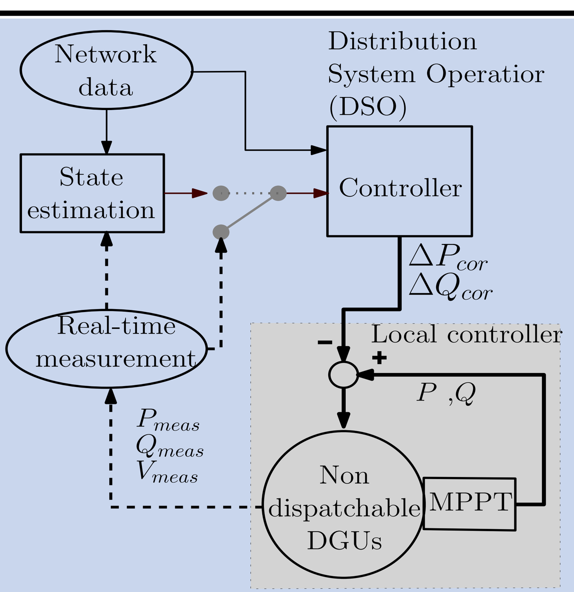
$$\Delta \boldsymbol{Q}_{cor}(k) = \boldsymbol{Q}_{ref}(k) - \boldsymbol{Q}_g(k)$$

Contexts of application

Various contexts of application, depending on the interactions and information transfers between entities acting on DGUs, in accordance with the regulatory policy :

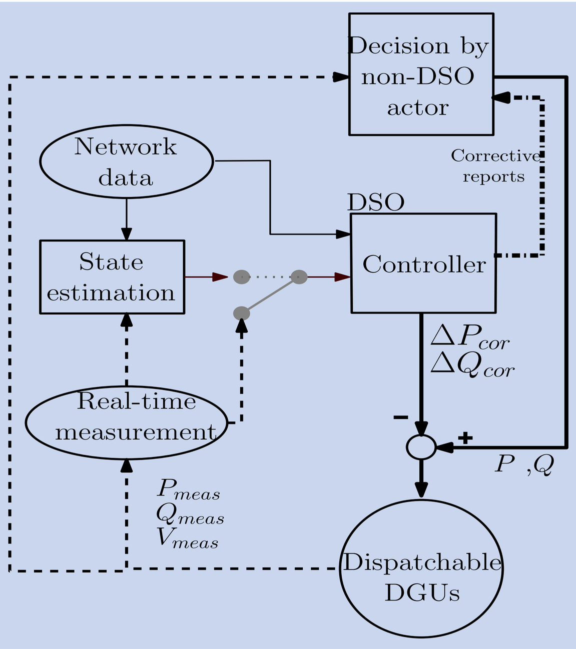
Mode 1

- applies to non-dispatchable DGUs operating in maximum power tracking mode
- once a limit has been exceeded, the controller sends power corrections to the units of concern.



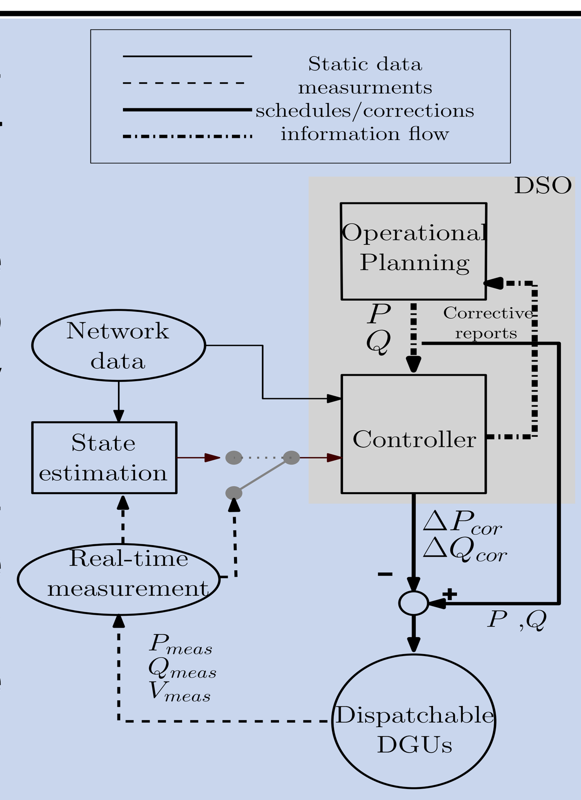
Mode 2

- applies to dispatchable DGUs under the control of another entity than the DSO
- DSO has no information to anticipate the DGU power evolution
- the corrections are applied *ex post*, as in Mode 1.



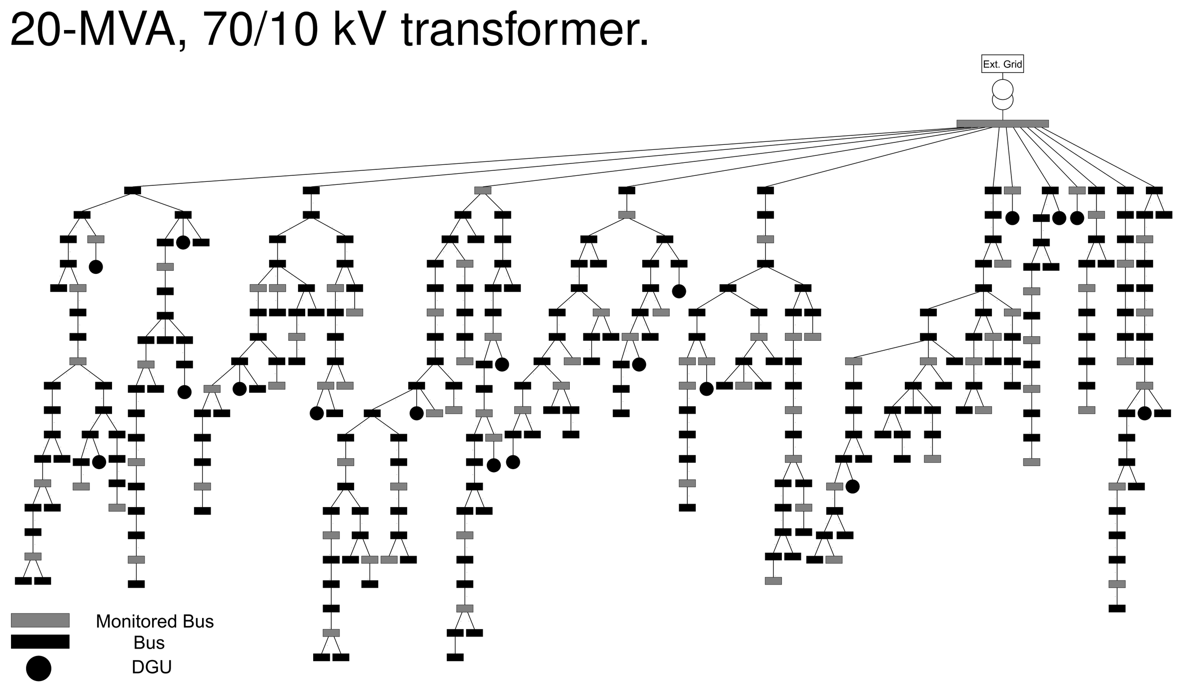
Mode 3

- applies to dispatchable DGUs under control of DSO
- unlike in Mode 2, the schedule imposed to the units is known by the DSO
- the MPC-based controller can anticipate most violations, which allows keeping the system within limits.



Simulation results on a real-life system

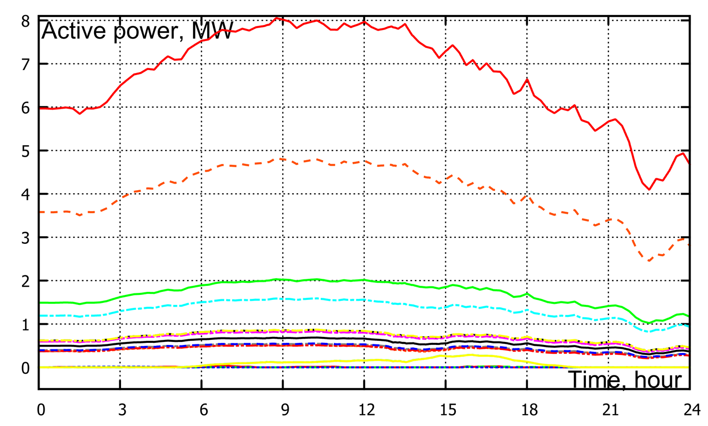
10-kV distribution grid controlled by ORES, with 328 nodes, connected to transmission network through a 20-MVA, 70/10 kV transformer.



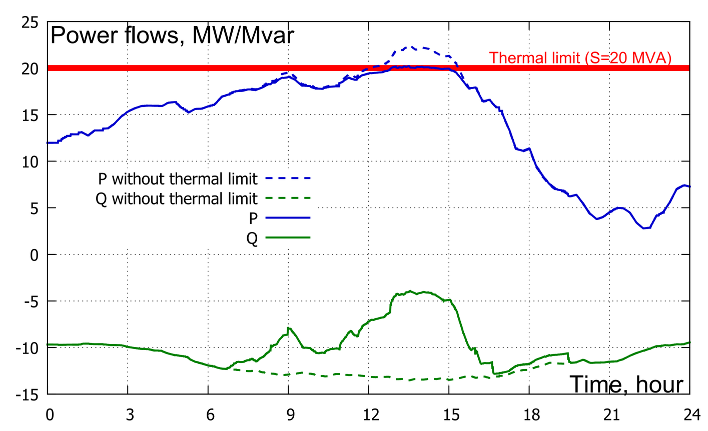
Algorithm run over a full day with a configuration expected to be representative of Year 2030 :

- 18 wind, Combined Heat and Power (CHP) and PhotoVoltaic (PV) DGUs. Total installed power : 34 MW
- 297 residential & industrial loads
- voltage and active/reactive power measurements in 96 buses/branches.

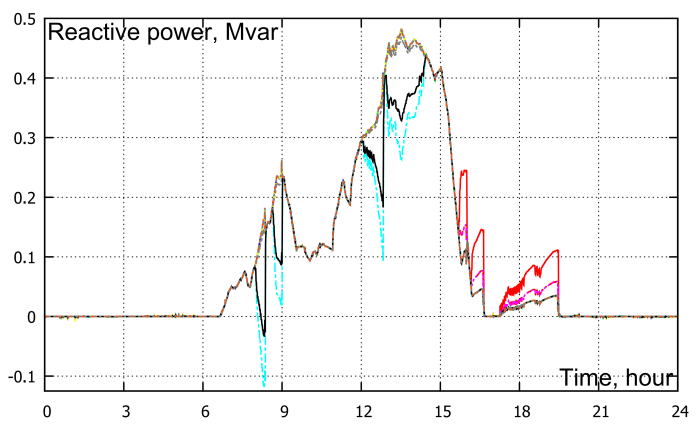
Correction of transformer thermal overload while avoiding overvoltages



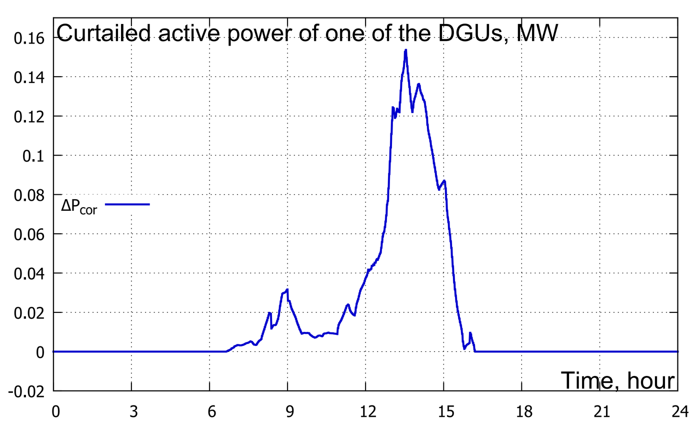
CHP units are out of service. PV units produce very little power. Wind units have high production and operate in Mode 1.



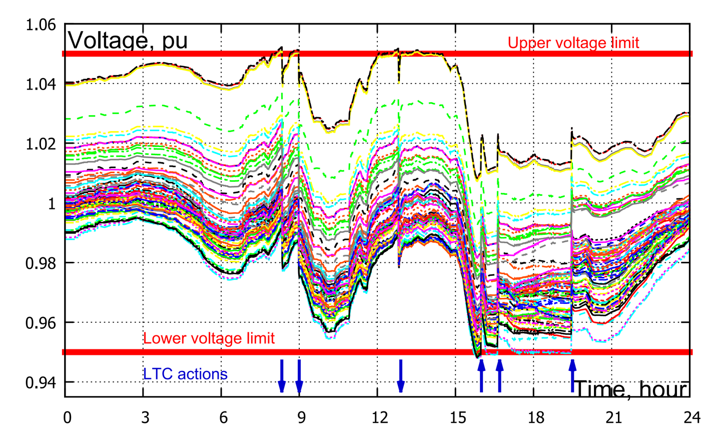
First, to reduce the transformer current, DGU reactive power productions are increased.



Since this is not enough, the active powers of some DGUs are curtailed until the remaining thermal overload is cleared.



That increase of DGU reactive powers would cause over-voltages at some nodes. To avoid that, the voltage set-point of the LTC is decreased by the controller.



Later on, when load increases, the wind units are reset to maximum available active power and to zero reactive power.

Related publication and acknowledgement

H. Soleimani Bidgoli, M. Glavic and T. Van Cutsem, "Receding-Horizon Control of Distributed Generation to Correct Voltage or Thermal Violations and Track Desired Schedules", Proc. 19th Power System Computation Conference, Genoa, Italy, July 2016.

Work supported by Public Service of Wallonia, Dept. of Energy and Sustainable Building, within the framework of the GREDOR project.

Les recherches menant aux présents résultats ont bénéficié d'un soutien financier de la Région Wallonne au titre du programme mobilisateur RELIABLE - Réseaux ELectriques Intelligents et durABLEs - organisé par la Direction générale opérationnelle de l'Aménagement du Territoire, du Logement, du Patrimoine et de l'Energie - Département de l'Energie et du Bâtiment durable en vertu de la convention No 1250487.