IEEE Webinar

Robust Constrained Model Predictive Voltage Control in Active Distribution Networks

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June 15, 2020

Presentation Outlines

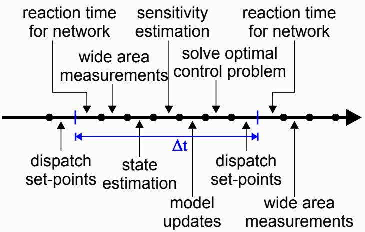
1. Closed-loop operation of the distribution networks
2. DER integration standards
3. Adjustment rule for local voltage control characteristics
4. Why robust control? Why not stochastic control?
5. Formulation of robust voltage control
6. Simulation of robust voltage control in the UKGDS network
7. Conclusions and future works

Closed-loop operation of the distribution network

Description

- $\mathbf{x}$: states ,$\mathbf{u}$: control inputs, and $\widehat{\mathbf{d}}$: disturbance vector
- Time step of network controller is generally 5 to 15 minutes[1,2].

Time division within each time-step (Δt) of control



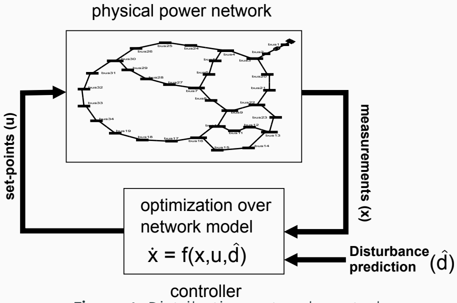


Figure 1: Distribution network control.

Note: computational efficiency is the necessity.

- mixed-integer-convex/convex modeling of optimization problem

[1] Valentina Dabic and Djordje Atanackovic. “Voltage VAR optimization real time closed loop deployment - BC Hydro challenges and opportunities”. In: *IEEE Power and Energy Society General Meeting* 2015-Septe (2015), pp. 1–5. ISSN: 19449933. DOI: 10.1109/PESGM.2015.7286313

[2] K P Schneider and T F Weaver. “A Method for Evaluating Volt-VAR Optimization Field Demonstrations”. In: *IEEE Transactions on Smart Grid* 5.4 (July 2014), pp. 1696–1703. ISSN: 1949-3053. DOI: 10.1109/TSG.2014.2308872

Implication of discrete time-step on distribution network model

- For each time-step, the distribution network is modeled ($\dot{x} = f(x, u, \hat{d})$).
- The disturbance is not a constant within the time-step rather stochastic.
- Therefore, the states of network also becomes stochastic in nature.

Example: PV generation as the disturbance input to a controller

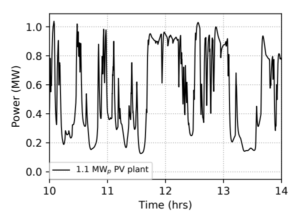


Figure 2: Instantaneous value.

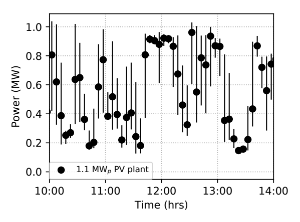


Figure 3: 5 min distribution.

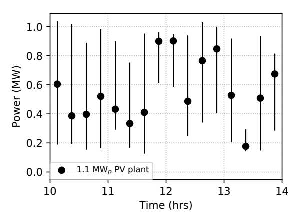


Figure 4: 15 min distribution.

- Generation uncertainty (band between lower and upper bound) is large at larger time-step[3].

[3] Enrica Scolari, Fabrizio Sossan, and Mario Paolone. “Irradiance prediction intervals for PV stochastic generation in microgrid applications”. In: *Solar Energy* 139 (2016), pp. 116–129. ISSN: 0038092X. DOI: `10.1016/j.solener.2016.09.030`. URL: `http://dx.doi.org/10.1016/j.solener.2016.09.030`

Robust voltage control

What is voltage control?

- Nodes' voltage are modeled as the state variables
- All node voltages are regulated within the desired limit

Challenge in voltage control at higher penetration of renewables

- Nodes' voltage are uncertain
- What to regulate? (expected value or lower/upper bounds)

What is robust voltage control?

- it regulates lower/upper bound of nodes' voltage

Why robust voltage control?

- generation uncertainties are predicted using short-term prediction intervals [4].
- short-term prediction intervals provides lower/upper bound of generation rather than probability distribution function (PDF).
- Without knowing PDF of uncertain variables, stochastic voltage control may not be feasible.
- Robust control can be designed with lower computational burden compared to stochastic control.

Why model predictive control?

- to minimize the frequent usage of resources (cost)
- trade-off voltage fluctuation and cost of control resources.

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[4] Qiang Ni et al. "An Optimized Prediction Intervals Approach for Short Term PV Power Forecasting". In: *Energies* 10.10 (Oct. 2017), p. 1669. ISSN: 1996-1073. DOI: *10.3390/en10101669*. URL: *http://www.mdpi.com/1996-1073/10/10/1669*

DER integration standard

- North America and Europe have defined the requirement of minimum Q-capability of DERs [5,6]
- local voltage support has become the requirement
- One of the local voltage control recommended in the standard is Q(V) control

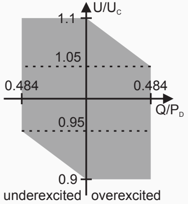

Figure 5: Minimum Q capability curve of DERs

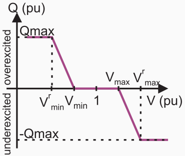

Figure 6: Local Q(V) characteristics.

[5] IEEE Standard Association. *IEEE Std. 1547-2018. Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces.* IEEE, 2018, pp. 1–138. ISBN: 9781504446396. DOI: 10.1109/IEEESTD.2018.8332112

[6] *Requirements for generating plants to be connected in parallel with distribution networks - Part 2: Connection to a MV distribution network.* 2015. URL: https://standards.globalspec.com/std/9900626/ds-clc-ts-50549-2

Implementation of local voltage control

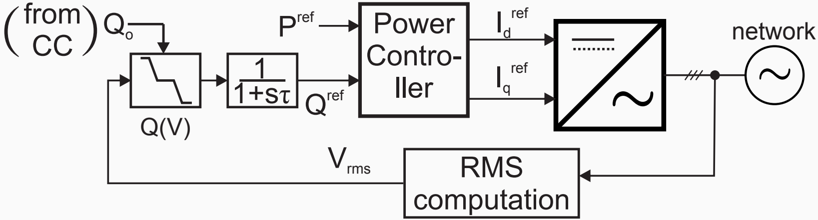

Figure 7: Local voltage control in DERs with Q(V) characteristics.

The first order delay is kept to meet the stability criteria[7,8]

[7] Filip Andren et al. “On the Stability of Local Voltage Control in Distribution Networks With a High Penetration of Inverter-Based Generation”. In: *IEEE Transactions on Industrial Electronics* 62.4 (Apr. 2015), pp. 2519–2529. ISSN: 0278-0046. DOI: 10.1109/TIE.2014.2345347

[8] Adrian Constantin and Radu Dan Lazar. “Open Loop Q(U) Stability Investigation in case of PV Power Plants”. In: *27th European Photovoltaic Solar Energy Conference and Exhibition OPEN*. 2012, pp. 3745–3749

Research Questions

- How to coordinate local controllers and centralized network controllers?
- How to robustly control the node voltage of the network?
- How to solve the robust problem efficiently?
- Do we really need robust or stochastic controllers in place of deterministic controllers?

Proposed Q(V) adjustment rule to follow centralized control

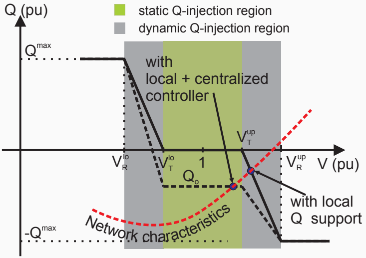

Figure 8: Local Q(V) characteristics altered by Q_o value.

$$Q(V) = \begin{cases} Q^{max} & \text{if } V \leq V_R^{lo} \\ Q_o + \frac{Q^{max} - Q_o}{V_R^{lo} - V_T^{lo}}(V_T^{lo} - V) & \text{if } V_R^{lo} \leq V \leq V_T^{lo} \\ Q_o & \text{if } V_T^{lo} \leq V \leq V_T^{up} \\ Q_o - \frac{Q^{max} + Q_o}{V_R^{up} - V_T^{up}}(V - V_T^{up}) & \text{if } V_R^{lo} \leq V \leq V_T^{lo} \\ -Q^{max} & \text{otherwise} \end{cases} \tag{1}$$

Formulation of the RCMPC controller

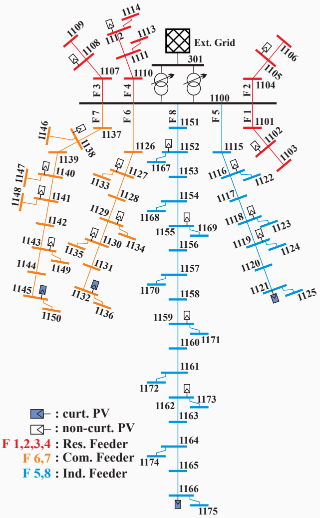

Figure 9: Test Distribution Network.

Formulation of the proposed RCMPC controller

Linear Model of distribution network

$$\mathsf{V}(t) = \mathsf{V}(t-1) + \mathbf{E}\Delta\mathbf{u}(t) + \mathbf{F}\Delta\mathbf{d}(t) + \xi(t) \quad t \in \mathcal{T} \tag{2}$$

where,

$$\mathbf{E} = \Big[\frac{\partial \mathsf{V}}{\partial Q_j}\Big|_{j\in\mathcal{I}^{CPV}}, \frac{\partial \mathsf{V}}{\partial Q_j}\Big|_{j\in\mathcal{I}^{PV}}, \frac{\partial \mathsf{V}}{\partial tap_{ij}}\Big|_{i,j\in\mathcal{I}^{OLTC}}\Big]$$

$$\mathbf{F} = \Big[\frac{\partial \mathsf{V}}{\partial P_j}\Big|_{j\in\mathcal{I}^{CPV}}, \frac{\partial \mathsf{V}}{\partial P_j}\Big|_{j\in\mathcal{I}^{PV}}, -\frac{\partial \mathsf{V}}{\partial P_j}\Big|_{i,j\in\mathcal{I}^{L}}, -\frac{\partial \mathsf{V}}{\partial Q_j}\Big|_{i,j\in\mathcal{I}^{L}}\Big]$$

$$\text{(control input)}\mathbf{u} = \big[Q_j|_{j\in\mathcal{I}^{CPV}}, Q_j|_{j\in\mathcal{I}^{PV}}, tap_{ij}|_{i,j\in\mathcal{I}^{OLTC}}\big]^T$$

$$\text{(disturbance input)}\mathbf{d} = \big[P_j|_{j\in\mathcal{I}^{CPV}}, P_j|_{j\in\mathcal{I}^{PV}}, P_j|_{j\in\mathcal{I}^{L}}, Q_j|_{j\in\mathcal{I}^{L}}\big]^T$$

$$\Delta\mathbf{u}(t) = \mathbf{u}(t) - \mathbf{u}(t-1), \quad \Delta\mathbf{d}(t) = \mathbf{d}(t) - \mathbf{d}(t-1)$$

- The disturbance input $(d(t))$ arise from PVs and loads, and are anticipated with uncertainty.
- A naive approach is to use Monte-Carlo method to determine node voltage states at various scenario.
- However, our interest lies on the lower and upper bound of node voltage, which we intend to arrest within the required limit.

Worst voltage perturbation under PV uncertainty

(a) Non-curtailable PVs

$$\Delta V_i^{pv}(t) = \sum_{j \in \mathcal{I}^{PV}} \left(\frac{\partial V_i}{\partial P_j}\right) \Delta P_j(t), \quad i \in \mathcal{I}^b \quad t \in \mathcal{T} \tag{3}$$

$$\text{where } \Delta P_j(t) = \hat{P}_j(t) - \hat{P}_j(t-1), \quad j \in \mathcal{I}^{PV} \tag{4}$$

$\hat{P}(t)$ is the short-term PV forecasting which is characterized by lower and upper bound values (i.e., $\hat{P}_j(t) \in [\hat{p}_j^{lo}(t), \hat{p}_j^{up}(t)]$)

Worst voltage perturbations under PV uncertainty

(a) Non-curtailable PVs

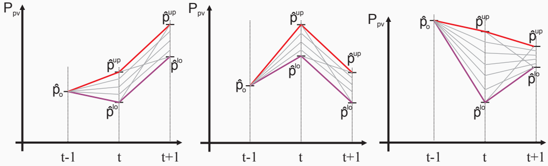

Figure 10: Probable transition in non-curtailable PV from t-1 to t+1 instant.

$$\Delta P_j^{max}(t) = \hat{p}_j^{up}(t) - \hat{p}_j^{up}(t-1) \tag{5}$$

$$\Delta P_j^{min}(t) = \hat{p}_j^{lo}(t) - \hat{p}_j^{lo}(t-1), \quad j \in \mathcal{I}^{PV} \quad t \in \mathcal{T} \tag{6}$$

$$\Delta V_i^{pv,up}(t) = \sum_{j \in \mathcal{I}^{PV}} \left(\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) sgn\left(\frac{\partial V_i}{\partial P_j}\right) + \Delta P_j^{min}(t) \left\{1 - sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right\}\right] \tag{7}$$

$$\Delta V_i^{pv,lo}(t) = \sum_{j \in \mathcal{I}^{PV}} \left(\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) \left\{1 - sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right\} + \Delta P_j^{min}(t) sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right] \tag{8}$$

Worst Voltage perturbations under PV uncertainty

(b) Curtailable PVs

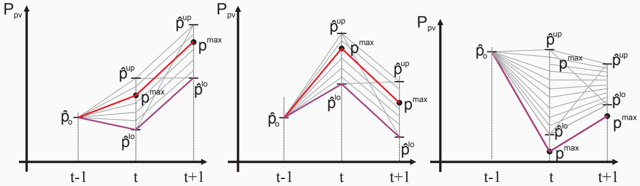

Figure 11: Limiting probable transition in curtailable PV from t-1 to t+1 instant.

Here, $p_j^{max}(t)$ be the desired upper limit of PV generation.

case 1

When $p_j^{max}(t)$ is in between the prediction band $[\hat{p}_j^{lo}(t), \hat{p}_j^{up}(t)]$:

$$\Delta P_j^{max}(t) = p_j^{max}(t) - p_j^{max}(t-1),$$
$$\Delta P_j^{min}(t) = \hat{p}_j^{lo}(t) - \hat{p}_j^{lo}(t-1).$$

case 2

When $p_j^{max}(t)$ is below $\hat{p}_j^{lo}(t)$:

$$\Delta P_j^{min}(t) = \Delta P_j^{max}(t)$$
$$= p_j^{max}(t) - p_j^{max}(t-1)$$

Worst Voltage perturbations under PV uncertainty

Curtailable PVs

Combine case 1 and case 2 to form a general expression:

$$\Delta P_j^{max}(t) = p_j^{max}(t) - p_j^{max}(t-1), \tag{9}$$

$$\Delta P_j^{min}(t) = \hat{p}_j^{lo}(t)(1-\delta_j(t)) - \hat{p}_j^{lo}(t-1)(1-\delta_j(t)) + z_j(t) - z_j(t-1) \tag{10}$$

Here, auxiliary variable $z_j(t)$ and binary variable $(\delta(t))$ are defined by:

$$z(t) = \delta_j(t) p_j^{max}(t) \tag{11}$$

$$\delta_j(t) = \begin{cases} 1, & \text{if } \hat{p}_j^{lo}(t) - p_j^{max}(t) > 0 \\ 0, & \text{otherwise} \end{cases} \tag{12}$$

$$\Delta V_i^{cpv,up}(t) = \sum_{j \in \mathcal{I}^{CPV}} \left(\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) sgn\left(\frac{\partial V_i}{\partial P_j}\right) + \Delta P_j^{min}(t) \left\{1 - sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right\}\right]$$

$$\Delta V_i^{cpv,lo}(t) = \sum_{j \in \mathcal{I}^{CPV}} \left(\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) \left\{1 - sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right\} + \Delta P_j^{min}(t) sgn\left(\frac{\partial V_i}{\partial P_j}\right)\right]$$

Worst voltage perturbations under load uncertainty

Active power uncertainty

$$\Delta V_i^{PL,up}(t) = \sum_{j \in \mathcal{I}^L} \left(-\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) sgn\left(-\frac{\partial V_i}{\partial P_j}\right) + \Delta P_j^{min}(t) \left\{1 - sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right\}\right]$$

$$\Delta V_i^{PL,lo}(t) = \sum_{j \in \mathcal{I}^L} \left(-\frac{\partial V_i}{\partial P_j}\right) \left[\Delta P_j^{max}(t) \left\{1 - sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right\} + \Delta P_j^{min}(t) sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right]$$

Reactive power uncertainty

$$\Delta V_i^{QL,up}(t) = \sum_{j \in \mathcal{I}^L} \left(-\frac{\partial V_i}{\partial Q_j}\right) \left[\Delta P_j^{max}(t)\ sgn\left(-\frac{\partial V_i}{\partial P_j}\right) + \Delta P_j^{min}(t)\ \left\{1 - sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right\}\right] tan(\theta_j)$$

$$\Delta V_i^{QL,lo}(t) = \sum_{j \in \mathcal{I}^L} \left(-\frac{\partial V_i}{\partial Q_j}\right) \left[\Delta P_j^{max}(t)\ \left\{1 - sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right\} + \Delta P_j^{min}(t)\ sgn\left(-\frac{\partial V_i}{\partial P_j}\right)\right] tan(\theta_j)$$

where, $\theta_j = acos(pf_j)$

lower and upper bound of node voltages in distribution network

Open loop node voltage:

$$\begin{aligned}\mathbf{V}^{open,up}(t) =& \mathsf{V}^{up}(t-1) + \Delta\mathbf{V}^{pv,up}(t) + \Delta\mathbf{V}^{cpv,up}(t) + \Delta\mathbf{V}^{PL,up}(t) + \Delta\mathbf{V}^{QL,up}(t)\\ \mathbf{V}^{open,lo}(t) =& \mathsf{V}^{lo}(t-1) + \Delta\mathbf{V}^{pv,lo}(t) + \Delta\mathbf{V}^{cpv,lo}(t) + \Delta\mathbf{V}^{PL,lo}(t) + \Delta\mathbf{V}^{QL,lo}(t)\end{aligned}$$

Closed loop node voltage:

$$\mathsf{V}^{up}(t) = \mathbf{V}^{open,up}(t) + \Delta\mathbf{V}^{ctrl} \tag{13}$$

$$\mathsf{V}^{lo}(t) = \mathbf{V}^{open,lo}(t) + \Delta\mathbf{V}^{ctrl} \tag{14}$$

$$\text{where, } \Delta\mathbf{V}^{ctrl} = \sum_{j\in\mathcal{I}^{CPV}} \left[\frac{\partial \mathsf{V}}{\partial Q_j}\right] \Delta Q_j(t) + \sum_{j\in\mathcal{I}^{PV}} \left[\frac{\partial \mathsf{V}}{\partial Q_j}\right] \Delta Q_j(t) + \sum_{i,j\in\mathcal{I}^{OLTC}} \left[\frac{\partial \mathsf{V}}{\partial tap_{ij}}\right] \Delta tap_{ij}(t)$$

Finally, (13) and (14) is the required model of lower and upper bound of node voltages in distribution network.

Robust Constrained Model Predictive Control

Robust Objective function

$$\mathbf{min}\sum_{t=\mathcal{T}}\Big[\overbrace{\Delta\mathbf{u}(t)\mathbf{R}_u\Delta\mathbf{u}(t)^T+\sum_{j\in\mathcal{I}^{CPV}} r_c(\hat{P}_j^{up}(t)-P_j^{max}(t))}^{\text{control effort}}+\overbrace{\sum_{i\in\mathcal{I}^b}\mathbf{max}\,\phi(V_i(t))}^{\text{voltage violations}}+\overbrace{r_v\Delta v_b}^{\text{vol. fluct.}}\Big]$$

$$\text{where,}\phi(V_i)=\begin{cases} c_d(V_{lim}^{lo}-V_i), \text{ if } V_i<V_{lim}^{lo},\\ c_d(V_i-V_{lim}^{up}), \text{ if } V_i>V_{lim}^{up},\\ 0, \text{ otherwise.}\end{cases}$$

- regulates the lower/upper bound of the voltage.
- optimizes the control effort over voltage quality.

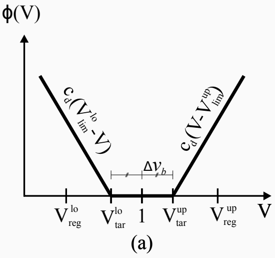

Figure 12: cost function(ϕ)

Conversion of min-max to simple min problem

An auxiliary variable $\epsilon(t)$ is introduced such that $\epsilon_i(t) = max\, \phi(V_i(t))$

$$\mathbf{min} \sum_{t=\mathcal{T}} \Big[\mathbf{u}(t)\mathbf{R}_u\, \mathbf{u}(t)^T + \sum_{j \in \mathcal{I}^{CPV}} r_c(\hat{P}_j^{up}(t) - P_j^{max}(t)) + \sum_{i \in \mathcal{I}^b} \epsilon_i(t) + r_v \Delta v_b \Big] \tag{15}$$

$$\epsilon_i(t) \geq \mathbf{max}\, c_d \left(V_T^{lo} - V_i(t) \right),$$
$$\epsilon_i(t) \geq \mathbf{max}\, c_d\, (V_i(t) - V_T^{up}),\ \epsilon_i(t) \geq 0 \quad i \in \mathcal{I}^b \tag{16}$$

The additional constraints are simplified as:

$$\epsilon_i(t) \geq \left(V_T^{lo} - V_i^{lo}(t) \right), \quad \epsilon_i(t) \geq (V_i^{up}(t) - V_T^{up}),$$
$$\epsilon_i(t) \geq 0. \quad i \in \mathcal{I}^b \tag{17}$$

Control Constraints and Framework of controller

$$-0.44S_j^{rat} \leq Q_j(t) \leq 0.44S_j^{rat}, \quad j \in \mathcal{I}^{PV}$$

$$0 \leq p_j^{max}(t) \leq \hat{p}_j^{up}(t), \quad j \in \mathcal{I}^{CPV}$$

$$0 < \Delta v_d < 0.05$$

$$(Q_j(t))^2 \leq S_j^2 - (p_j^{max})^2, \quad j \in \mathcal{I}^{CPV}$$

$$Tap^{min} \leq tap_{ij}(t) \leq Tap^{max}, \quad i, j \in \mathcal{I}^{OLTC}$$

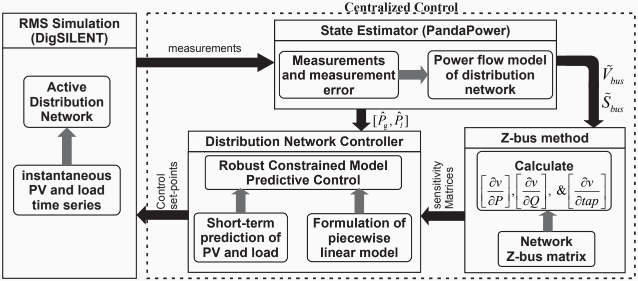

Figure 13: Centralized scheme for implementing RCMPC control.

Test System

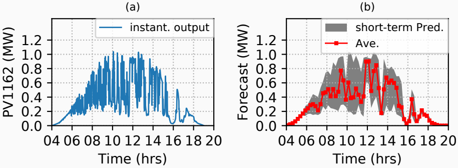

Figure 14: Instantaneous and forecasted PV profile (node 1162).

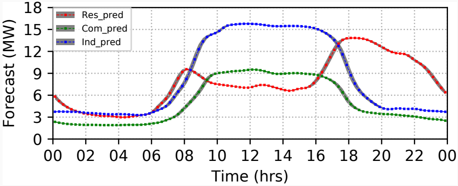

Figure 15: Forecasted load profile of customers in aggregated form.

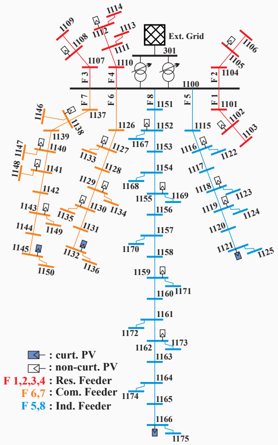

Figure 16: Test Distribution Network.

Simulation Results

Without centralized control

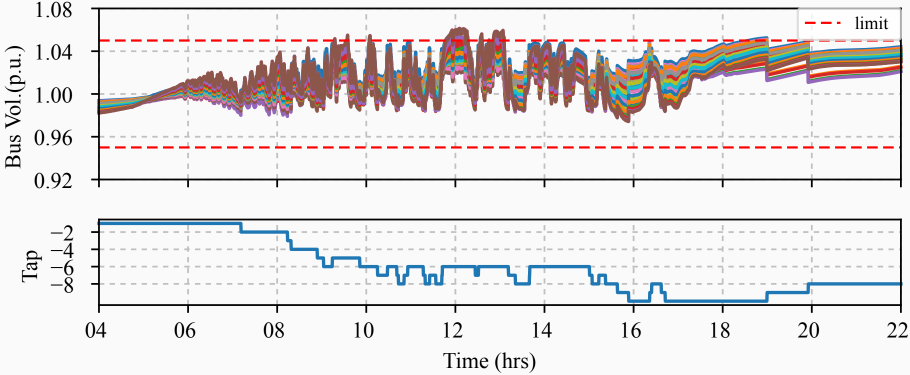

Figure 17: Day simulation of UKGDS network with only OLTC control.

- Duration of voltage violation = 48.8 minutes
- no. of tap operation = 36

Verification of lower/upper bound estimation of nodes voltage

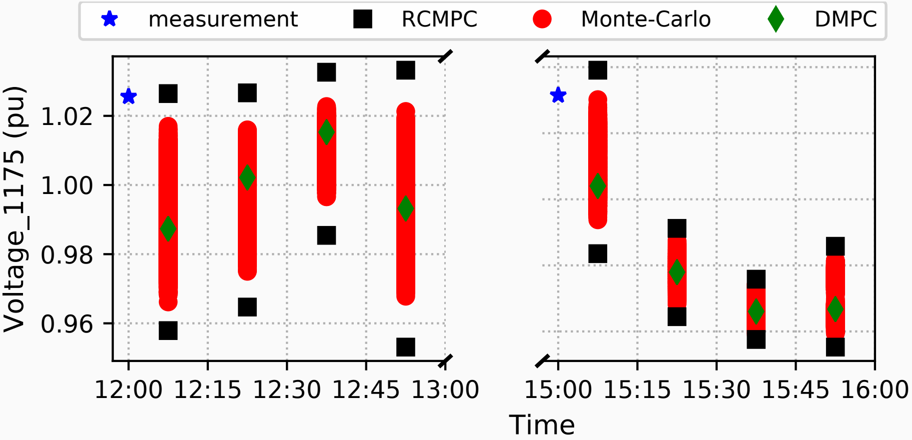

Figure 18: Open-loop boundary voltage estimation at bus 1175 by RCPMC and DMPC at 12:00 and 15:00, and their comparison with the Monte-Carlo method.

With Deterministic MPC control

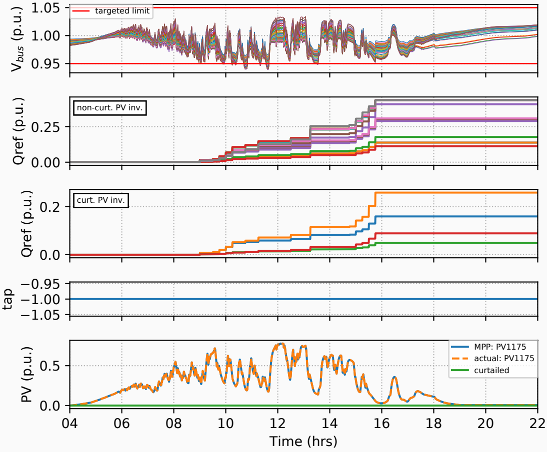

Figure 19: A day simulation result of network voltage and control resources with DMPC control.

- Duration of voltage violations = 31.86 minutes
- no. of tap operation = 0

Simulations Results

RCMPC with fixed targeted limit

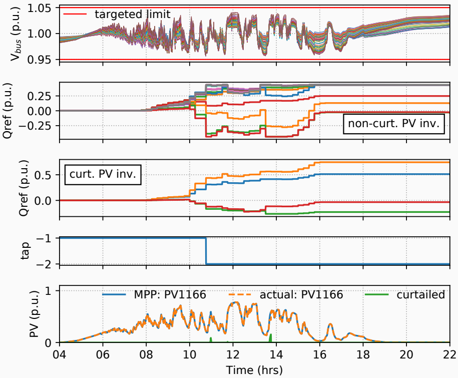

Figure 20: A day simulation of the test distribution network with RCMPC control considering fixed targeted limit.

RCMPC with optimal targeted limit

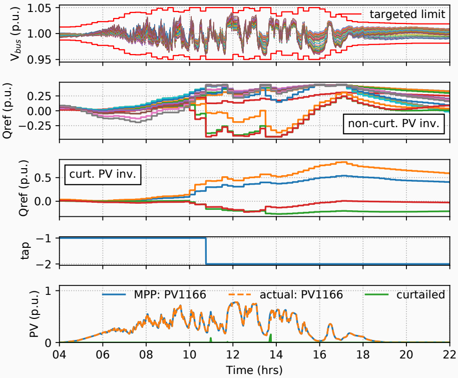

Figure 21: A day simulation results of test distribution network with RCMPC control with an optimal targeted limit.

Simulation Results

Local control response at voltage dip

(a) considering first order delay

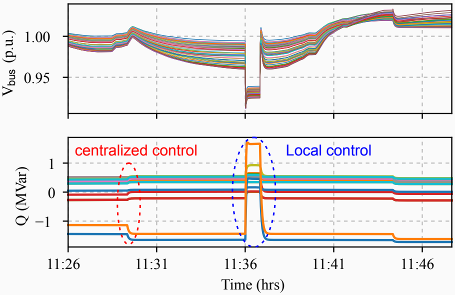

Figure 22: Local Q(U) controller responses during a voltage dip of 0.9 p.u.

(b) without first order delay

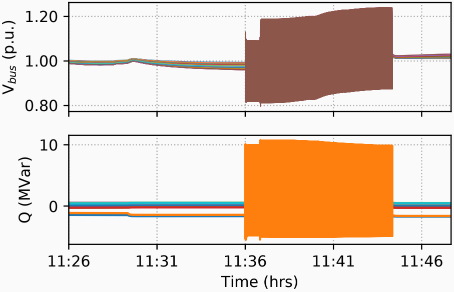

Figure 23: Local Q(U) controller responses during a voltage dip of 0.9 p.u.

Simulation results summary

Table 1: Performance vs control resource usage

TS min	Controller type	Qpv (MVARh)	PV-curt. (MWh)	tap	TLV (min)
5	DMPC fix TL	99.75	0	0	1.17
	RCMPC fix TL	147.47	0	0	0
	RCMPC opt TL	144.42	0	0	0
10	DMPC fix TL	94.64	0	0	3.8
	RCMPC fix TL	154.03	0.025	0	0
	RCMPC opt TL	150.05	0.025	0	0
15	DMPC fix TL	86.34	0	0	31.86
	RCMPC fix TL	181.39	0.093	1	0
	RCMPC opt TL	170.72	0.093	1	0

Conclusions

- An adjustment rule in local Q(V) control characteristics to follow the Q-injection as directed by the centralized controller.
- The **RCMPC based centralized voltage controller** which robustly regulate the node voltage between the targeted limit under the uncertainty of renewable DERs and loads. Moreover, it is also capable of **dynamically optimizing the targeted limit** to trade-off control resources usage and voltage fluctuations band.
- Performance comparisons are carried out between DMPC and RCMPC at the various time-steps of centralized control.

Future works

1. Robust techno-economic control: RCMPC based centralized techno-economic control considering uncertainty of PVs and loads.
2. Distributed control using ADMM.

Thank you for listening

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