Emergency Voltage Regulation in Power Systems via Ripple-Type Control

G. Cavraro, M. K. Singh, A. Bernstein, V. Kekatos

Challenges in Power Systems

- Integration of renewables at large scale

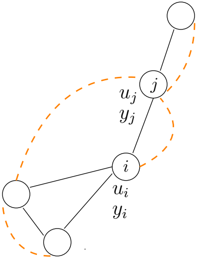
- Unexpected events undermines the systems' stability

(controllers and measurement units failure)

(natural disasters)

- Emergency control schemes are required

Power Transmission Network Modeling



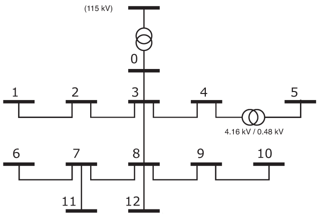
- A power system can be modeled as a networked systems of agents
- u_i is the control input of agent i, y_i is the observation taken by i
- Agents communicate over a communication network

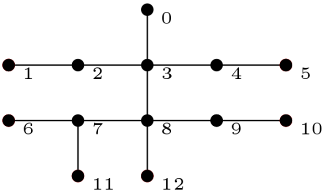
- A power system can be modeled as a graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$
- $\mathcal{N} = \{1, \ldots, N\}$, $\mathcal{L} = \{(m, n) : m, n \in \mathcal{V}\}$ collect buses and lines

Power Transmission Network Modeling

Buses

- p_i, q_i are the active power and the reactive power of bus i
- v_i, θ_i are the voltage magnitude and angle of bus i
- Collect the variables in the vectors $\mathbf{p}, \mathbf{q}, \mathbf{v}, \boldsymbol{\theta} \in \mathbb{R}^N$
- The slack bus behaves like an ideal voltage generator, (v, θ) are fixed
- Generators are modeled as PV buses, (p, v) are fixed
- Loads are modeled as PQ buses, (p, q) are fixed

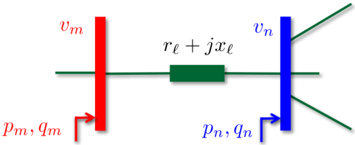




Power Transmission Network Modeling

Lines

- $r_\ell + ix_\ell$ impedance of line $\ell = (m, n), \ell \in \mathcal{L}$
- Impedances collected in vectors $\mathbf{r} + i\mathbf{x}$
- Grid connectivity captured by incidence matrix $\mathbf{A} \in \{0, \pm 1\}^{L \times (N+1)}$
- In transmission networks $\mathbf{r} \simeq \mathbf{0}$
- The bus admittance matrix is $\quad \mathbf{B} = -i\mathbf{A}^\top \text{diag}(\mathbf{x})^{-1}\mathbf{A}$



$$\mathbf{a}_\ell = \begin{bmatrix} 0 \\ +1 \\ 0 \\ -1 \\ 0 \end{bmatrix} \begin{matrix} \\ \longleftarrow \text{node } m \\ \\ \longleftarrow \text{node } n \\ \\ \end{matrix}$$

Power Flow Equations

- We have the approximated model

$$\mathbf{q} = \text{diag}(\mathbf{v})\mathbf{B}\mathbf{v}.$$

Resilient Power System Operations

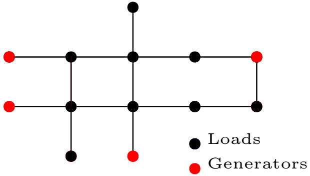
Optimal Power Flow (OPF)

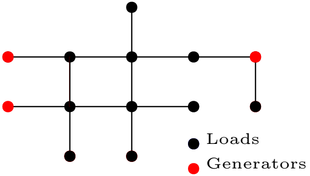
A network operator solves, at regular intervals, OPF Problems

$$\begin{aligned} \min_{\mathbf{u}} \quad & c(\mathbf{u}, \mathbf{y}) \\ \text{s.to} \quad & \mathbf{y} = \mathrm{F}(\mathbf{u}) \\ & \mathbf{h}(\mathbf{u}, \mathbf{y}) \leq 0 \\ & \underline{\mathbf{u}} \leq \mathbf{u} \leq \bar{\mathbf{u}} \\ & \mathbf{y} \geq \underline{\mathbf{y}} \end{aligned}$$

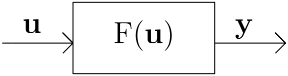
- $c(\mathbf{u}, \mathbf{y})$ model the generation cost
- $\mathrm{F}(\mathbf{u})$ represents the power flow equations
- Soft constraints like line flow limitation.
- Hard constraints like limited generation capabilities and mandatory voltage requirements.
- Solutions are dispatched to buses periodically

Resilient Power System Operations

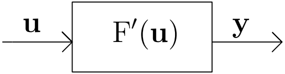




System input-output model



Input-output model after an event



- Unexpected events change the model from $\mathrm{F}(\mathbf{u})$ to $\mathrm{F}'(\mathbf{u})$ between two OPF solutions
- The new model could be unknown
- Under the new configuration, voltage constraints might be not satisfied
- Goal: Avoid dangerous voltage constraint violations after a disruptive event. The system must be steered inside the safe region

$$\mathcal{S} = \{\mathbf{u} : \ \mathbf{y} = \mathrm{F}'(\mathbf{u}), \ \underline{\mathbf{u}} \leq \mathbf{u} \leq \bar{\mathbf{u}}, \mathbf{y} \geq \underline{\mathbf{y}}\}$$

Ripple-type Control for Networked Systems

Recent feedback-based optimization controllers

- meet the desired constraints in an optimal way
- are inspired by classical optimization algorithms

Optimization Problem

$$\min_{\mathbf{u}} \quad g(\mathbf{u}, \mathbf{y})$$
$$\text{s.to} \quad \varphi(\mathbf{u}, \mathbf{y}) \leq 0$$

Algorithm

$$u_n(t+1) = k(\mathbf{u}(t), \mathbf{y}(t)) + \mathbf{a}_n^\top \boldsymbol{\mu}(\boldsymbol{t})$$
$$\mu_n(t+1) = \max\{0, \mu_n(t) + \epsilon\varphi_n(\mathbf{u}(t), \mathbf{y})\}$$

S. Bolognani, R. Carli, G. Cavraro, S. Zampieri (2015)
Distributed Feedback Reactive Power Control for Voltage Regulation and Loss Minimization

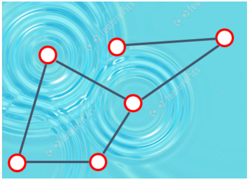
General Features

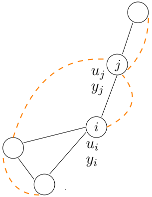
1. They are designed such that a local constraint violation is immediately taken care by the (whole) system.
2. They rely on the model knowledge
3. They have precise requirements on the communication network.

Ripple-type Control for Networked Systems

In the Ripple-type Control paradigm

- First, agents try to fix local constraints autonomously
- Agents ask assistance when their control resources have been depleted
- The process continues until all the constraints are met





General Features

1. We try to interfere as little as possible with the agents' control inputs
2. The knowledge of the model is not needed
3. There are mild requirements on the communication network
4. An optimal configuration is not sought

Also a water system application is considered in

M.Singh, G. Cavraro, A. Bernstein, V. Kekatos (2021)
Ripple-Type Control for Enhancing Resilience of Networked Physical Systems

Ripple-type Control for Resilient System Operations

- Partition $\mathcal{N}$ into generator and load buses as $\mathcal{N} = \mathcal{N}_G \oplus \mathcal{N}_L$
- Arrange $\mathbf{v}$ and $\mathbf{q}$ as $\mathbf{v} = \begin{bmatrix} \mathbf{v}_G \\ \mathbf{v}_L \end{bmatrix}, \mathbf{q} = \begin{bmatrix} \mathbf{q}_G \\ \mathbf{q}_L \end{bmatrix}$

$$\mathcal{S} = \{\mathbf{u} : \ \mathbf{y} = \mathrm{F}'(\mathbf{u}),\ \underline{\mathbf{u}} \le \mathbf{u} \le \bar{\mathbf{u}}, \mathbf{y} \ge \underline{\mathbf{y}}\}$$

Control Inputs

Generators can control $\mathbf{v}_G$, loads can control $\mathbf{q}_L$, $\mathbf{u} = \begin{bmatrix} \mathbf{v}_G \\ \mathbf{q}_L \end{bmatrix}$

System Outputs to be controlled

To avoid voltage collapse, $\mathbf{v}_L$ must be kept above a safe value, $\mathbf{y} = \mathbf{v}_L$

Ripple-type Control for Resilient System Operations

System Model

Arranging $\mathbf{B}$ according to the former partition, we obtain

$$\mathbf{q}_L = \text{diag}(\mathbf{v}_L)\begin{bmatrix}\mathbf{B}_{LG} & \mathbf{B}_{LL}\end{bmatrix}\begin{bmatrix}\mathbf{v}_G \\ \mathbf{v}_L\end{bmatrix}, \quad \mathbf{v}_L = \mathrm{F}(\mathbf{v}_G, \mathbf{q}_L)$$

Assumption: the input-output mapping F is such that

$$\frac{\partial\, \mathbf{v}_L}{\partial\, \mathbf{v}_G} \geq 0, \qquad \frac{\partial\, \mathbf{v}_L}{\partial\, \mathbf{q}_L} \geq 0$$

Safe Region

$$\mathcal{S} = \left\{ \begin{bmatrix}\mathbf{v}_G \\ \mathbf{q}_L\end{bmatrix} : \ \mathbf{y} = \mathrm{F}'(\mathbf{u}), \underline{\mathbf{v}}_G \leq \mathbf{v}_G \leq \bar{\mathbf{v}}_G, \underline{\mathbf{q}}_L \leq \mathbf{q}_L \leq \bar{\mathbf{q}}_L, \mathbf{v}_L \geq \underline{\mathbf{v}}_L \right\}$$

Ripple-type Control for Resilient System Operations

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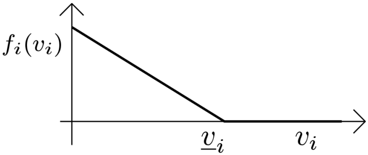
Ripple-type Control for Resilient System Operations

- $\mathbf{L}$ is the communication network's adjacency matrix
- Define the constraint violation function

$$f_i(v_i) := \begin{cases} \underline{v}_i - v_i, & v_i < \underline{v}_i \\ 0, & \text{otherwise.} \end{cases}$$



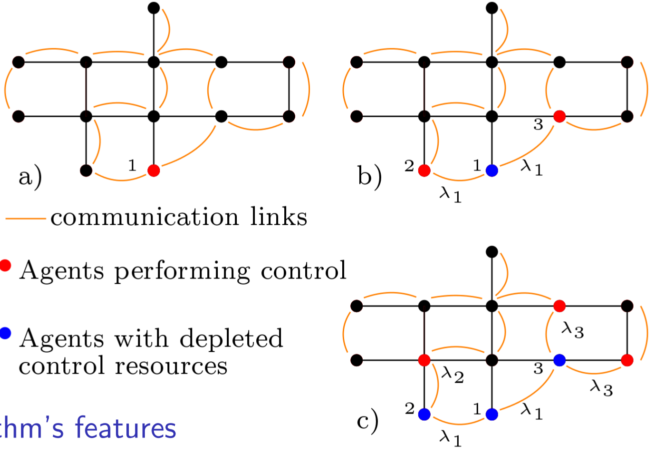
Resilient System Operations

Agent i:

1. computes the constraint violation $f_i(v_i(t))$
2. computes a target setpoint $\hat{u}_i(t+1) = u_i(t) + \eta_1 f_i(v_i(t)) + \eta_2 \mathbf{L}_i \boldsymbol{\lambda}(t)$
3. computes the variable $\lambda_i(t+1) = \max\{0, \eta_3(\hat{u}_i(t+1) - \bar{u}_i)\}$
4. physically implements $u_i(t+1) = \min\{\hat{u}_i(t+1), \bar{u}_i\}$

with $\eta_1, \eta_2, \eta_3 > 0$.

Ripple-type Control for Resilient System Operations



Algorithm's features

- $\hat{u}_i$ is computed using local info and the $\{\lambda_j\}$ sent from peers
- $\lambda_i > 0$ only when the local control resources are depleted
- λ_i is as a beacon for assistance communicated across peer nodes
- The algorithm is model free

Ripple-type Control for Resilient System Operations

Agent i:

$$\hat{u}_i(t+1) = u_i(t) + \eta_1 f_i(v_i(t)) + \eta_2 \mathbf{L}_i \boldsymbol{\lambda}(t)$$
$$\lambda_i(t+1) = \max\{0, \eta_3(\hat{u}_i(t+1) - \bar{u}_i)\}$$
$$u_i(t+1) = \min\{\hat{u}_i(t+1), \bar{u}_i\}$$

Proposition (Algorithm's Convergence)

Given any control input initial condition $\mathbf{u}(0)$, the sequence $\{\mathbf{u}(t)\}$ converges asymptotically. •

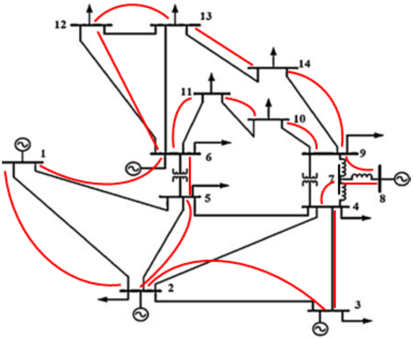
Proposition (Characterization of Equilibria)

Let $\mathcal{S} \neq \emptyset$, the communication network be connected, and

$$\eta_2 \; \eta_3 \; \|\mathbf{L}\| < 1.$$

A pair $(\mathbf{x}, \; \boldsymbol{\lambda})$ is an equilibrium for the proposed scheme if and only if $\mathbf{x}$ belongs to $\mathcal{S}$ and $\boldsymbol{\lambda} = \mathbf{0}$. •

Numerical Tests: a Power System Case



- IEEE 14 bus test feeder
- Agents communicate through the communication network
- Optimal setpoints are dispatched every 15 minutes.
- $\mathbf{v}_L \geq 0.95$ pu, 0.95 pu $\leq \mathbf{v}_G \leq 1.05$ pu
- Loads are elastic and can change their power demand up to 2 MVAR.

Numerical Tests: a Power System Case

- At $t = 5$ min, lines (6,12) and (6,13) go down
- Undervoltage at buses 12 and 13
- Corrective actions at buses 12 - 13 and 6 are enough

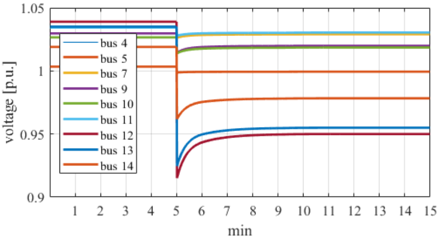
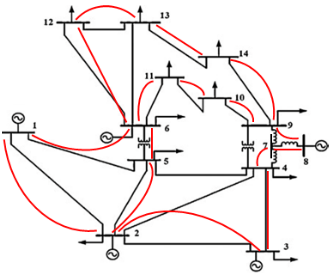


Figure: Load voltage trajectories



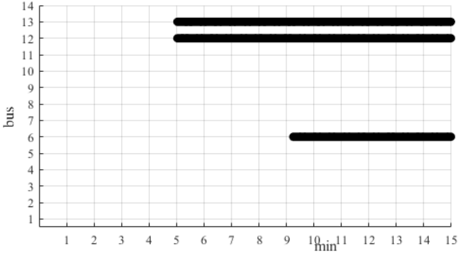
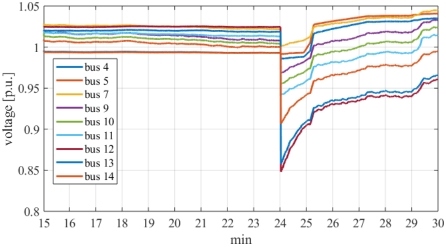


Figure: Control Action Sequences

Numerical Tests: a Power System Case

- At $t = 24$ min, the generator at bus 6 has a failure
- Severe undervoltage at buses 11 – 14
- Eventually all the agents correct their control inputs



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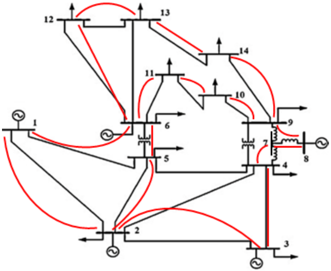

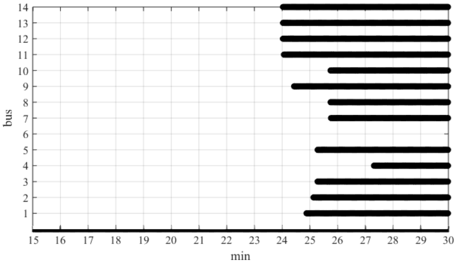

Figure: Control Action Sequences

Conclusions

- An emergency voltage control algorithm for transmission networks has been proposed
- The algorithm has been shown to be effective in avoiding voltage collapse
- Generators and controllable loads act based upon local control rules
- When local resources have been depleted, agents solicit help from neighbors in a communication network
- The participation of various agents propagates over neighboring nodes in a ripple-type manner

Thanks!

Guido Cavraro

National Renewable Energy Laboratory (NREL)

guido.cavraro@nrel.gov