ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

# Real-Time Control of Electrical Distribution Grids

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NREL
2018 March 23

[1] https://people.epfl.ch/105633/research

[2] http://smartgrid.epfl.ch

# Credits

***Joint work***
EPFL-DESL (Electrical Engineering)
and LCA2 (Computer Science)

***Supported by***

**Energy Turnaround**
National Research Programme NRP 70

SCCER - FURIES
Shaping the FUtuRe SwIss Electrical InfraStructure

nano-tera.ch

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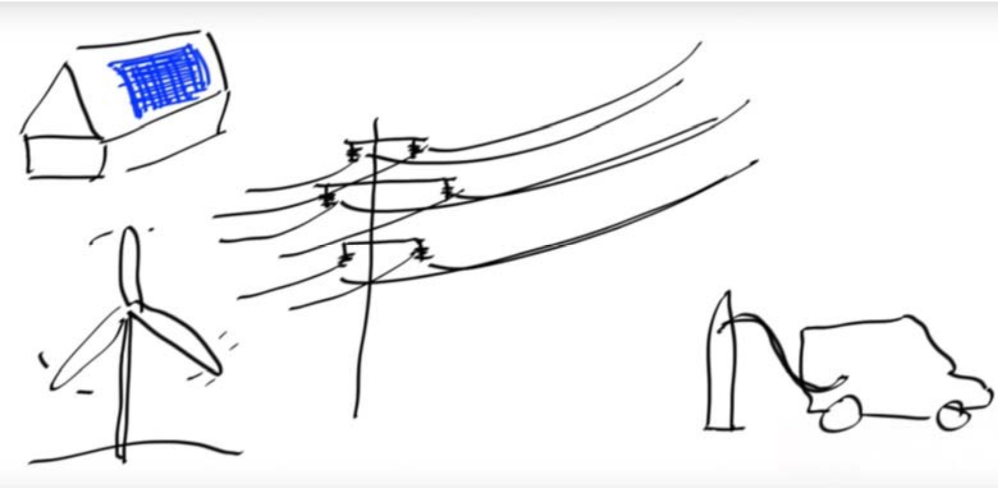
# 1. Real-Time Operation of Microgrid: Motivation



Absence of inertia (inverters)

Stochastic generation (PV)

Storage, demand response

Grid stress (charging stations, heat pumps)

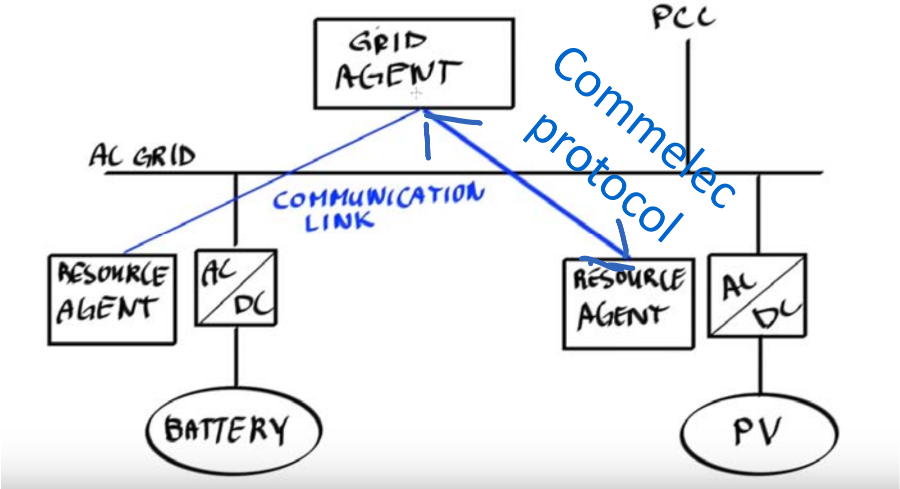
Support main grid (frequency, AGC)

$\Rightarrow$ Agent based, real-time control of microgrid

# COMMELEC Uses Explicit Power Setpoints

Grid Agent = software agent, manages grid, uses PMUs

Resource Agent = software agent, manages device



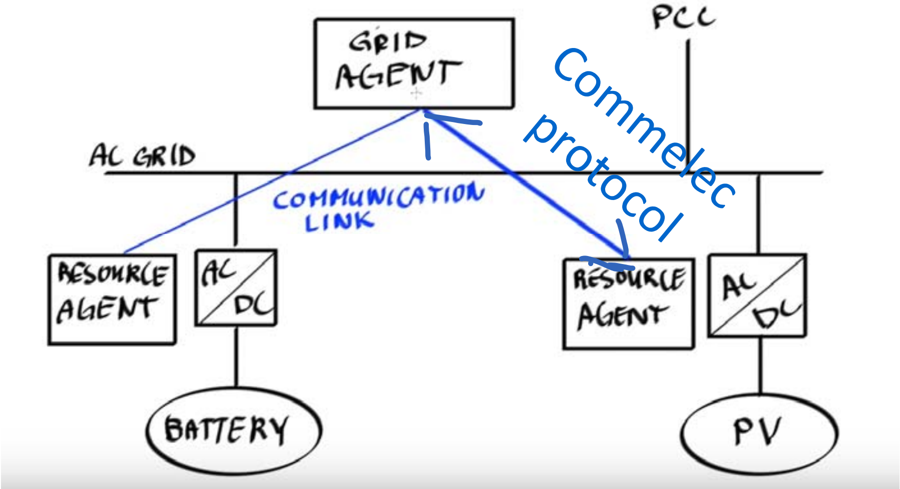

Grid Agent sends explicit power setpoints to Resource Agents

Goal: manage quality of service in grid; support main grid; use resources optimally. [Bernstein et al 2015, Reyes et al 2015]

# COMMELEC Principle of Operation

Every 100 msec

- Resource agent sends to grid agent: PQ profile, Virtual Cost and Belief Function
- Grid agent sends power setpoints




PQ profile = set of setpoints that this resource is willing to receive

Virtual cost = cost attached to receiving a setpoint

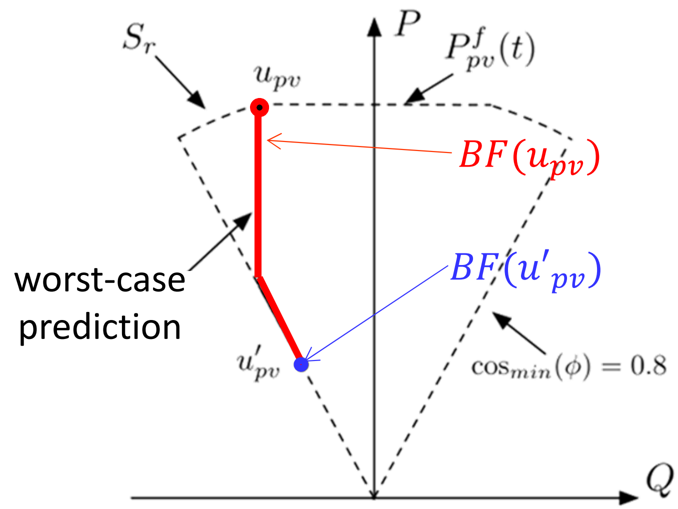
# Belief Function

Say grid agent requests setpoint $(P_{\text{set}}, Q_{\text{set}})$ from a resource; actual setpoint $(P, Q)$ will, in general, differ.

Belief function exported by resource agent means: the resource implements $(P, Q) \in BF(P_{\text{set}}, Q_{\text{set}})$

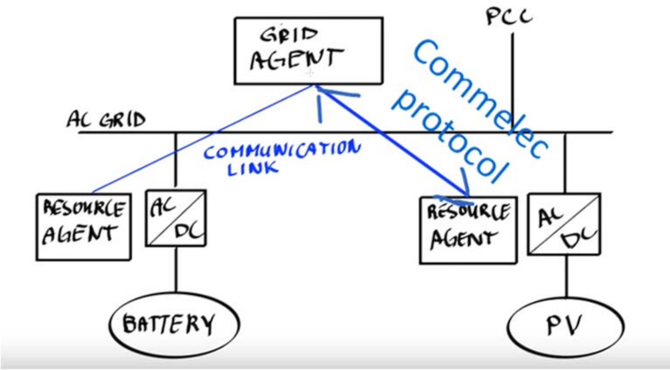
Quantifies uncertainty

Essential for safe operation




Belief Function for a PV resource

# Operation of Grid Agent




Grid agent computes a setpoint vector $x$ that minimizes

Cost of power flow at point of common connection

$$J(x) = \sum_i w_i C_i(x_i) + W(z) + J_0(x_0)$$

Virtual cost of the resources

Penalty function of grid electrical state $Z$ (e.g., voltages close to 1 p.u., line currents below the ampacity)

subject to admissibility.

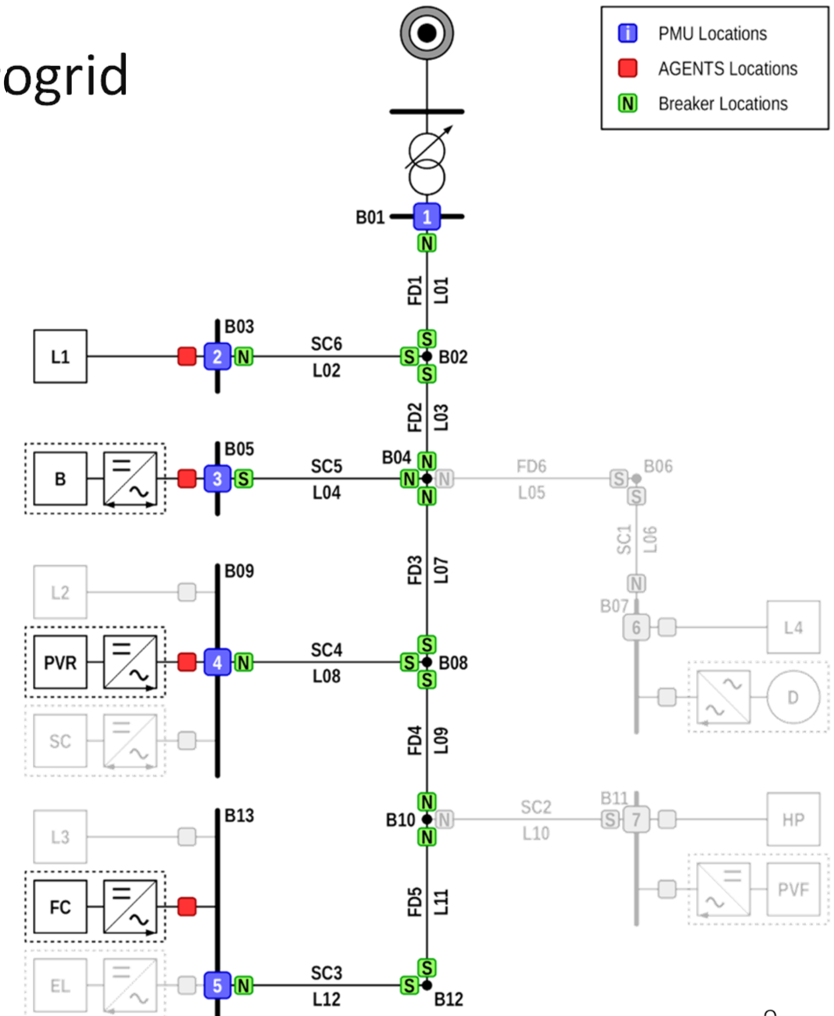
$x$ is admissible $\Leftrightarrow (\forall x' \in BF(x),\quad x'$ satisfies security constraints)

# Implementation / EPFL Microgrid

Topology: 1:1 scale of the Cigré low-voltage microgrid benchmark TF C6.04.02 [Reyes et al, 2018]

- Phasor Measurement Units:
  nodal voltage/current syncrophasors
- Phasor Data Concentrator
- Discrete Kalman Filter State estimator
- PVs, Battery, Load (flex house)

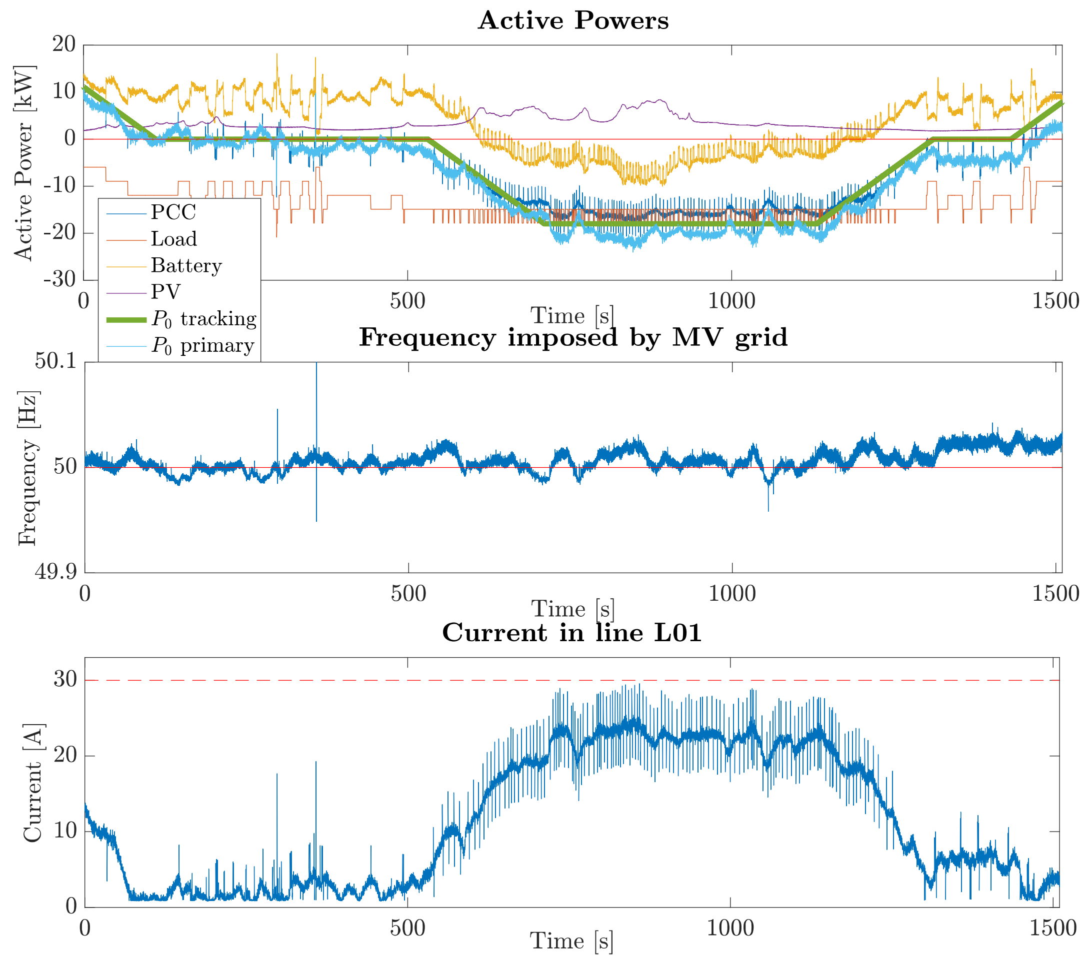
PMU and PDC
data frame rate:
50 fps



# Dispatch and Primary-Frequency Support

Superposition of dispatch and primary frequency control (i.e., primary droop control) with a max regulating energy of 200 kW/Hz

In parallel, keep the internal state of the local grid in a feasible operating condition.

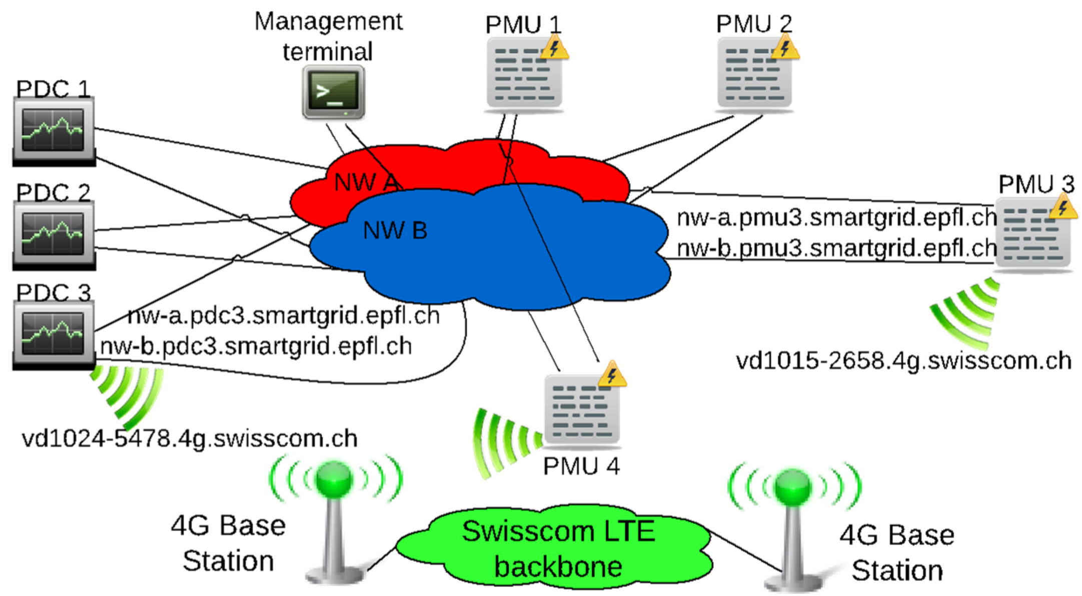


# COMMELEC Uses iPRP for UDP Packet Duplication

Controllers and sensors are connected to 2 independent networks

iPRP software duplicates packets at source and removes duplicates at destination

fully transparent to application
– works with any application that streams UDP packets [Popovic et al 2016]



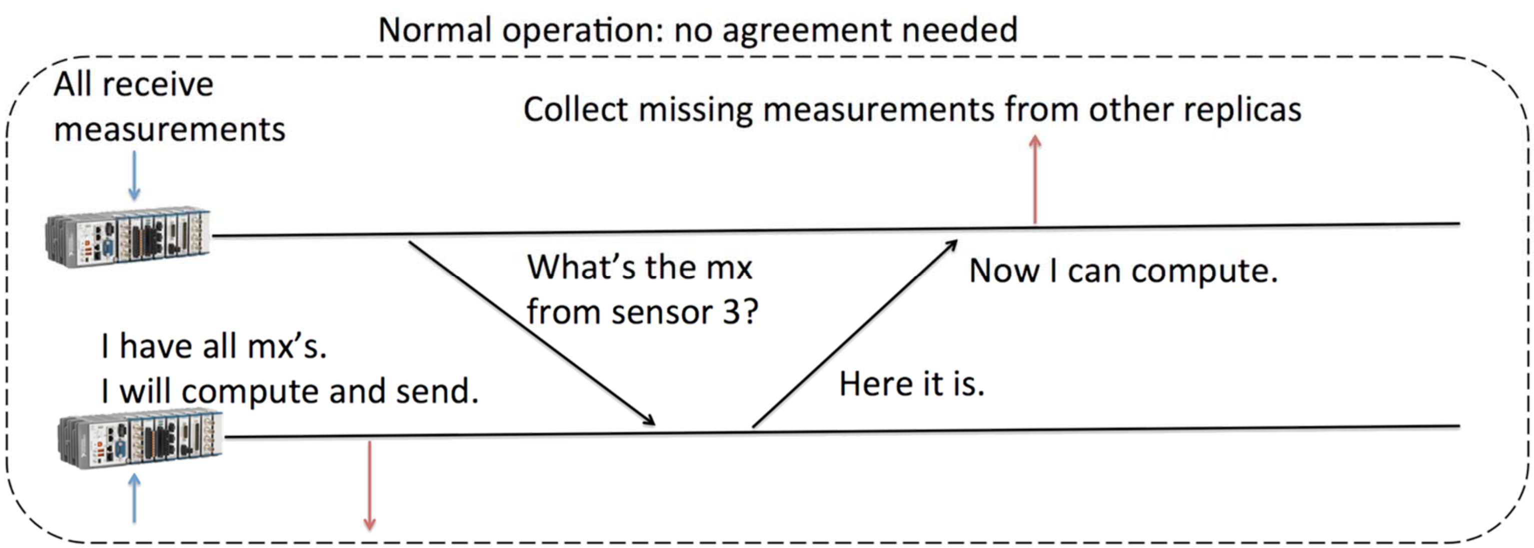

Open-source implementation:
[https://github.com/LCA2-EPFL/iprp](https://github.com/LCA2-EPFL/iprp)

# COMMELEC Uses Active Replication with Real-Time Consensus

Axo: makes sure delayed messages are not used

Quarts: grid agents perform agreement on input

Added latency ≤ one RTT – compare to consensus's unbounded delay [Mohiuddin et al 2017, Saab et al 2017]



# 2. Controlling the Electrical State with Uncertain Power Setpoints [Wang et al 2017b]

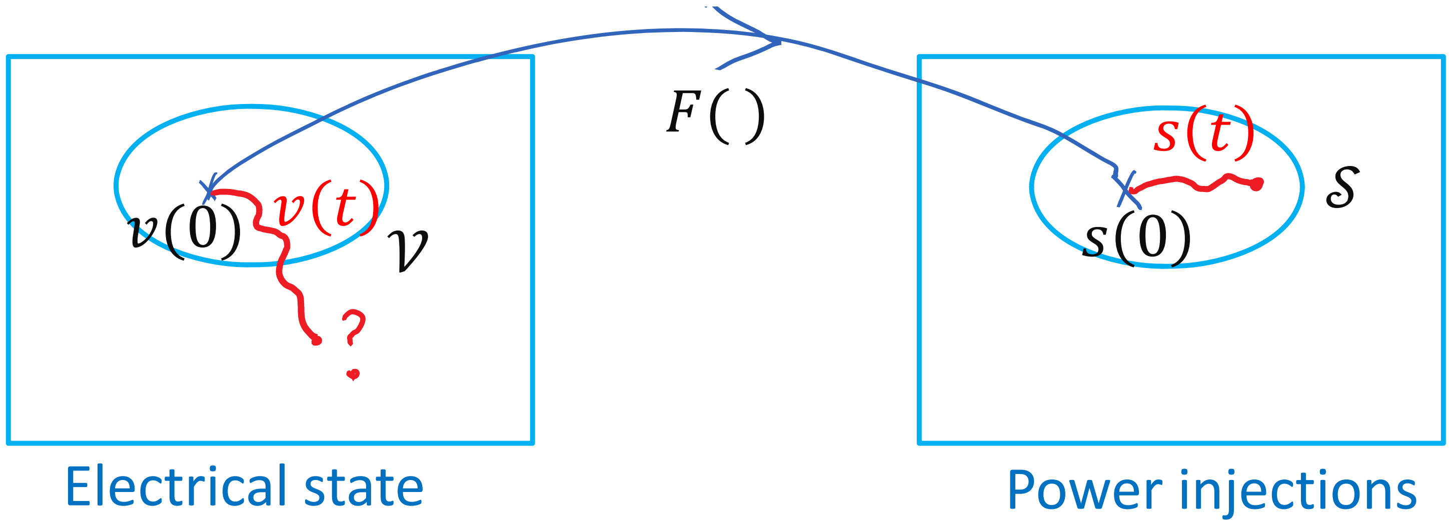
Admissibility test: when issueing power setpoint $x$, grid agent tests whether the grid is safe during the next control interval for all power injections in the set $S = BF(x)$.

The abstract problem is:

- given an initial electrical state $v$ of the grid
- given that the power injections $s$ remain in some uncertainty set $\mathcal{S}$

can we be sure that the resulting state of grid satisfies security constraints and is non-singular ?

# $\mathcal{V}$-Control



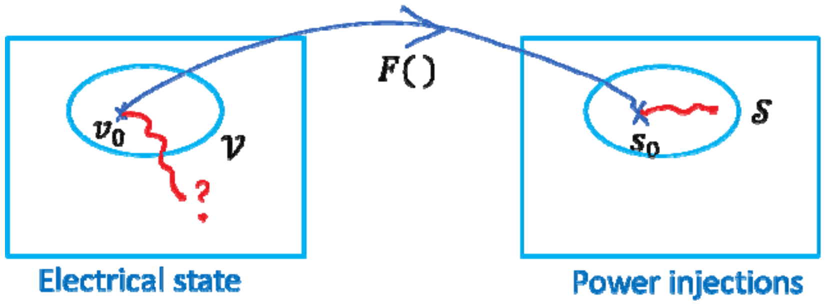

$\mathcal{S}$ is a domain of $\mathcal{V}$- control $\Leftrightarrow$ whenever $t \mapsto v(t)$ is continuous, knowing that $v(0) \in \mathcal{V}$ and $\forall t \geq 0, F\big(v(t)\big) \in \mathcal{S}$ ensures that $\forall t \geq 0, v(t) \in \mathcal{V}$.

3-phase grid with one slack bus and $N$ PQ buses; $v =$ electrical state = complex voltage at all non slack buses; $s =$ power injection vector at all non slack buses

$s = F(v)$ is the power-flow equation

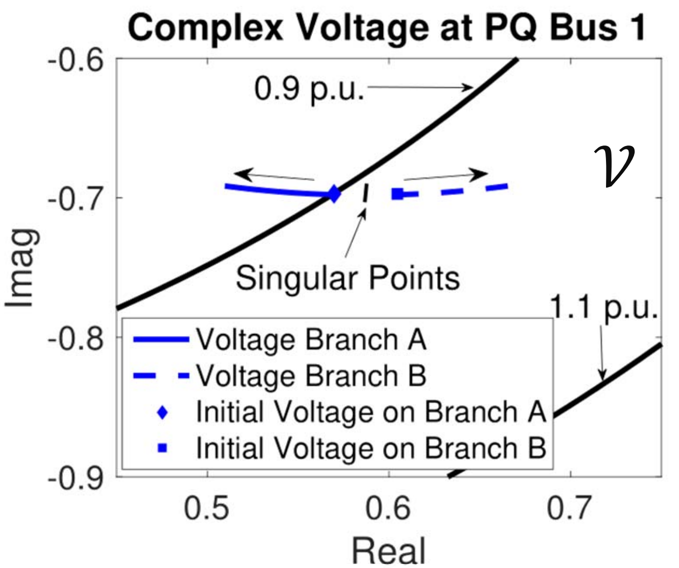
$\mathcal{V}$ is typically defined by voltage and ampacity constraints + non-singularity of $\nabla F$

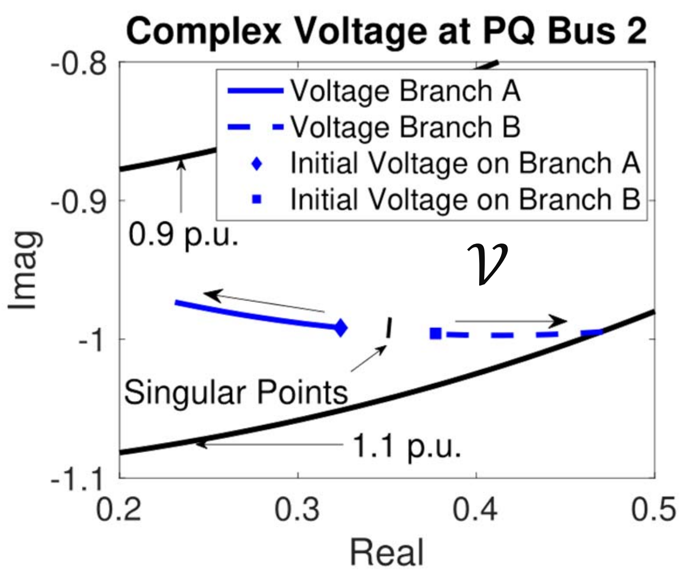
# Existence of Load Flow Solution Does not Imply V-control

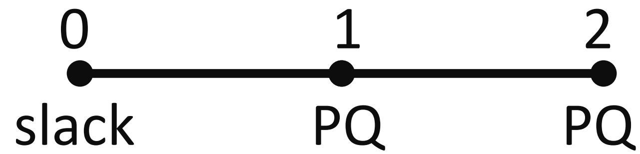



For $\mathcal{S}$ to be a domain of $\mathcal{V}$-control it is necessary that every $s \in \mathcal{S}$ has a load-flow solution in $\mathcal{V}$.

But this is not sufficient.



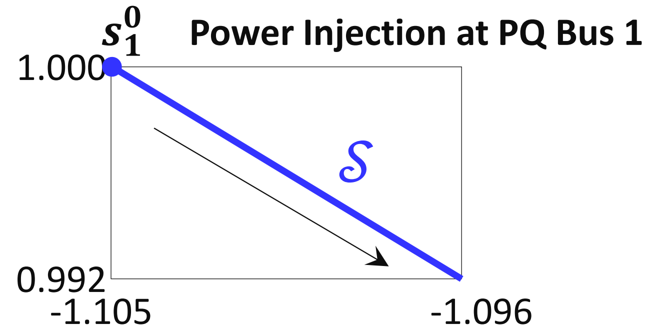



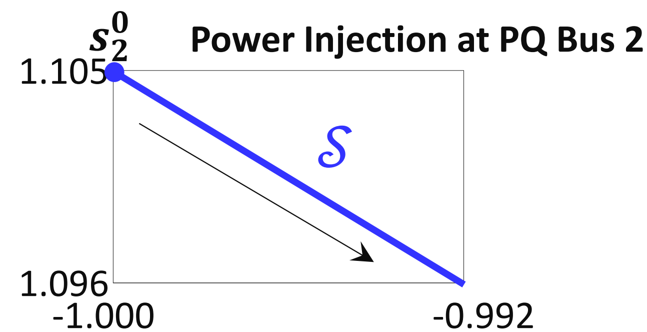




[Nguyen Turitsin 2014]

Every $s \in \mathcal{S}$ has a load-flow solution in $\mathcal{V}$.

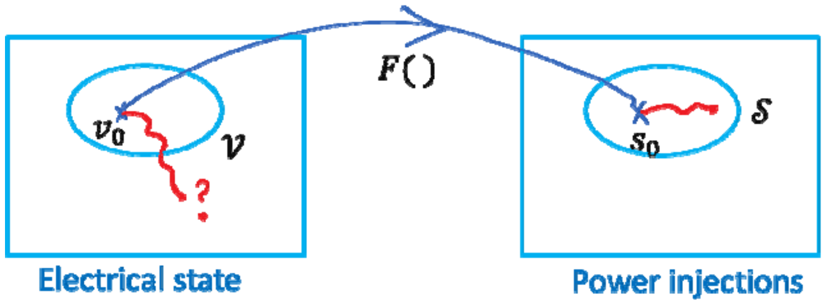
But starting from $s^0$ and $v =\diamond$ we exit $\mathcal{V}$.



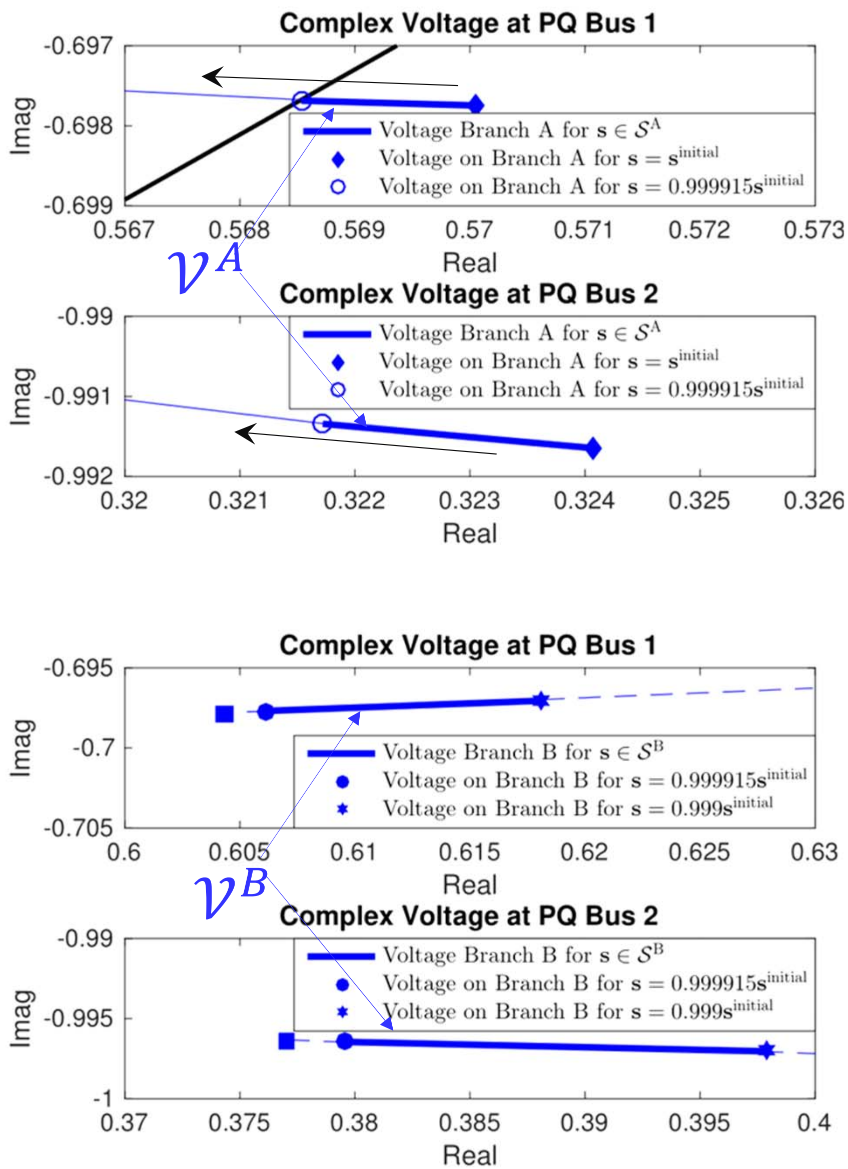

$\mathcal{V} = \{v: |v_1|, |v_2| \in [0.9; 1.1] \text{ and } \nabla F_v \text{ non singular}\}$
$\mathcal{S} = \{s = \kappa(s_1^0, s_2^0), \kappa \in [0.992; 1]\}$
$v =\diamond$ is in interior of $\mathcal{V}$, close to boundary (in $s_1$)

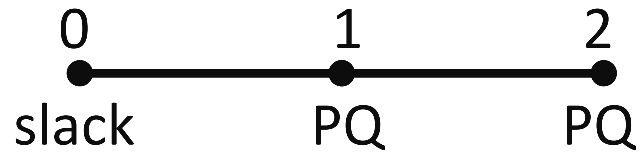
# *Unique* Load Flow Solution Does not Imply V-control




Assume that every $s \in \mathcal{S}$ has a unique load-flow solution in $\mathcal{V}$.

This is not sufficient to guarantee that $\mathcal{S}$ is a domain of $\mathcal{V}$-control.

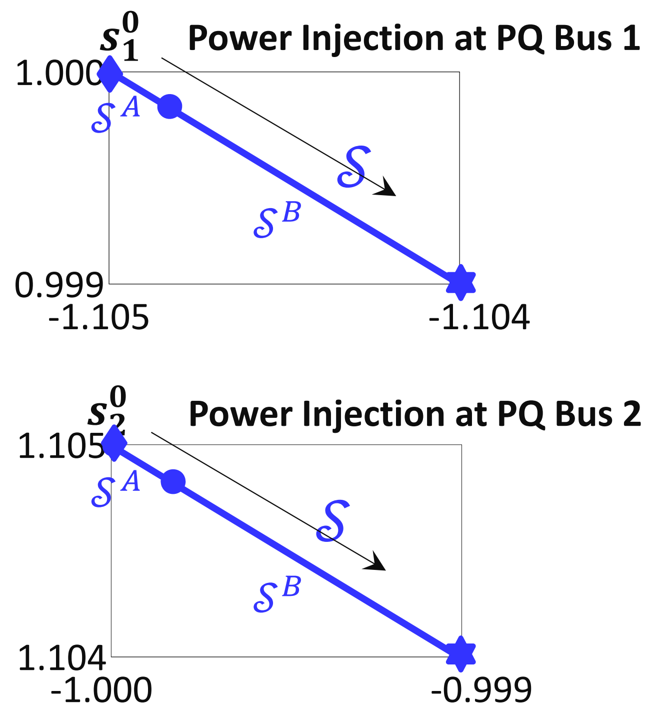



[Nguyen Turitsin 2014]

Every $s \in \mathcal{S}$ has a unique load-flow solution in $\mathcal{V}$.

But starting from $s^0$ and $v = \diamond$ we exit $\mathcal{V}$.



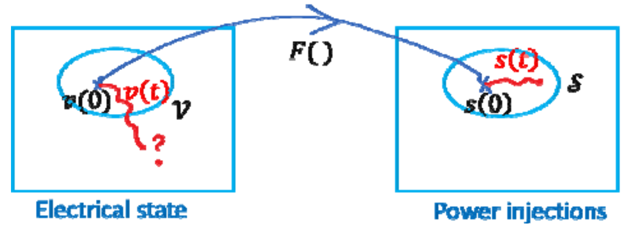

$\mathcal{V} = \mathcal{V}^A \cup \mathcal{V}^B$

$\mathcal{S} = \{s = \kappa(s_1^0, s_2^0), \kappa \in [0.999; 1]\} = \mathcal{S}^A \cup \mathcal{S}^B$

$\mathcal{S}^A = \{s = \kappa(s_1^0, s_2^0), \kappa \in (0.999915; 1]\}$

$\mathcal{S}^B = \{s = \kappa(s_1^0, s_2^0), \kappa \in [0.999; 0.999915]\}$

# Sufficient Condition for V-control




**Theorem 3** in [Wang et al 2017b]

If

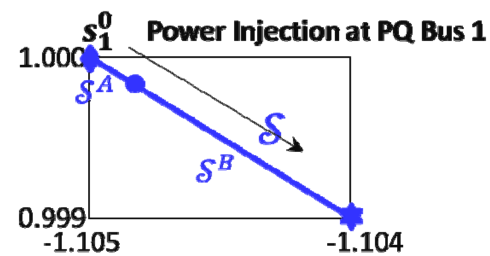
*1.* $\mathcal{V}$ is open in $\mathbb{C}^{3N}$

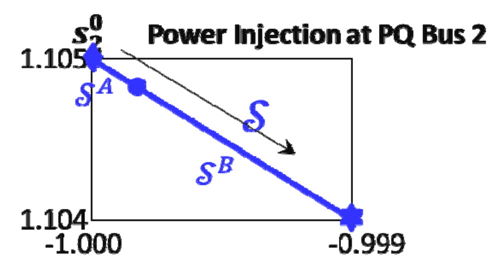
*2.* $\mathcal{S}$ is open in $\mathbb{C}^{3N}$

*3.* $\forall s \in \mathcal{S}$ there is a unique load-flow solution in $\mathcal{V}$

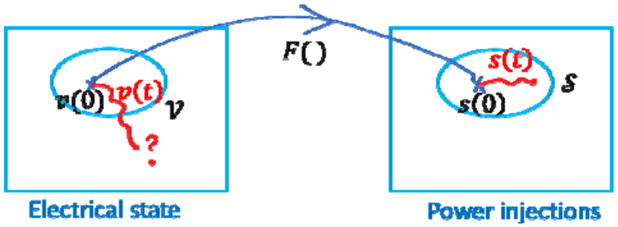
then $\mathcal{S}$ is a domain of $\mathcal{V}$-control.

In the previous example, neither $\mathcal{V}$ nor $\mathcal{S}$ is open.



# V-control and Non-Singularity




We call $v$ non-singular if $\nabla F_v$ is non-singular.

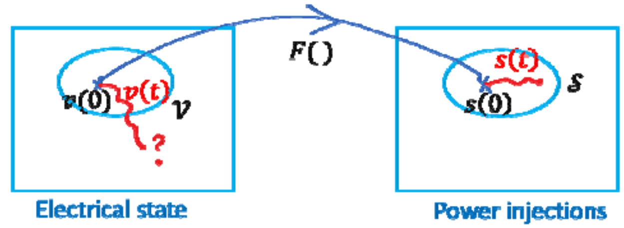
**Theorem 3** in [Wang et al 2017b]

If

1. $\mathcal{V}$ is open in $\mathbb{C}^{3N}$
2. $\mathcal{S}$ is open in $\mathbb{C}^{3N}$
3. $\forall s \in \mathcal{S}$ there is a unique load-flow solution in $\mathcal{V}$

then $\mathcal{S}$ is a domain of $\mathcal{V}$-control.
Furthermore, every $v \in \mathcal{V}$ such that $F(v) \in \mathcal{S}$ is non-singular.

# Uniqueness and Non-Singularity



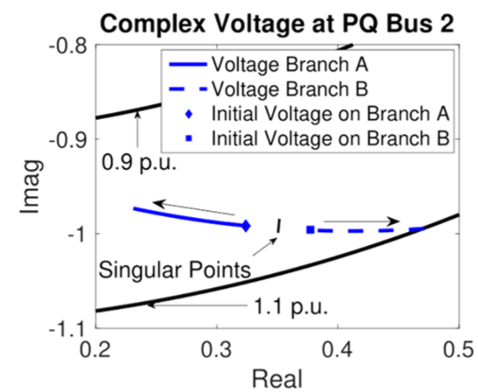

We call $\mathcal{V}$ a domain of uniqueness iff

$\forall v \in \mathcal{V}, \forall v' \in \mathcal{V}, v \neq v' \Rightarrow F(v) \neq F(v')$

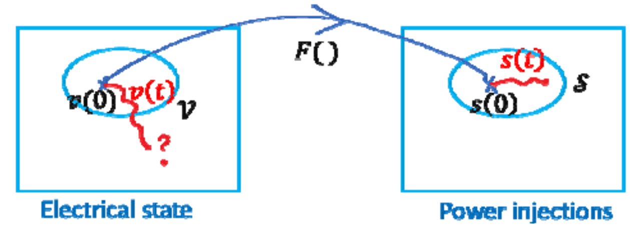
**Theorem 1** in [Wang et al 2017b]

If $\mathcal{V}$ is open in $\mathbb{C}^{3N}$ and is a domain of uniqueness then every $v \in \mathcal{V}$ is non-singular.

In this previous example, $\mathcal{V}$ is not a domain of uniqueness



# Other Sufficient Condition for V-control




**Lemma 2** in [Wang et al 2017b]

If

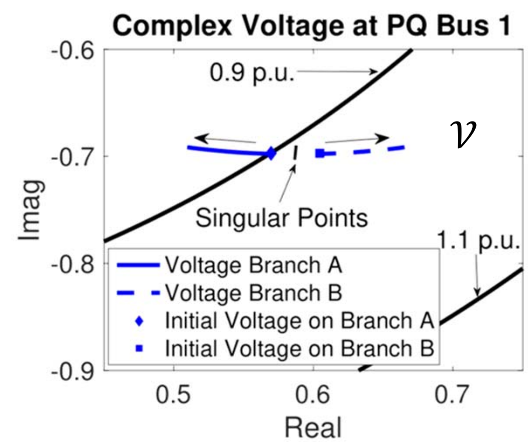
*1.* $\mathcal{V}$ is open in $\mathbb{C}^{3N}$

*2.* $\mathcal{V}$ is non-singular

*3.* $\forall s \in \mathcal{S}$ there is a unique load-flow solution in $\mathcal{V}$

then $\mathcal{S}$ is a domain of $\mathcal{V}$-control.

In the previous example $\mathcal{V}$ is open but has singularities.



# Grid Agent's Admissibiliy Test, Re-Visited

Problem (P): Given a set of power injections $\mathcal{S}^{uncertain}$, find a set of electrical states $\mathcal{V}$ such that

*1.* $v(0) \in \mathcal{V}$

*2.* $\mathcal{V}$ is open

*3.* $\mathcal{V}$ is a domain of uniqueness

*4.* $\mathcal{V}$ satisfies security constraints (voltages and line currents)

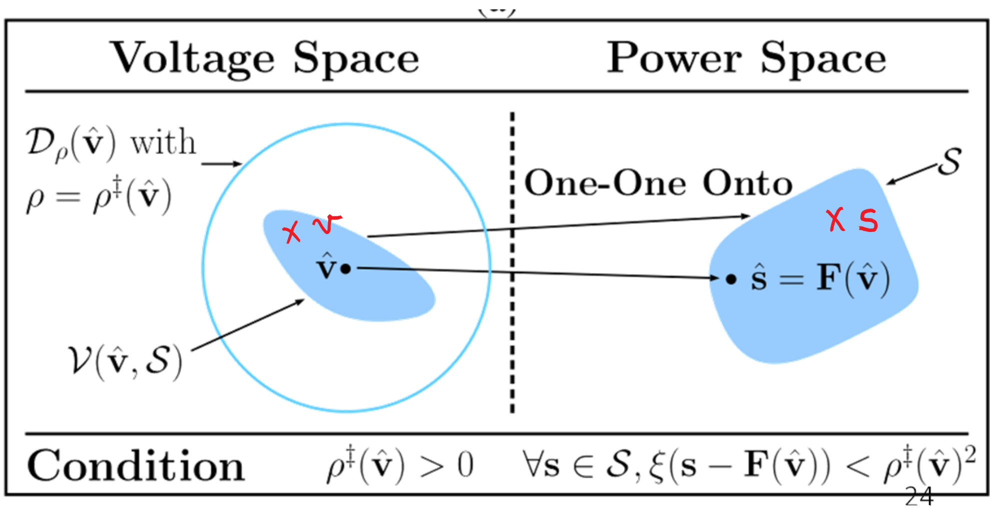
*5.* $\mathcal{S}^{uncertain} \subseteq F(\mathcal{V})$

By Theorems 1 and 3 (applied to $\mathcal{V}$ and $\mathcal{S} = F(\mathcal{V})$ ), this will imply that $\mathcal{V}$ is non singular and $\mathcal{S}^{uncertain}$ is a domain of $\mathcal{V}$-control.

# Solving (P): Part A

Use sufficient conditions for uniqueness and existence of load flow. **Theorem 1** in [Wang et al 2017a]

Given is a load-flow pair $(\hat{v}, \hat{s})$. If $\xi(s - \hat{s}) < \rho^{\ddagger}(\hat{v})^2$ then $s$ has a unique load flow solution in a disk around $\hat{v}$ with radius $\rho^{\ddagger}(\hat{v})$. The norm $\xi()$ and $\rho^{\ddagger}$ are derived from the Y matrix.

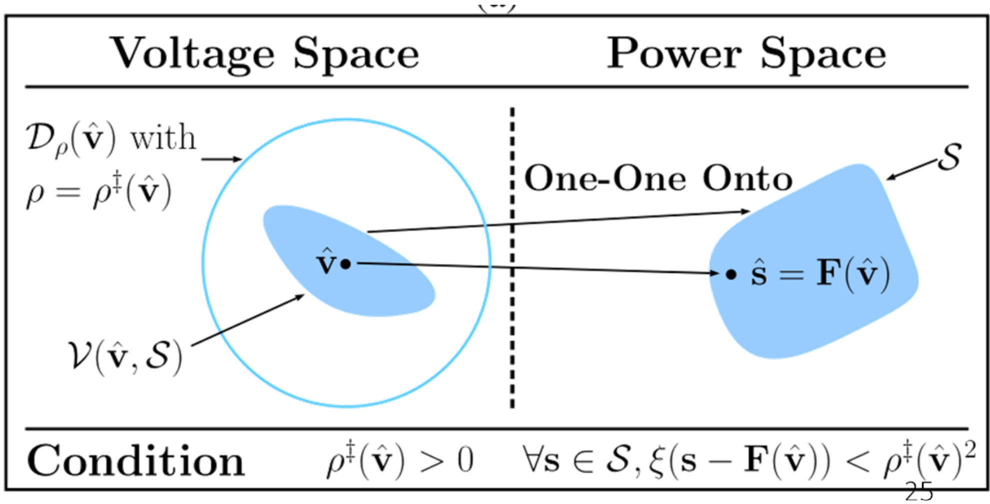


# Solving (P): Part A

Given is a set $\mathcal{S}$ and a load-flow pair $(\hat{v}, \hat{s})$ such that $\hat{s} \in \mathcal{S}$.

Assume (C1) $\sup_{s \in \mathcal{S}} \xi\big(s - F(\hat{v})\big) < \rho^{\ddagger}(\hat{v})^2$

Then $\mathcal{V}(\hat{v}, \mathcal{S}) = \{v \in \mathbb{C}^{3N},\ F(v) \in \mathcal{S}\} \cap D_{\rho^{\ddagger}(\hat{v})}(\hat{v})$ is a domain of uniqueness.



# Solving (P): Part A

Given is a set $\mathcal{S}$ and a load-flow pair $(\hat{v}, \hat{s})$ such that $\hat{s} \in \mathcal{S}$.

Assume (C1) $\sup_{s \in \mathcal{S}} \xi\big(s - F(\hat{v})\big) < \rho^{\ddagger}(\hat{v})^2$

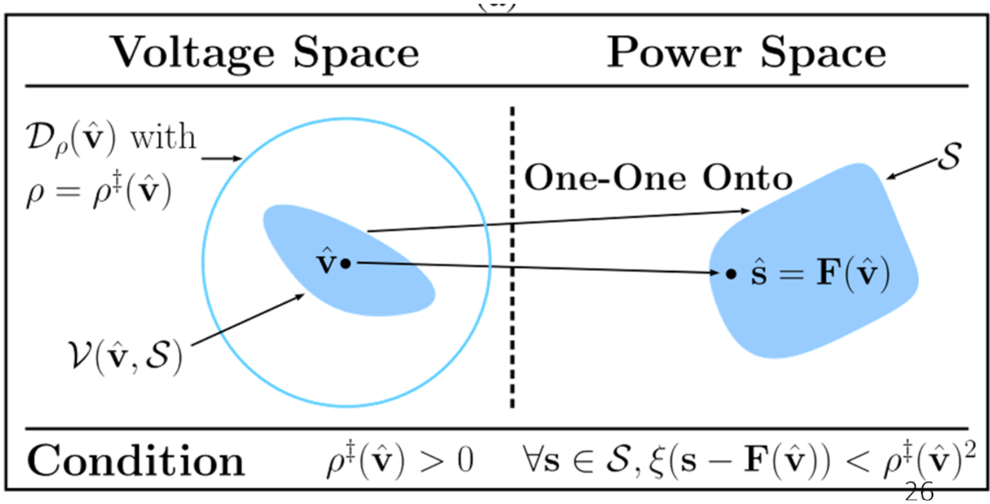
Assume in addition (C2) (Def.3 in [Wang et al 2017b])

$\sup_{s \in \mathcal{S}} \delta_j(s, \hat{v}) < \kappa_j$ for $j = 1 \dots 6N$

Then $\mathcal{V}(\hat{v}, \mathcal{S})$ is secured domain of uniqueness.

If $\mathcal{S}^{uncertain} \subseteq \mathcal{S}$

then Problem (P) is solved !



# Notation [Wang et al 2017b]

$$\boldsymbol{\delta}_j(\hat{\mathbf{v}}, \mathbf{s}) \triangleq \frac{\sum_{\ell=1}^{N} |\boldsymbol{\Gamma}_{j,\ell}||\mathrm{diag}(\mathbf{w}_\ell)^{-1}|\boldsymbol{\eta}_\ell(\hat{\mathbf{v}}, \mathbf{s})}{u_{\min}(\hat{\mathbf{v}})(u_{\min}(\hat{\mathbf{v}}) - \rho^\dagger(\hat{\mathbf{v}}, \mathbf{s}))}; \qquad (6)$$

zero-load nodal voltage $\mathbf{w} \triangleq -\mathbf{Y}_{LL}^{-1}\mathbf{Y}_{L0}\mathbf{v}_0$

- $\boldsymbol{\Gamma}_{j,\ell}$, $j, \ell \in \mathcal{N}^{PQ}$ is the $3 \times 3$ submatrix formed by rows $\{3j-2, 3j-1, 3j\}$ and columns $\{3\ell-2, 3\ell-1, 3\ell\}$ of $\mathbf{Y}_{LL}^{-1}$;

| Notation | Definition |
|---|---|
| $\mathbf{W}$ | $\mathrm{diag}(\mathbf{w})$ |
| $\xi(\mathbf{s})$ | $\lVert\mathbf{W}^{-1}\mathbf{Y}_{LL}^{-1}\overline{\mathbf{W}}^{-1}\mathrm{diag}(\bar{\mathbf{s}})\rVert_\infty$ |
| $u_{\min}(\mathbf{v})$ | $\min_{j\in\mathcal{N}^{PQ}, \gamma\in\{a,b,c\}} \lvert v_j^\gamma / w_j^\gamma \rvert$ |
| $\rho^\ddagger(\mathbf{v})$ | $\frac{1}{2}\left(u_{\min}(\mathbf{v}) - \xi(\mathbf{F}(\mathbf{v}))/u_{\min}(\mathbf{v})\right)$ |
| $\rho^\dagger(\mathbf{v}, \mathbf{s}')$ | $\rho^\ddagger(\mathbf{v}) - \sqrt{\rho^\ddagger(\mathbf{v})^2 - \xi(\mathbf{s}' - \mathbf{F}(\mathbf{v}))}$ |
| $\boldsymbol{\eta}_\ell(\mathbf{v}, \mathbf{s}')$ | $u_{\min}(\mathbf{v})\lvert\mathbf{s}'_\ell - \mathbf{F}_\ell(\mathbf{v})\rvert + \rho^\dagger(\mathbf{v}, \mathbf{s}')\lvert\mathbf{F}_\ell(\mathbf{v})\rvert$ |

# Recap: Part A

Solve $6N + 1$ optimization problems over the set $S^{uncertain}$.

The optimization problems are quasiconvex and maximum is always at a vertex.

If conditions (C1) and (C2) hold, then problem (P) is solved and admissibility test succeeds

(i.e. we can be certain that the grid will remain secured and non-singular as long as the power injections are in $S^{uncertain}$)

# Solving (P): Part B: Patching

Step A succeeds if we find an $\mathcal{S}$ that covers $\mathcal{S}^{uncertain}$ , which often works, but may fail when $\mathcal{S}^{uncertain}$ is large.

Solution: patching !

**Theorem 6** in [Wang et al 2017b]: Assume we find a collection of pairs $(\hat{v}_k, \mathcal{S}_k)$ such that $\mathcal{S}^{uncertain} \subseteq \bigcup_k \mathcal{S}_k$ + condition (11) in [Wang et al 2017b]. Then the patching is consistent, i.e. the patchwork is a domain of uniqueness, secured, and non-singular and problem (P) is solved.

## Condition (11) in [Wang et al 2017b]

**Definition 4.** Candidate pairs $(\hat{\mathbf{v}}, \mathcal{S})$, $(\hat{\mathbf{v}}', \mathcal{S}')$ are *consistent* if

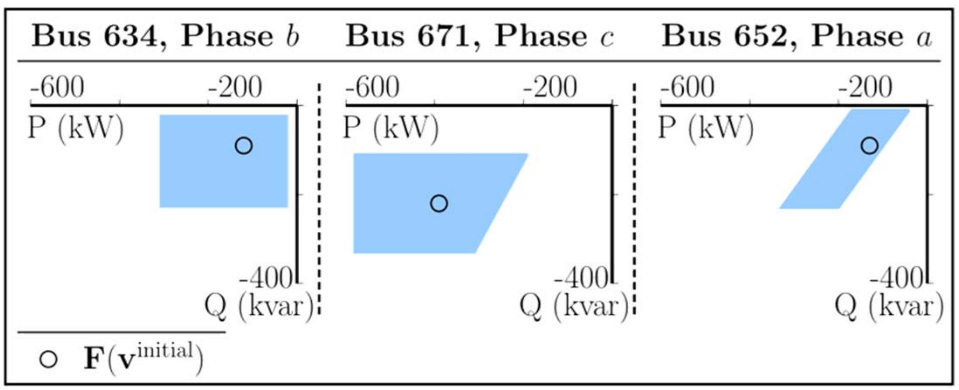
$$\begin{aligned} &\|\mathbf{W}^{-1}(\hat{\mathbf{v}} - \hat{\mathbf{v}}')\|_\infty \\ &< \max\{\rho^\ddagger(\hat{\mathbf{v}}) - \sup_{\mathbf{s}' \in \mathcal{S}'} \rho^\dagger(\hat{\mathbf{v}}', \mathbf{s}'), \rho^\ddagger(\hat{\mathbf{v}}') - \sup_{\mathbf{s} \in \mathcal{S}} \rho^\dagger(\hat{\mathbf{v}}, \mathbf{s})\}. \end{aligned} \tag{11}$$

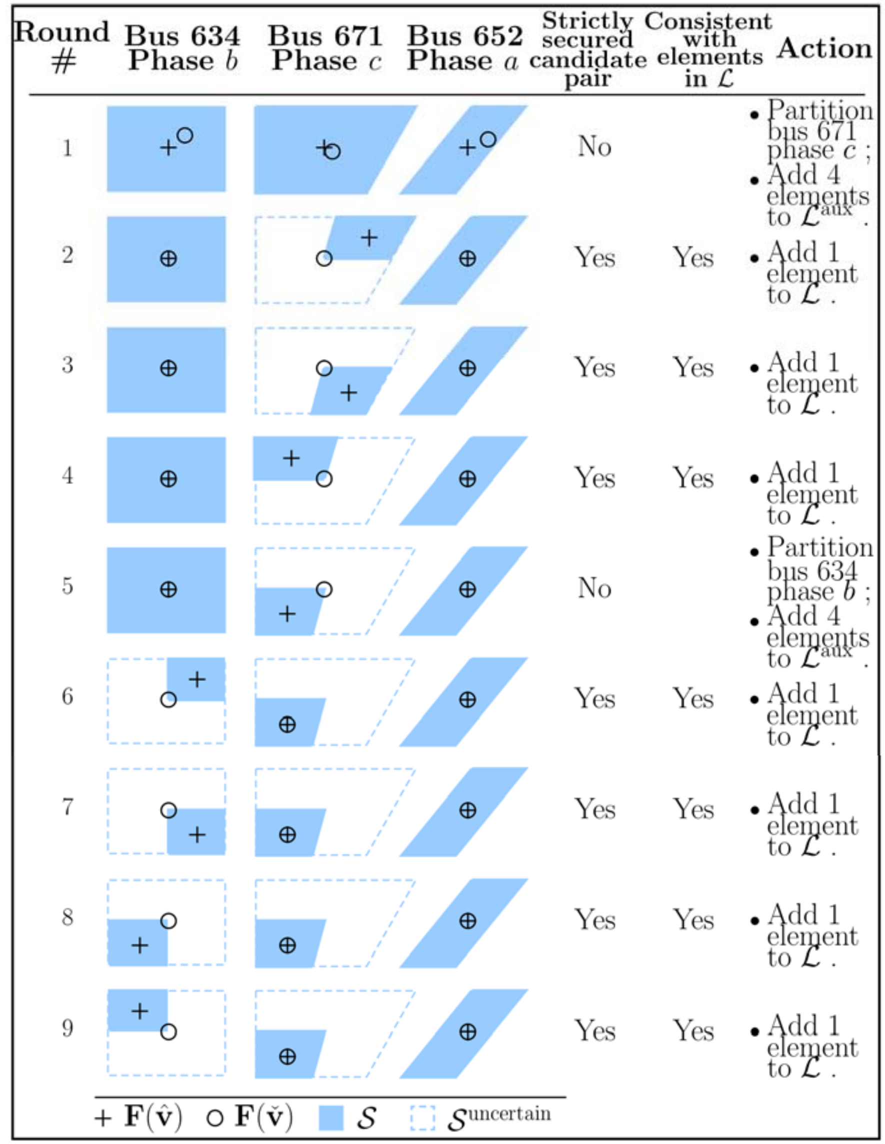
# The Patching Algorithm, Example

The algorithm tries if a single $(\hat{v}, \mathcal{S})$ works, else breaks the set $\mathcal{S}$ into pieces and patches them.

IEEE 13-bus feeder, 3-phase configuration 602.

**Uncertainty set**



# Performance Evaluation

IEEE 37 bus feeder. $\mathcal{S}^{uncertain}$= $[0, \kappa] \times$ benchmark values on all loaded phases. For $0 \leq \kappa \leq 1.15$ algorithm declares $\mathcal{S}^{uncertain}$ safe in one partition and <20 msec runtime on one i7; for $\kappa > 1.15$ the algorithm needs multiple partitions but lowest voltage bound is close to limit.

IEEE 123 bus feeder. $\mathcal{S}^{uncertain}$= $\left[1 - \frac{\kappa}{2}, 1 + \frac{\kappa}{2}\right] \times$ benchmark values on all loaded phases. For $0 \leq \kappa \leq .31$ algorithm declares $\mathcal{S}^{uncertain}$ safe in one partition and <30 msec runtime; for $\kappa > .31$ the algorithm needs multiple partitions but highest branch current is close to limit.

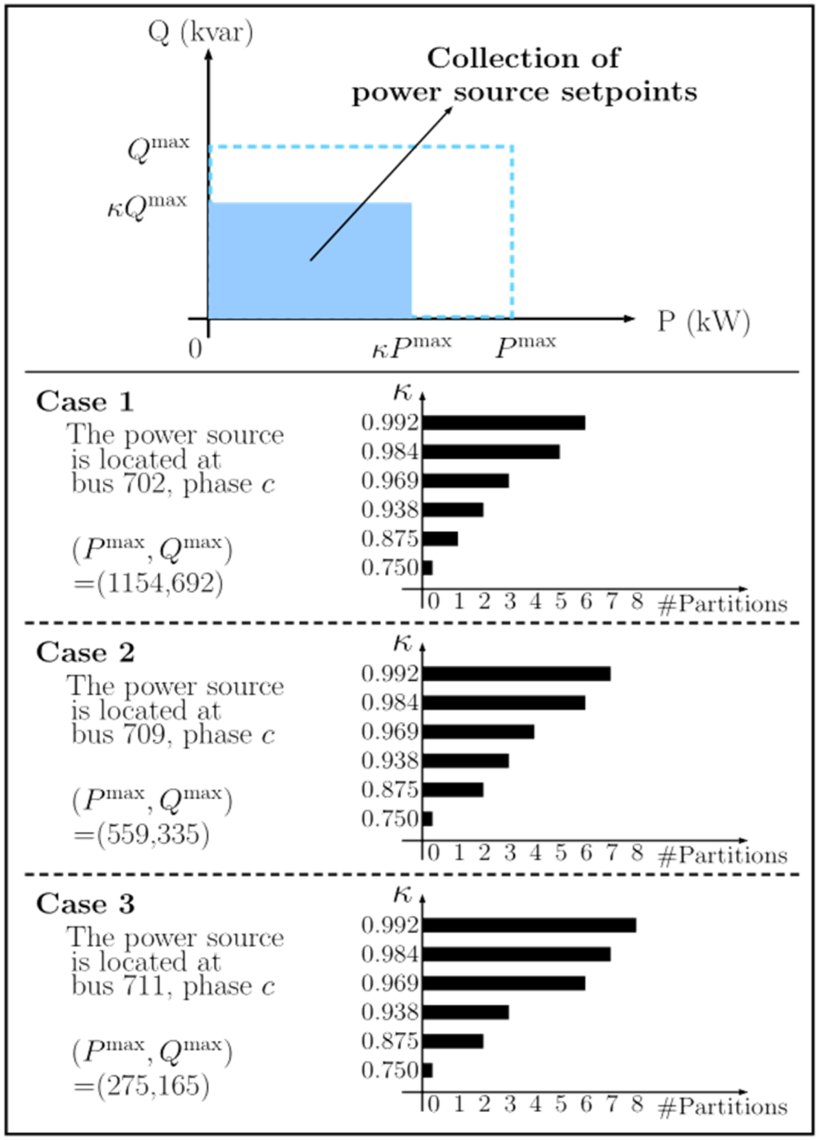
# Performance Evaluation

IEEE 37 bus feeder. One source added to one unloaded phase. Uncertainty set as shown. We limit the number of partitions to 8.

For $\kappa \leq 0.750$ no partition.

For $\kappa = 0.992$, 8 partitions and run-time < 200 msec. Low voltage bound is close.

Incidentally, lowest voltage is not at $(0,0)$ nor $(P^{\max}, Q^{\max})$ (non-monotonicity)



# Conclusions

Controlling state of a grid by controlling power injections is needed in dynamic settings.

The theoretical problem is an inverse problem. It can be solved using the concept of V-control.

Uniqueness, existence, topological openness play an essential role.

A domain of uniqueness (of electrical states) is necessarily non-singular.

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