Stability and power sharing in microgrids

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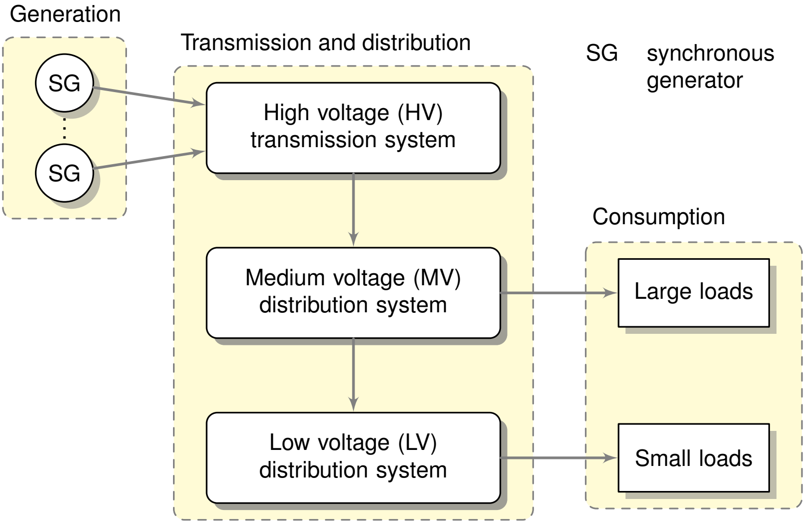
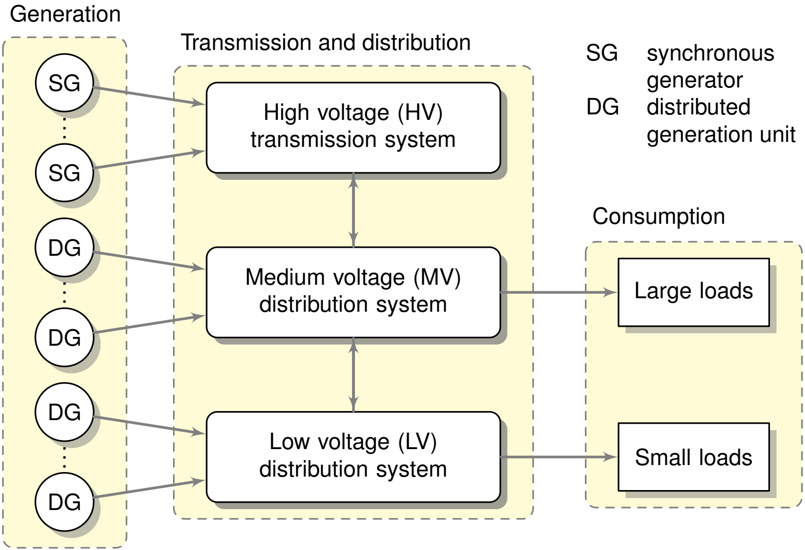
Outline

Renewables change power system structure



SG synchronous generator

Renewables change power system structure



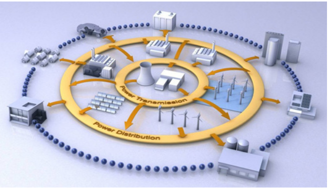
Need change in power system operation

- Increasing amount of renewable DG units

⇒ highly affects in-feed structure of existing power systems

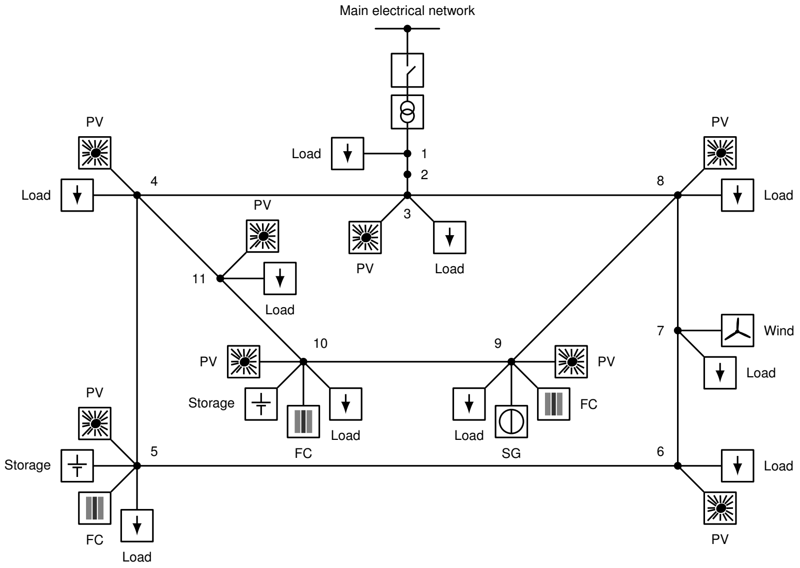
- Most renewable DG units interfaced to network via AC inverters
- Physical characteristics of inverters largely differ from characteristics of SGs

⇒ Different control and operation strategies are needed



Source: siemens.com

The microgrid concept



Modeling of microgrids

Main network components

- DG units interfaced to network via inverters or SGs
- Loads
- Power lines and transformers

Standard modeling assumptions

- Loads can be modeled by impedances
- Line dynamics can be neglected
- Lossless admittances

$\Rightarrow$ Work with Kron-reduced network

$\Rightarrow$ DG unit connected at each node in reduced network

Main focus: inverter-based microgrids

Main operation modes of inverters in microgrids

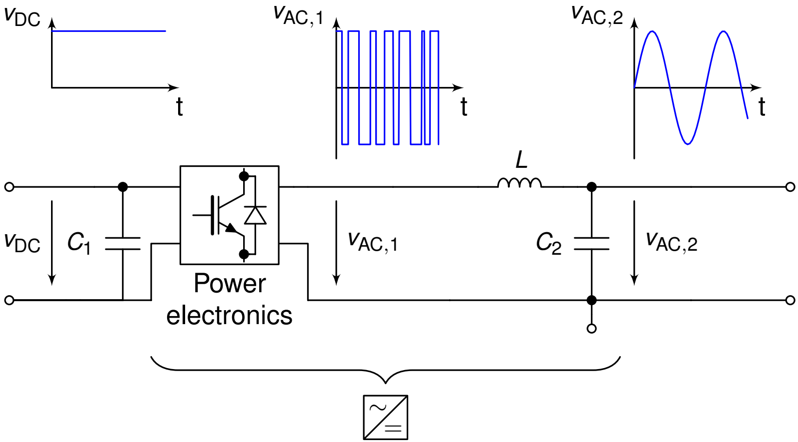
1. Grid-feeding mode
2. Grid-forming mode

- Grid-forming units are essential components in power systems
- Tasks
  - To provide a synchronous frequency
  - To provide a certain voltage level at all buses in the network

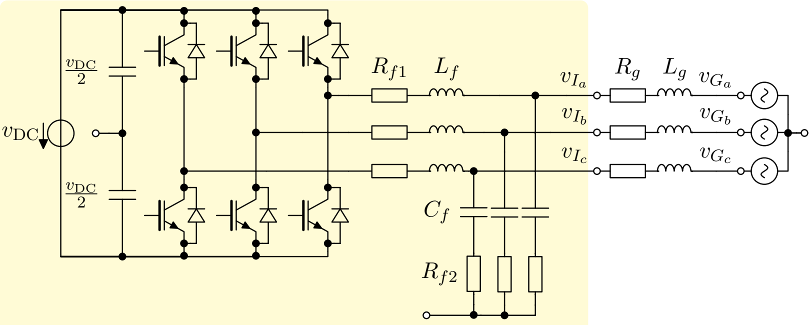
  $\Leftrightarrow$ To provide a stable operating point

$\Rightarrow$ Focus on inverters in grid-forming mode

Basic functionality of DC-AC voltage inverters



Inverter operated in grid-forming mode



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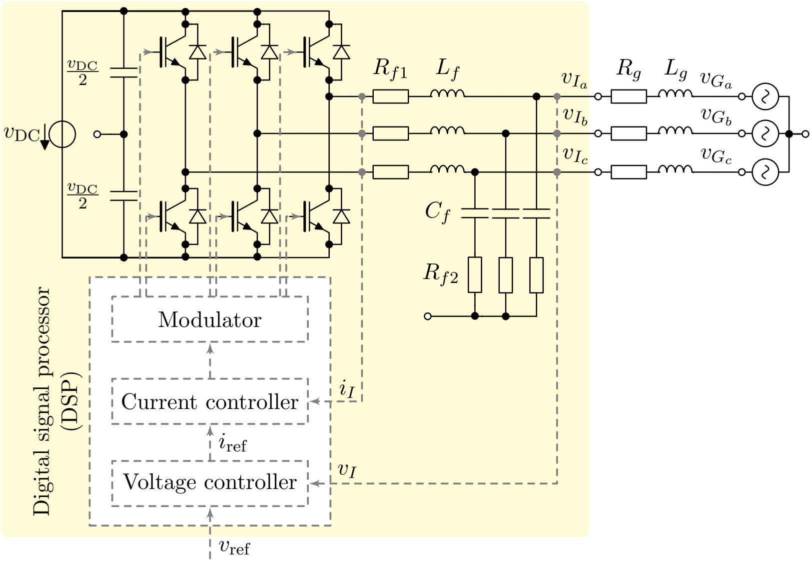
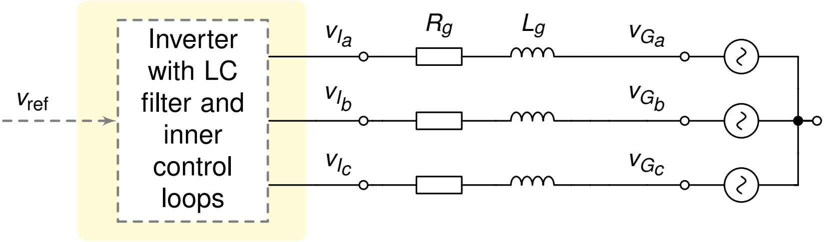


Grid-forming inverter as controllable voltage source

Model assumptions:

- Inverter is operated in grid-forming mode
- Its inner current and voltage controllers track references ideally
- If inverter connects intermittent DG unit to network, it is equipped with some sort of fast-reacting storage



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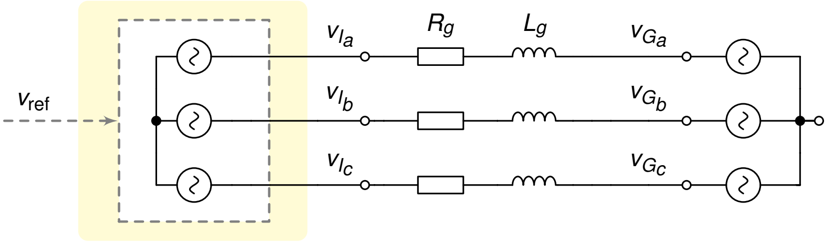

Inverter model

Inverter dynamics

$$\dot{\delta}_i = u_i^\delta,$$
$$\tau_{P_i} \dot{P}_i^m = -P_i^m + P_i,$$
$$V_i = u_i^V,$$
$$\tau_{P_i} \dot{Q}_i^m = -Q_i^m + Q_i$$

Power flows at i-th node

$$P_i = \sum_{k \sim \mathcal{N}_i} |B_{ik}| \sin(\delta_{ik}) V_i V_k$$
$$Q_i = |B_{ii}| V_i^2 - \sum_{k \sim \mathcal{N}_i} |B_{ik}| \cos(\delta_{ik}) V_i V_k$$

δ_i	phase angle
V_i	voltage magnitude
u_i^δ, u_i^V	control inputs
P_i	active power
Q_i	reactive power
P_i^m	measured active power
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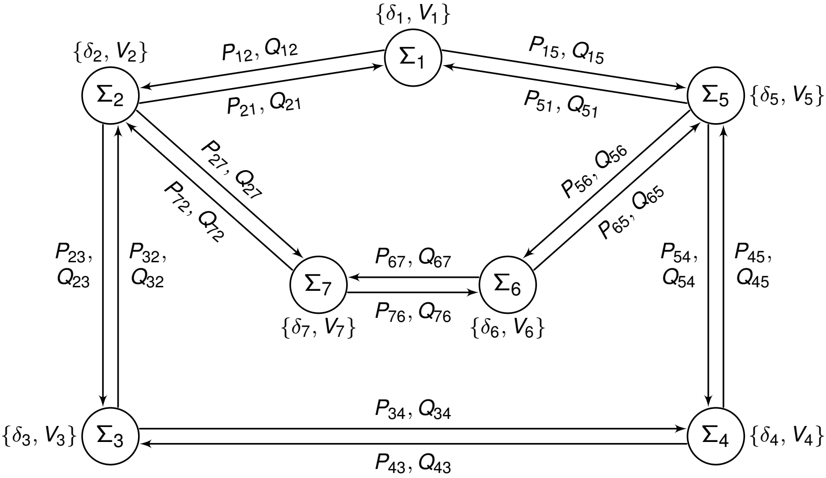
τ_{P_i}	time constant of meas. filter

Example network



Inverters in grid-forming mode represented by $\Sigma_i,\ i = 1, \ldots, 7$

Power sharing in microgrids

Definition (Power sharing)

- Consider an AC electrical network, e.g. an AC microgrid
- Denote its set of nodes by $\mathcal{N} = [1, n] \cap \mathbb{N}$
- Choose positive real constants $\gamma_i, \gamma_k, \chi_i$ and χ_k
- Proportional active, respectively reactive, power sharing between units at nodes $i \in \mathcal{N}$ and $k \in \mathcal{N}$, if

$$\frac{P_i^s}{\gamma_i} = \frac{P_k^s}{\gamma_k}, \quad \text{respectively} \quad \frac{Q_i^s}{\chi_i} = \frac{Q_k^s}{\chi_k}$$

Power sharing is an agreement problem

- $N \subseteq \mathcal{N}$
- $U = \text{diag}(1/\gamma_i), \quad i \in N$
- $D = \text{diag}(1/\chi_i), \quad i \in N$
- Control objective

$$\lim_{t\to\infty} UP_N(\delta, V) = \upsilon \underline{1}_{|N|},$$
$$\lim_{t\to\infty} DQ_N(\delta, V) = \beta \underline{1}_{|N|}, \quad \upsilon \in \mathbb{R}_{>0}, \quad \beta \in \mathbb{R}_{>0}$$

Motivation for droop control of inverters

1. Droop control: widely used in SG-based power systems to address problems of frequency stability and active power sharing

$\Rightarrow$ Adapt droop control to inverters

$\Rightarrow$ Make inverters mimic behavior of SGs with respect to frequency and active power

2. How to couple actuactor signals ($\dot{\delta}$ and V) with powers (P and Q) to achieve power sharing?

$\Rightarrow$ Pose MIMO control design problem as set of decoupled SISO control design problems

$\Rightarrow$ Analyze couplings in power flow equations over a power line

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⇒ Analyze couplings in power flow equations over a power line

Power flows over a power line

Assumptions

- Dominantly inductive power line with admittance $Y_{ik} \in \mathbb{C}$ between nodes i and k
- Small phase angle differences, i.e. $\delta_i - \delta_k \approx 0$

$\Rightarrow$ Approximations

$$Y_{ik} = G_{ik} + jB_{ik} \approx jB_{ik}, \quad \sin(\delta_{ik}) \approx \delta_{ik}, \quad \cos(\delta_{ik}) \approx 1$$

$\Rightarrow$ Active and reactive power flows simplify to

$$P_{ik} = -B_{ik} V_i V_k \delta_{ik},$$
$$Q_{ik} = -B_{ik} V_i^2 + B_{ik} V_i V_k = -B_{ik} V_i (V_i - V_k)$$

Standard droop control for inverters

Frequency droop control

$$u_i^\delta = \omega^d - k_{P_i}(P_i^m - P_i^d)$$

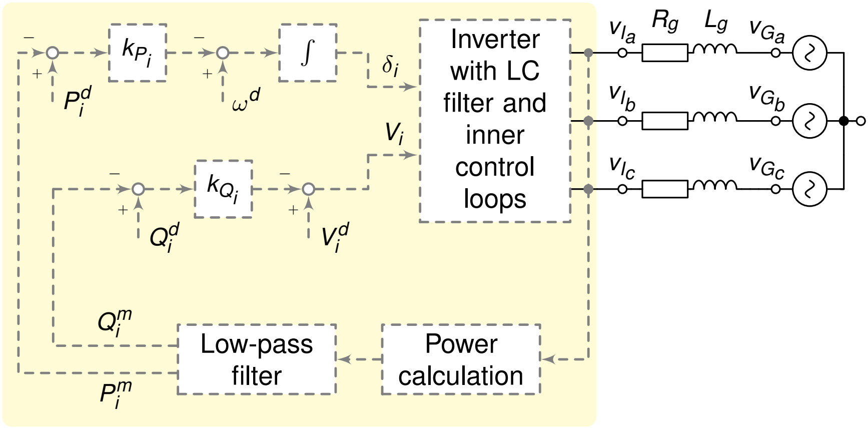
Voltage droop control

$$u_i^V = V_i^d - k_{Q_i}(Q_i^m - Q_i^d)$$

Further details: see, e.g., Chandorkar et al. (1993)

$k_{P_i} \in \mathbb{R}_{>0}$	frequency droop gain
$\omega^d \in \mathbb{R}_{>0}$	desired (nominal) frequency
$P_i^d \in \mathbb{R}$	active power setpoint
$P_i^m \in \mathbb{R}$	active power measurement
$k_{Q_i} \in \mathbb{R}_{>0}$	voltage droop gain
$V_i^d \in \mathbb{R}_{>0}$	desired (nominal) voltage amplitude
$Q_i^d \in \mathbb{R}$	reactive power setpoint
$Q_i^m \in \mathbb{R}$	reactive power measurement

Droop control - schematic representation



Closed-loop droop-controlled microgrid

$$\dot{\delta}_i = \omega^d - k_{P_i}(P_i^m - P_i^d),$$
$$\tau_{P_i}\dot{P}_i^m = -P_i^m + P_i,$$
$$V_i = V_i^d - k_{Q_i}(Q_i^m - Q_i^d),$$
$$\tau_{P_i}\dot{Q}_i^m = -Q_i^m + Q_i$$

$\Downarrow$

change of variables

$+$

vector notation

$\Downarrow$

$$\dot{\delta} = \omega,$$
$$T\dot{\omega} = -\omega + \mathbb{1}_n\omega^d - K_P(P - P^d),$$
$$T\dot{V} = -V + V^d - K_Q(Q - Q^d)$$

$$\delta = \text{col}(\delta_i) \in \mathbb{R}^n$$
$$\omega = \text{col}(\omega_i) \in \mathbb{R}^n$$
$$V = \text{col}(V_i) \in \mathbb{R}^n$$
$$V^d = \text{col}(V_i^d) \in \mathbb{R}^n$$
$$T = \text{diag}(\tau_{P_i}) \in \mathbb{R}^{n\times n}$$
$$K_P = \text{diag}(k_{P_i}) \in \mathbb{R}^{n\times n}$$
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change of variables
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$$P^d = \text{col}(P_i^d) \in \mathbb{R}^n$$
$$Q^d = \text{col}(Q_i^d) \in \mathbb{R}^n$$

Problem statement

1. Derive conditions for asymptotic stability of generic droop-controlled microgrids

2. Investigate if droop control is suitable to achieve control objective of active power sharing, i.e.,

$$\frac{P_i^s}{\gamma_i} = \frac{P_k^s}{\gamma_k}, \quad \gamma_i \in \mathbb{R}_{>0}, \quad \gamma_k \in \mathbb{R}_{>0}$$

Stability analysis

- Coordinate transformation
- Follow interconnection and damping assignment passivity-based control (IDA-PBC) approach (Ortega et al. (2002))
- Represent microgrid dynamics in port-Hamiltonian form
- Can easily identify energy function

Port-Hamiltonian systems

$$\dot{x} = (J(x) - R(x))\,\nabla H + g(x)u, \quad x \in \mathbb{X} \subseteq \mathbb{R}^n, \quad u \in \mathbb{R}^m,$$
$$y = g^T(x)\nabla H, \quad y \in \mathbb{R}^m$$

- $J(x) \in \mathbb{R}^{n \times n}$, $J(x) = -J(x)^T$ (interconnection matrix)
- $R(x) \geq 0 \in \mathbb{R}^{n \times n}$ for all $x \in \mathbb{X}$ (damping matrix)
- $H : \mathbb{X} \to \mathbb{R}$ (Hamiltonian), $\nabla H = \left(\frac{\partial H}{\partial x}\right)^T$
- Power balance equation

$$\underbrace{\dot{H}}_{\text{stored power}} = -\underbrace{\nabla H^T R(x) \nabla H}_{\text{dissipated power}} + \underbrace{u^T y}_{\text{supplied power}} \leq u^T y$$

Synchronized motion

- Synchronized motion starting in $(\delta^s, \underline{1}_n\omega^s, V^s) \in \mathbb{S}^n \times \mathbb{R}^n \times \mathbb{R}^n_{>0}$

$$\delta^*(t) = \mathrm{mod}_{2\pi}\left\{\delta^s + \underline{1}_n\omega^s t\right\},$$

$$\omega^*(t) = \underline{1}_n\omega^s,$$

$$V^*(t) = V^s$$

- Aim: derive conditions, under which solutions of microgrid converge asymptotically to synchronized motion

Power flows depend on angle differences δ_{ik}

$$P_i(\delta_1, \dots, \delta_n, V_1, \dots, V_n) = \sum_{k \sim \mathcal{N}_i} |B_{ik}| \sin(\delta_{ik}) V_i V_k,$$

$$Q_i(\delta_1, \dots, \delta_n, V_1, \dots, V_n) = |B_{ii}| V_i^2 - \sum_{k \sim \mathcal{N}_i} |B_{ik}| \cos(\delta_{ik}) V_i V_k$$

$\Rightarrow$ Flow of system can be described in reduced angle coordinates

$\Rightarrow$ Transform convergence problem into classical stability problem

Main result (1) - Stability

Proposition (A condition for local asymptotic stability)

- *Fix* τ_{P_i}, k_{P_i}, ω^d *and* P_i^d
- *If* V_i^d, k_{Q_i} *and* Q_i^d *are chosen such that*

$$\mathcal{D} + \mathcal{T} - \mathcal{W}^\top \mathcal{L}^{-1} \mathcal{W} > 0 \qquad (1)$$

$\Rightarrow$ *equilibrium point is locally asymptotically stable*

$$\mathcal{L} > 0, \quad \mathcal{T} > 0, \quad \mathcal{D} = \text{diag}\left(\frac{V_i^d + k_{Q_i} Q_i^d}{k_{Q_i} (V_i^s)^2}\right) > 0$$

- Condition (1) ensures that Hamiltonian is locally positive definite

Main result (2) - Active power sharing

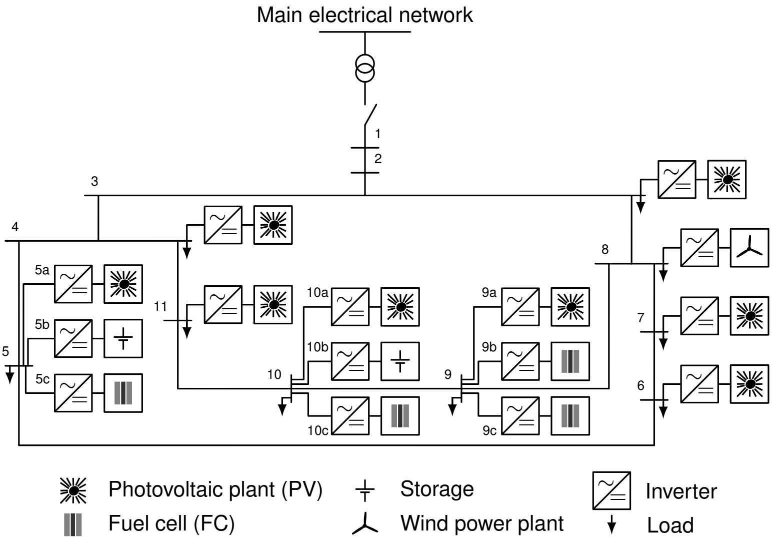
Lemma (A condition for active power sharing)

- *Assume microgrid possesses synchronized motion*
- *Then all generation units share active power proportionally with respect to γ_i and γ_k in steady-state if*

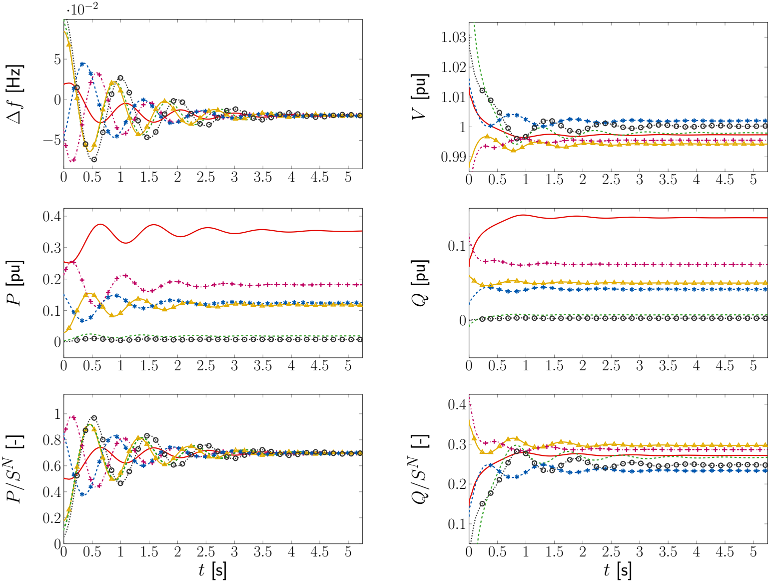
$$k_{P_i}\gamma_i = k_{P_k}\gamma_k \quad \text{and} \quad \frac{P_i^d}{\gamma_i} = \frac{P_k^d}{\gamma_k}, \quad i \sim \mathcal{N}, \quad k \sim \mathcal{N}$$

- Condition holds independently of line admittances

CIGRE MV benchmark model



Simulation example



Reactive power sharing

- Voltage droop control does, in general, not guarantee desired reactive power sharing

⇒ Several other or modified (heuristic) decentralized voltage control strategies proposed in literature
(Zhong (2013), Li et al. (2009), Sao et al. (2005), Simpson-Porco et al. (2014),...)

- But: no general conditions or formal guarantees for reactive power sharing are given

Inverter model revisited

Inverter dynamics

$$
\begin{aligned}
\dot{\delta}_i &= u_i^{\delta}, \\
\tau_{P_i} \dot{P}_i^m &= -P_i^m + P_i, \\
V_i &= u_i^V, \\
\tau_{P_i} \dot{Q}_i^m &= -Q_i^m + Q_i
\end{aligned}
$$

Reactive power flow at i-th node

$$
Q_i(\delta_1, \ldots, \delta_n, V_1, \ldots, V_n) = |B_{ii}| V_i^2 - \sum_{k \sim \mathcal{N}_i} |B_{ik}| \cos(\delta_{ik}) V_i V_k
$$

δ_i	phase angle
V_i	voltage magnitude
u_i^δ, u_i^V	control inputs
P_i	active power
Q_i	reactive power
P_i^m	measured active power
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Reactive power flow at i-th node with $\delta_{ik} \approx 0$

$$Q_i(V_1, \ldots, V_n) = |B_{ii}| V_i^2 - \sum_{k \sim \mathcal{N}_i} |B_{ik}| V_i V_k$$

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Problem statement - Voltage stability and reactive power sharing

Problem

Design a voltage control law such that

1. *the microgrid possesses an asymptotically stable equilibrium point*
2. *the DG units share their reactive powers proportionally in steady-state*

$\Leftrightarrow \lim_{t\to\infty} DQ(V) = \beta \underline{1}_n, \quad D = diag(1/\chi_i) \in \mathbb{R}^{n\times n}, \quad \beta \in \mathbb{R}$

Consensus-based distributed voltage control (DVC)

$$u_i^V = V_i^d - k_i \int_0^t e_i(\tau) d\tau,$$

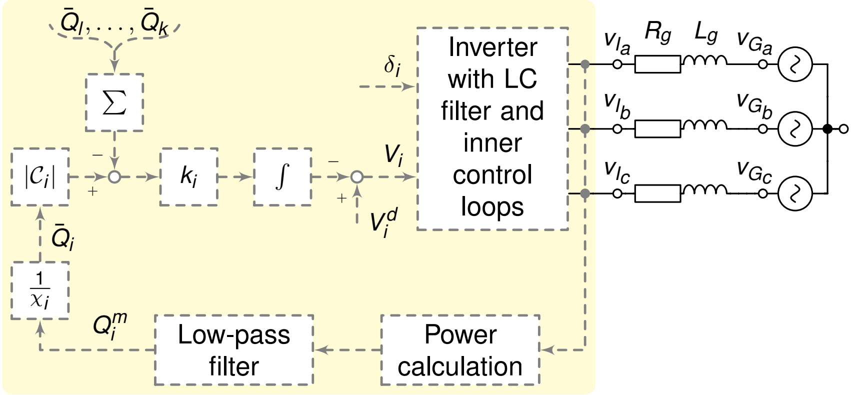
$$e_i = \sum_{k \sim \mathcal{C}_i} \left(\frac{Q_i^m}{\chi_i} - \frac{Q_k^m}{\chi_k} \right)$$

$$= \sum_{k \sim \mathcal{C}_i} (\bar{Q}_i - \bar{Q}_k)$$

$V_i^{\mathrm{d}} \in \mathbb{R}_{>0}$	desired (nominal) voltage magnitude
$k_i \in \mathbb{R}_{>0}$	feedback gain
$\mathcal{C}_i$	set of neighbor nodes of node *i* in graph induced by communication network

- Assumption: graph induced by communication network is connected and undirected

Consensus-based distributed voltage control (DVC)



Closed-loop voltage and reactive power dynamics

$$\dot{V}_i = -k_i e_i = -k_i \sum_{k \sim \mathcal{C}_i} \left(\frac{Q_i^m}{\chi_i} - \frac{Q_k^m}{\chi_k} \right), \quad V_i(0) = V_i^d$$

$$\tau_{P_i} \dot{Q}_i^m = -Q_i^m + Q_i, \qquad Q_i^m(0) = Q_{0_i}^m \in \mathbb{R}$$

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vector notation
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$$\dot{V} = -K\mathcal{L}DQ^m, \quad V(0) = V^d$$
$$T\dot{Q}^m = -Q^m + Q, \quad Q^m(0) = Q_0^m$$

$V = \mathrm{col}(V_i) \in \mathbb{R}^n_{>0}$
$Q^m = \mathrm{col}(Q_i^m) \in \mathbb{R}^n$
$Q = \mathrm{col}(Q_i) \in \mathbb{R}^n$
$K = \mathrm{diag}(k_i) \in \mathbb{R}^{n \times n}$
$D = \mathrm{diag}(1/\chi_i) \in \mathbb{R}^{n \times n}$
$T = \mathrm{diag}(\tau_{P_i}) \in \mathbb{R}^{n \times n}$

$\mathcal{L} \in \mathbb{R}^{n \times n}$ ... Laplacian matrix of connected undirected graph induced by communication network

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$$\begin{aligned} \dot{V} &= -K\mathcal{L}DQ^m, & V(0) &= V^d \\ T\dot{Q}^m &= -Q^m + Q, & Q^m(0) &= Q_0^m \end{aligned}$$

$V = \mathrm{col}(V_i) \in \mathbb{R}^n_{>0}$
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$\mathcal{L} \in \mathbb{R}^{n \times n}$ ... Laplacian matrix of connected undirected graph induced by communication network

Main result (3) - Reactive power sharing in steady-state

Claim

The DVC achieves proportional reactive power sharing in steady-state.

Sketch of proof

- $\mathcal{L} \dots$ Laplacian matrix of connected undirected graph

$\Rightarrow$ $\mathcal{L} = \mathcal{L}^T \geq 0, \quad \mathcal{L}\underline{1}_n = \underline{0}_n, \quad v^T \mathcal{L} v > 0$ for all $v \in \mathbb{R} \setminus \{\beta \underline{1}_n\}, \beta \in \mathbb{R}$

- Steady-state

$$\dot{V} = \underline{0}_n = -K\mathcal{L}DQ^s \Leftrightarrow DQ^s = \beta \underline{1}_n \Leftrightarrow \frac{Q_i^s}{\chi_i} = \frac{Q_k^s}{\chi_k}$$

Voltage conservation law

- $\underline{1}_n^T \mathcal{L} = \underline{0}_n^T$

$\Rightarrow$ $\underline{1}_n^T K^{-1} \dot{V} = \underline{1}_n^T K^{-1} K \mathcal{L} D Q^m = \underline{0}_n^T D Q^m$

$\Leftrightarrow$ $\sum_{i=1}^n \frac{\dot{V}_i}{k_i} = 0$

$\Rightarrow$ Describe flow of system in reduced voltage coordinates for stability analysis

$$V_R = \text{col}(V_i) \in \mathbb{R}_{>0}^{n-1},$$
$$V_n = V_n(V_R) = \sum_{i=1}^{n} \frac{V_i(0)}{k_i} - \sum_{i=1}^{n-1} \frac{k_n}{k_i} V_i$$

Main result (4) - Necessary and sufficient condition for local exponential stability

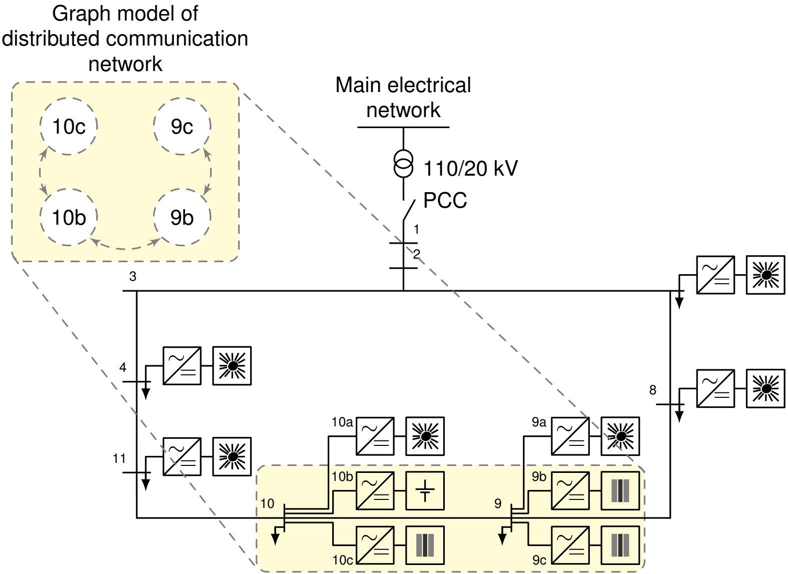
Proposition

- *Fix D and a positive real constant τ*
- *Set $\tau_{P_i} = \tau$, $i \sim \mathcal{N}$ and $K = \kappa D$, $\kappa \in \mathbb{R}_{>0}$*
- *Let $N = \frac{\partial Q}{\partial V}\big|_{x^s}$*
- *Let $\mu_i = a_i + jb_i$ be the i-th nonzero eigenvalue of the matrix product $ND\mathcal{L}D$ with $a_i \in \mathbb{R}$ and $b_i \in \mathbb{R}$*
- *Then $\mu_i \in \mathbb{C}^+$*
- *Furthermore, x^s is a locally exponentially stable equilibrium point if and only if the positive real parameter κ is chosen such that*

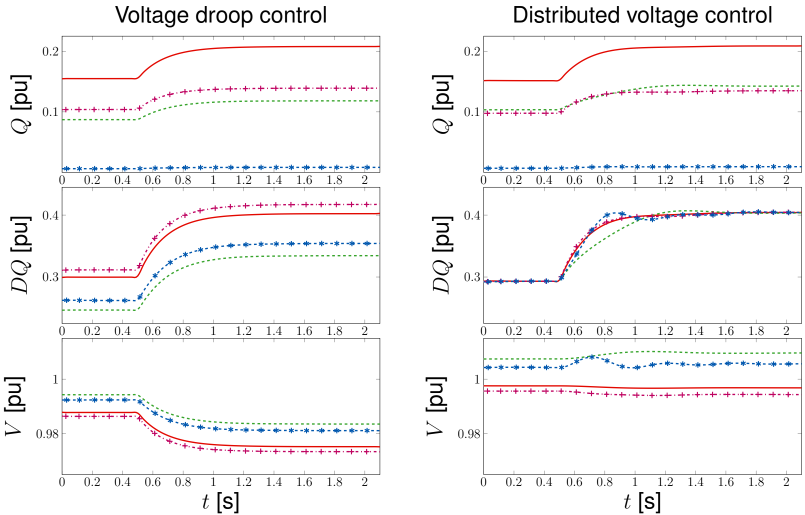
  $$\tau \kappa b_i^2 < a_i$$

  for all μ_i
- *Moreover, x^s is locally exponentially stable for any positive real κ if and only if $ND\mathcal{L}D$ has only real eigenvalues*

Subnetwork 1 of CIGRE MV benchmark model



Simulation example



Conclusions and outlook

- Microgrids are a promising concept in networks with large amount of DG
- Condition for local asymptotic stability in lossless droop-controlled inverter-based microgrids
- Selection criterion for parameters of frequency droop control that ensures desired active power sharing in steady-state
- Proposed distributed voltage control (DVC), which solves open problem of reactive power sharing

Outlook and related work

- Analysis of microgrids with frequency droop control and distributed voltage control (DVC)
- Control schemes for highly ohmic networks
- Influence of clock drift and delay induced by digital controllers of inverters on microgrid performance (submitted to ACC'15)

- Secondary frequency control
  (Simpson-Porco et al. (2013), Bürger et al. (2014), Andreasson et al. (2012), Bidram et al. (2013), Shafiee et al. (2014))
- Optimal operation control
  (Dörfler et al. (2014), Bolognani et al. (2013), Hans et al.(2014))
- Alternative inverter control schemes
  (Zhong et al. (2011), Torres et al. (2014), Dhople et al. (2014))

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