Decentralized Control of Cascaded Inverter Systems

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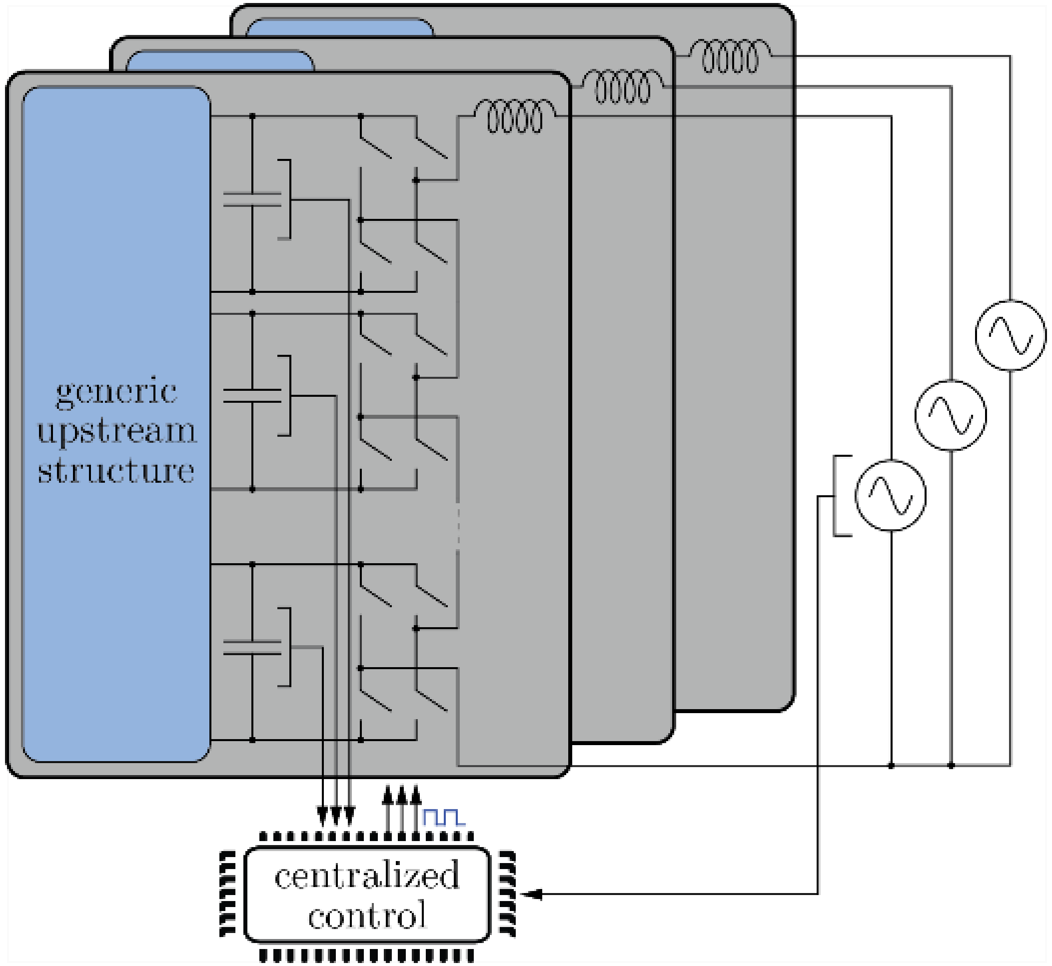
Brian’s IEEE Style Guide

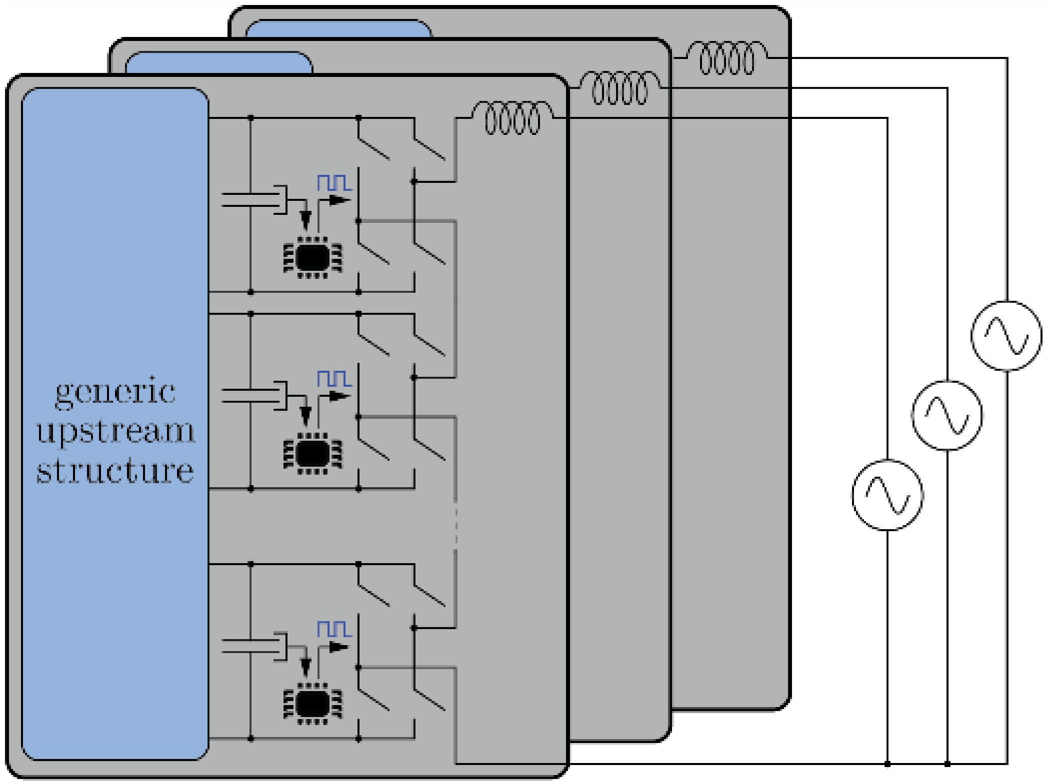
- What better place to wear my IEEE Transactions on Power Electronics shirt than the PACE meeting??

Issues with Series-connected Systems



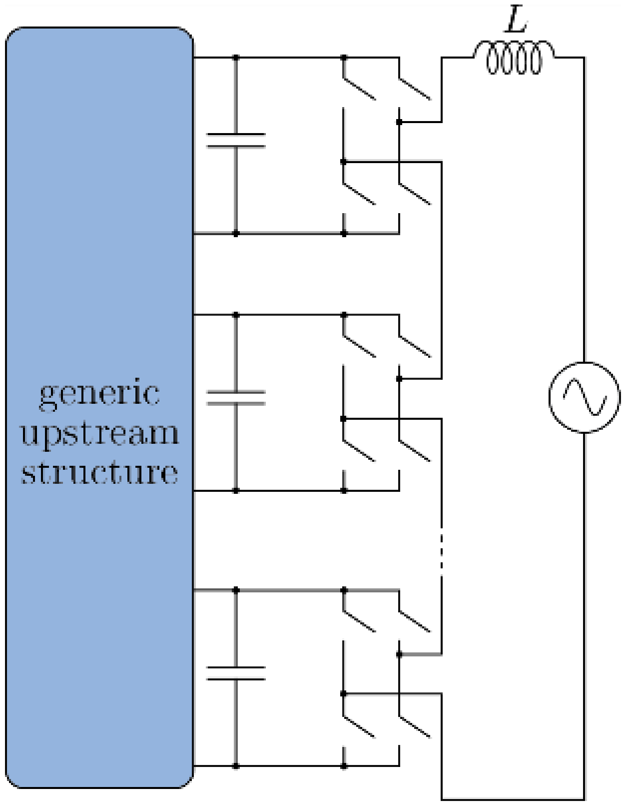
- Comms typically used since grid voltage is not directly measurable by each converter
- Centralized controls bring single point of failure
- Wiring for top-down controls bring isolation-related issues & noise high dv/dt

What We Will Show Today



- A PLL is not needed for grid synchronization during operation
- Can get automatic voltage & power sharing
- Modularized control is possible

Some Prior Related Works

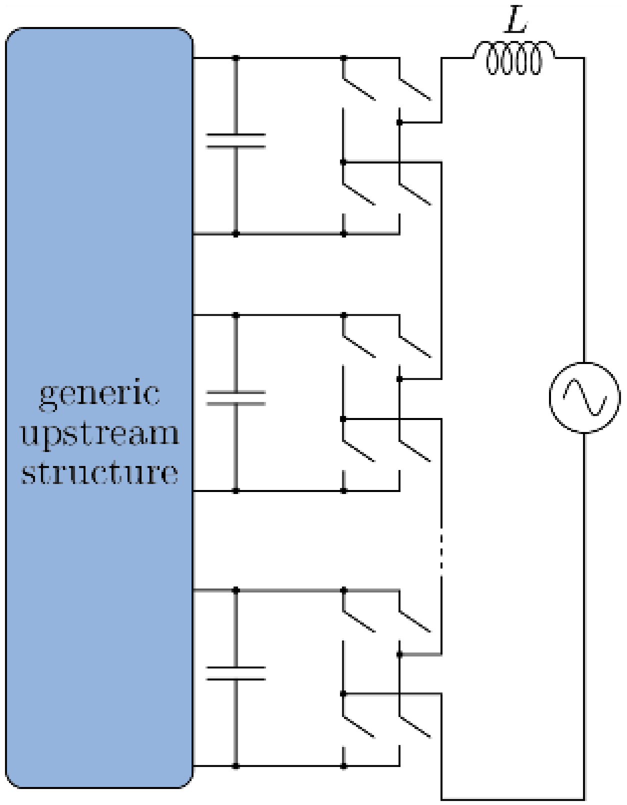


- Centralized controls done in many papers such as [1]
- Decentralized controls for islanded setups [2]
- Grid-connected setup but reactive power stability unaddressed [3]

1 Zhao, Wang, Bhattacharya, Huang, "Voltage and power balance control for a cascaded H-bridge converter-basedssolid-state transformer," TPEL, 2012.
2 He, Li, Liang, Wang, "Inverse power factor droop control for decentralized power sharing in series-connected-microconverters based islanding microgrids," TIE, 2017.
[3] Hou, Sun, Zhang, Zhang, Lu, Blaabjerg, "A self-synchronized decentralized control for series-connected H-bridge rectifiers," TPEL, 2019.

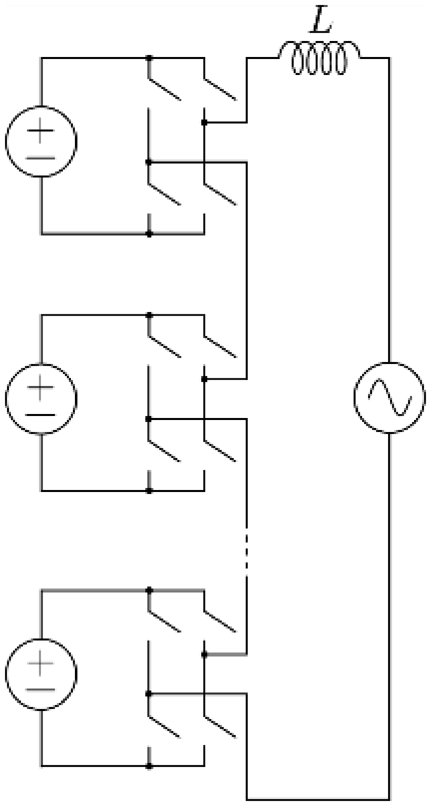
System Description and Model

Setting the Stage for AC Side Modeling



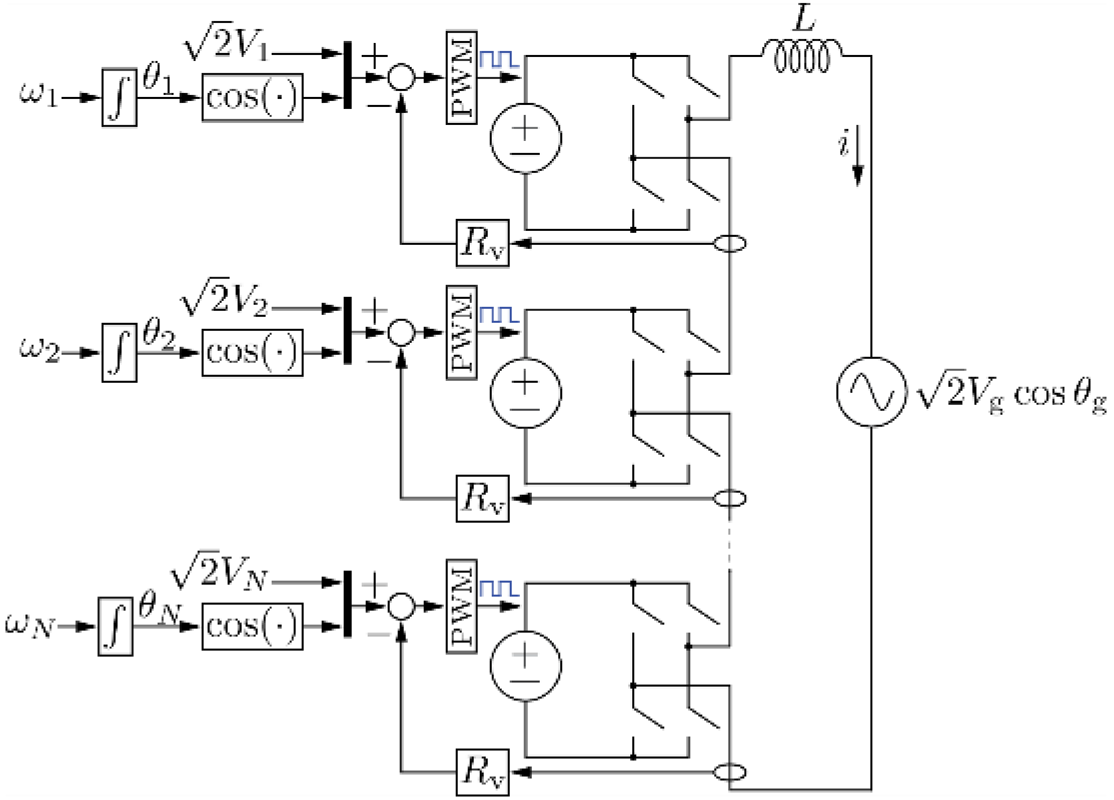
- Upstream structure abstracted away & focus on one leg of H-bridges from here forward

Setting the Stage for AC Side Modeling



- Upstream structure abstracted away & focus on one leg of H-bridges from here forward

Modulate Switch Terminals to Mimic Thevenin Equivalents



Equivalent AC Side Model

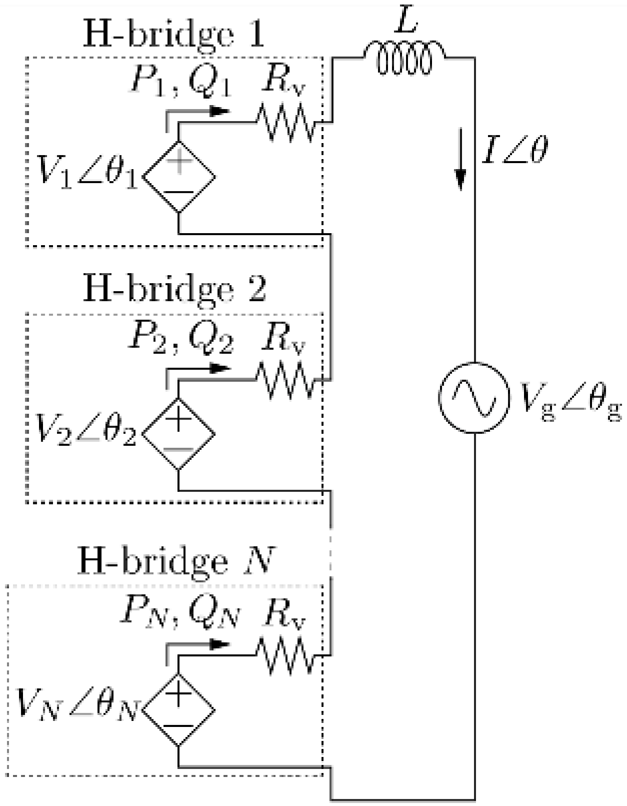
Power delivered by j-th source

$$P_j = \sum_{k=1}^{N} \frac{V_j V_k}{Z_\mathrm{f}} \cos(\theta_{jk} + \theta_\mathrm{f}) - \frac{V_j V_\mathrm{g}}{Z_\mathrm{f}} \cos(\theta_{j\mathrm{g}} + \theta_\mathrm{f}),$$

$$Q_j = \sum_{k=1}^{N} \frac{V_j V_k}{Z_\mathrm{f}} \sin(\theta_{jk} + \theta_\mathrm{f}) - \frac{V_j V_\mathrm{g}}{Z_\mathrm{f}} \sin(\theta_{j\mathrm{g}} + \theta_\mathrm{f}),$$

where

$$\theta_{jk} = \theta_j - \theta_k,\ Z_\mathrm{f}\angle\theta_\mathrm{f} = NR_\mathrm{v} + j\omega_\mathrm{o}L.$$



Equivalent AC Side Model

Pick virtual resistance s.t. $NR_\text{v} \gg \omega_\text{o} L$ & we get

$$P_j \approx \sum_{k=1}^{N} \frac{V_j V_k}{Z_\text{f}} - \frac{V_j V_\text{g}}{Z_\text{f}},$$

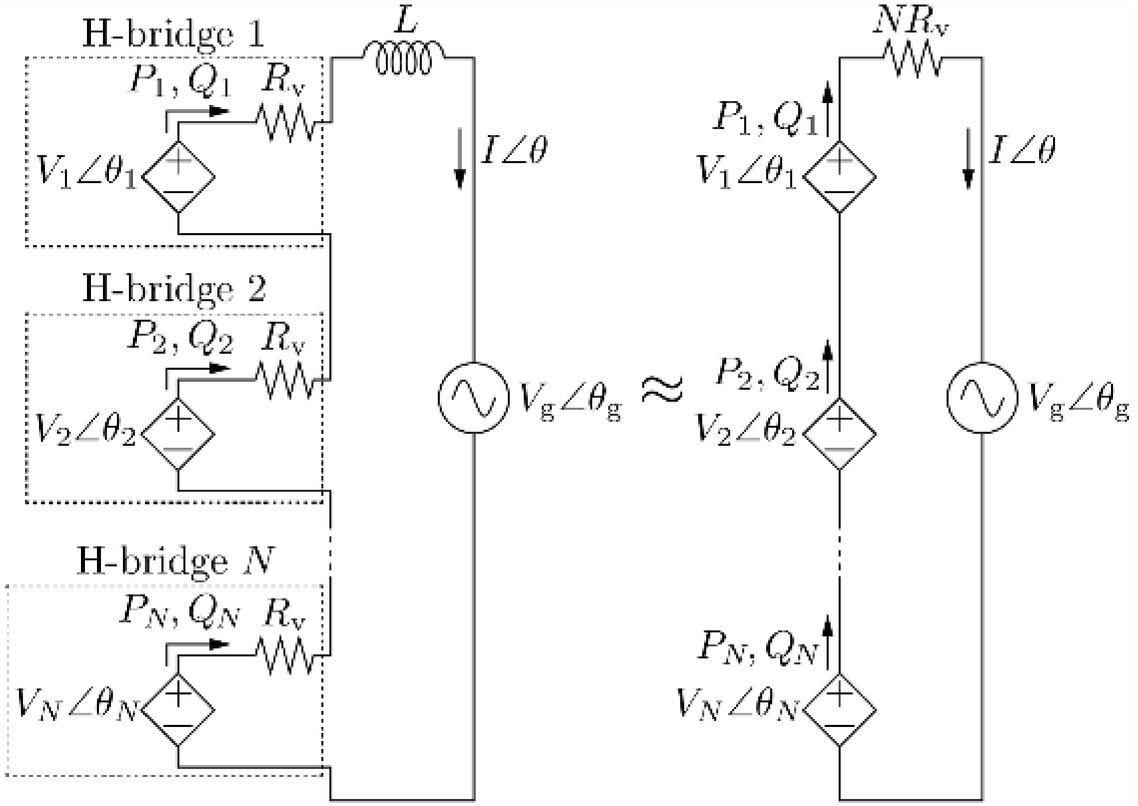
$$Q_j \approx \sum_{k=1}^{N} \frac{V_j V_k}{Z_\text{f}} \theta_{jk} - \frac{V_j V_\text{g}}{Z_\text{f}} \theta_{j\text{g}},$$

where $\theta_\text{f} \approx 0$ & we assume small angle differences.

Above relations imply these droop laws for control:

$$V_j = V_{j,\text{nom}} + K_P \left(P_{j,\text{ref}} - P_j\right),$$

$$\omega_j = \omega_\text{o} - K_Q (Q_{j,\text{ref}} - Q_j).$$



Stability Analysis

System Equilibria for Basic Droop + Thevenin Control

Assume steady-state with equal power/voltages

$$P_{1\mathrm{o}} = P_{2\mathrm{o}} = \cdots = P_{N\mathrm{o}} = P_\mathrm{o},$$
$$Q_{1\mathrm{o}} = Q_{2\mathrm{o}} = \cdots = Q_{N\mathrm{o}} = Q_\mathrm{o} = P_\mathrm{o} \tan\phi,$$
$$V_{1\mathrm{o}} = V_{2\mathrm{o}} = \cdots = V_{N\mathrm{o}} = V_\mathrm{o},$$

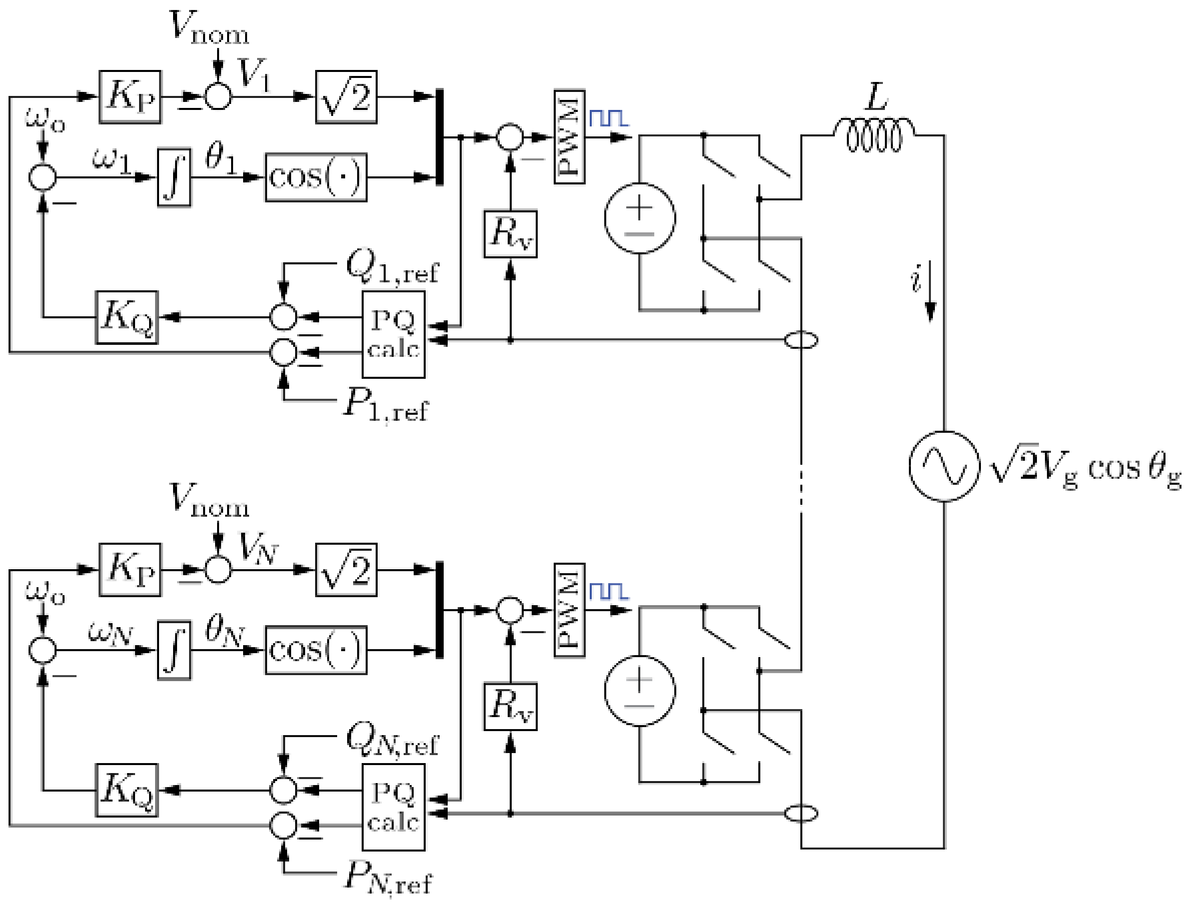
and near unity power factor gives small ϕ.

Small reactive power values imply

$$\theta_\mathrm{o} \approx 0,\ \pi,$$

And solving for voltage gives

$$V_\mathrm{o} = \frac{V_\mathrm{g}\cos\theta_\mathrm{o} \pm \sqrt{V_\mathrm{g}^2\cos^2\theta_\mathrm{o} + 4NP_\mathrm{o}Z_\mathrm{f}}}{2N} = \frac{V_\mathrm{g}}{M}.$$



Small-signal Model for Basic Droop + Thevenin Control

Linearize around steady-state voltages/angles.

Angle stability driven by Q-ω droop, estimate Q as

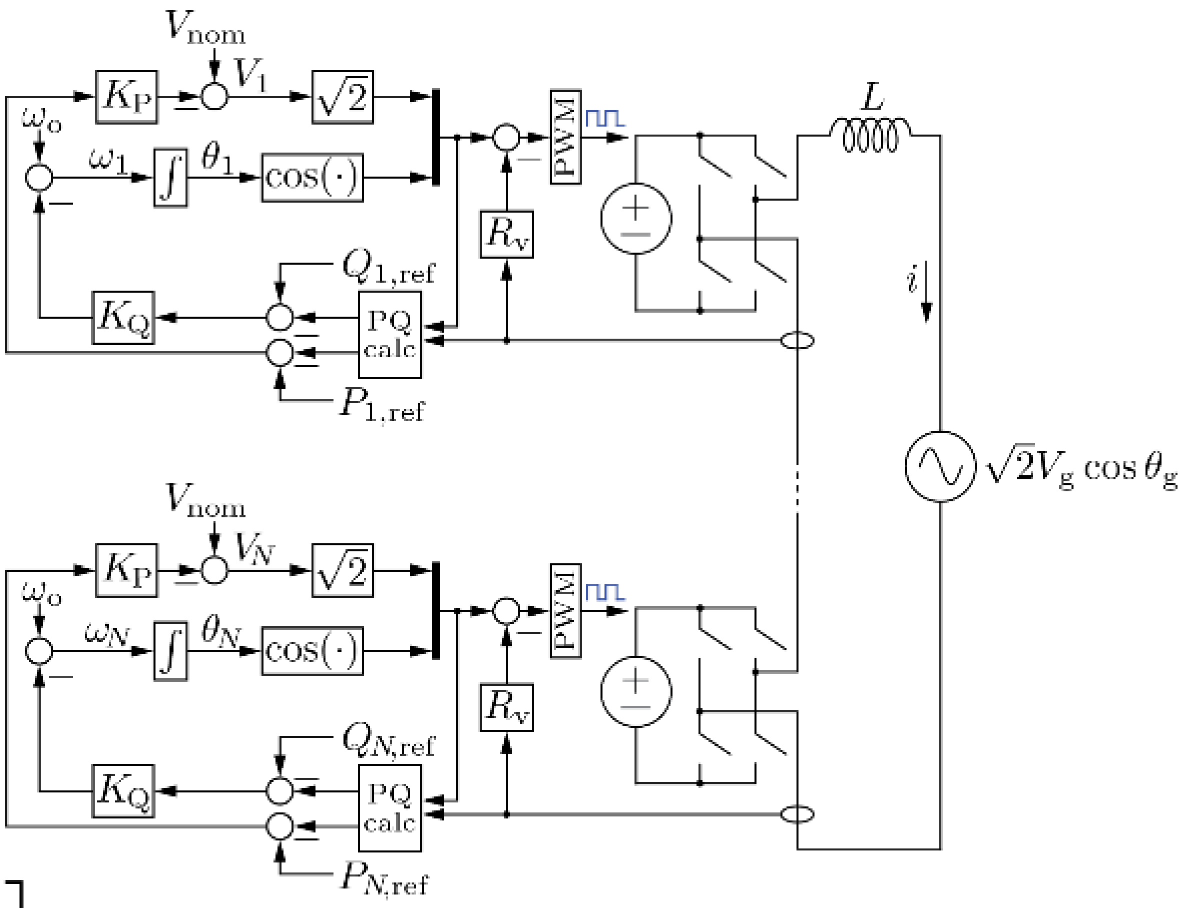
$$\widetilde{Q}_j \approx \frac{V_{j\mathrm{o}}}{Z_\mathrm{f}} \left(\sum_{k \neq j}^{N} V_{k\mathrm{o}} - V_\mathrm{g} \cos\theta_{j\mathrm{go}} \right) \widetilde{\theta}_j - \frac{V_{j\mathrm{o}}}{Z_\mathrm{f}} \sum_{k \neq j}^{N} V_{k\mathrm{o}} \widetilde{\theta}_k,$$

and define the vectors

$$\widetilde{\theta} = \begin{bmatrix} \widetilde{\theta}_1 \\ \vdots \\ \widetilde{\theta}_N \end{bmatrix}, \widetilde{Q} = \begin{bmatrix} \widetilde{Q}_1 \\ \vdots \\ \widetilde{Q}_N \end{bmatrix}, \widetilde{Q}_\mathrm{ref} = \begin{bmatrix} \widetilde{Q}_{1,\mathrm{ref}} \\ \vdots \\ \widetilde{Q}_{N,\mathrm{ref}} \end{bmatrix}.$$

Rewrite Q equation above as $\widetilde{Q} = C\widetilde{\theta}$ where

$$C = \frac{V_\mathrm{g}^2}{Z_\mathrm{f} M^2} \begin{bmatrix} N-1-M\cos\theta_\mathrm{o} & \cdots & -1 \\ \vdots & \ddots & \vdots \\ -1 & \cdots & N-1-M\cos\theta_\mathrm{o} \end{bmatrix}.$$



Small-signal Model for Basic Droop + Thevenin Control

Plug in droop, $\dot{\tilde{\theta}} = K_Q(\tilde{Q} - \tilde{Q}_{\text{ref}})$, and rework as

$$\dot{\tilde{\theta}} = A\tilde{\theta} + B\tilde{Q}_{\text{ref}}.$$

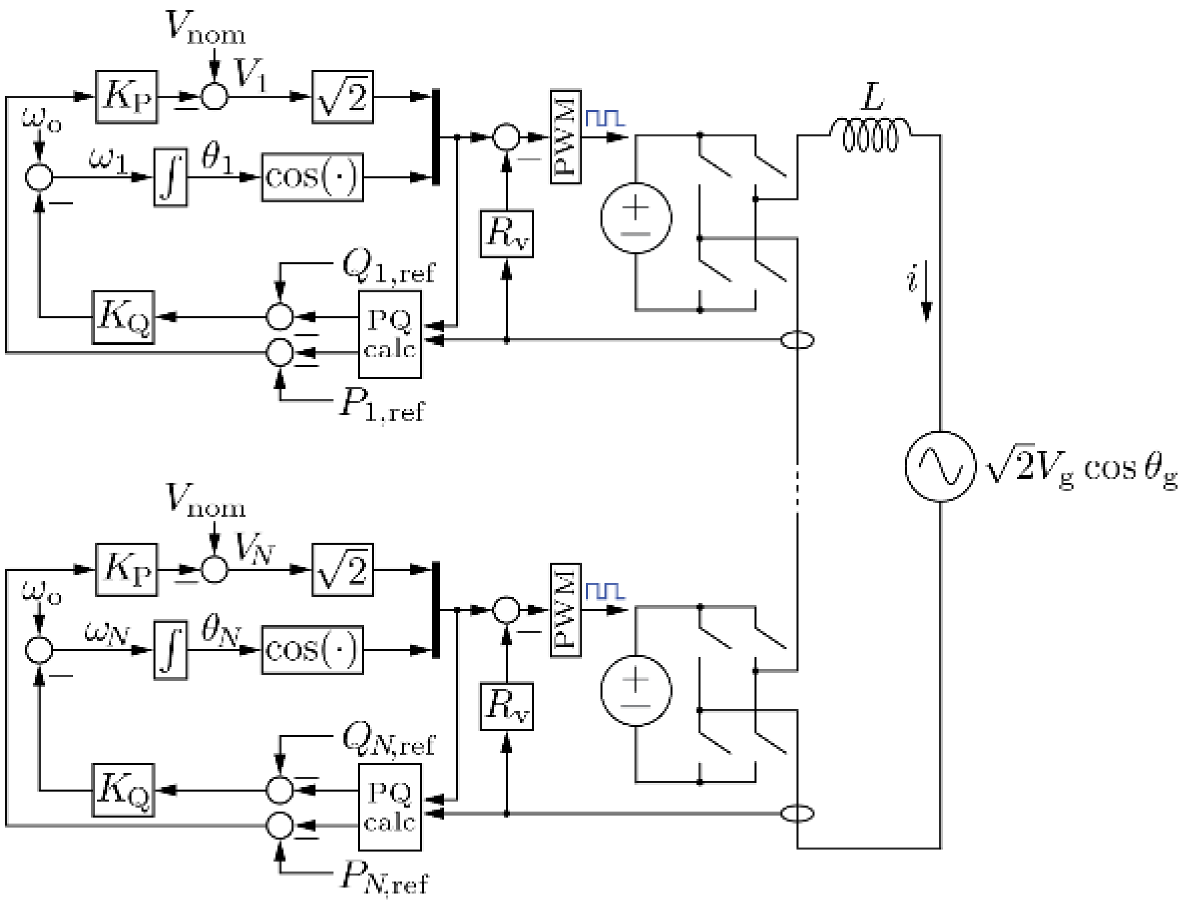
Eigenvalues of A look like

$$\lambda_1(A) = -KM\cos\theta_o,$$
$$\lambda_2(A) = \ldots = \lambda_N(A) = K(N - M\cos\theta_o),$$

where K is a constant. N-1 eigenvalues in LHP when

$$P_j = P_o = \frac{V_g^2}{M^2 Z_f}(N - M) < 0.$$

H bridges may only absorb power. Too restrictive!



New Controller with Basic Droop + Thevenin Control + State-Feedback

Use pole-placement method to stabilize system.

Rejigger $\dot{\widetilde{\theta}} = A\widetilde{\theta} + B\widetilde{Q}_{\mathrm{ref}}$ as $\dot{\widetilde{\theta}} = (A+F)\widetilde{\theta} + B\widetilde{Q}^{\star}$,

where $\widetilde{Q}_{\mathrm{ref}} = \widetilde{Q}^{\star} + (k_{\mathrm{q}}/K_{\mathrm{Q}})\widetilde{\theta}$ now gives the setpoint.

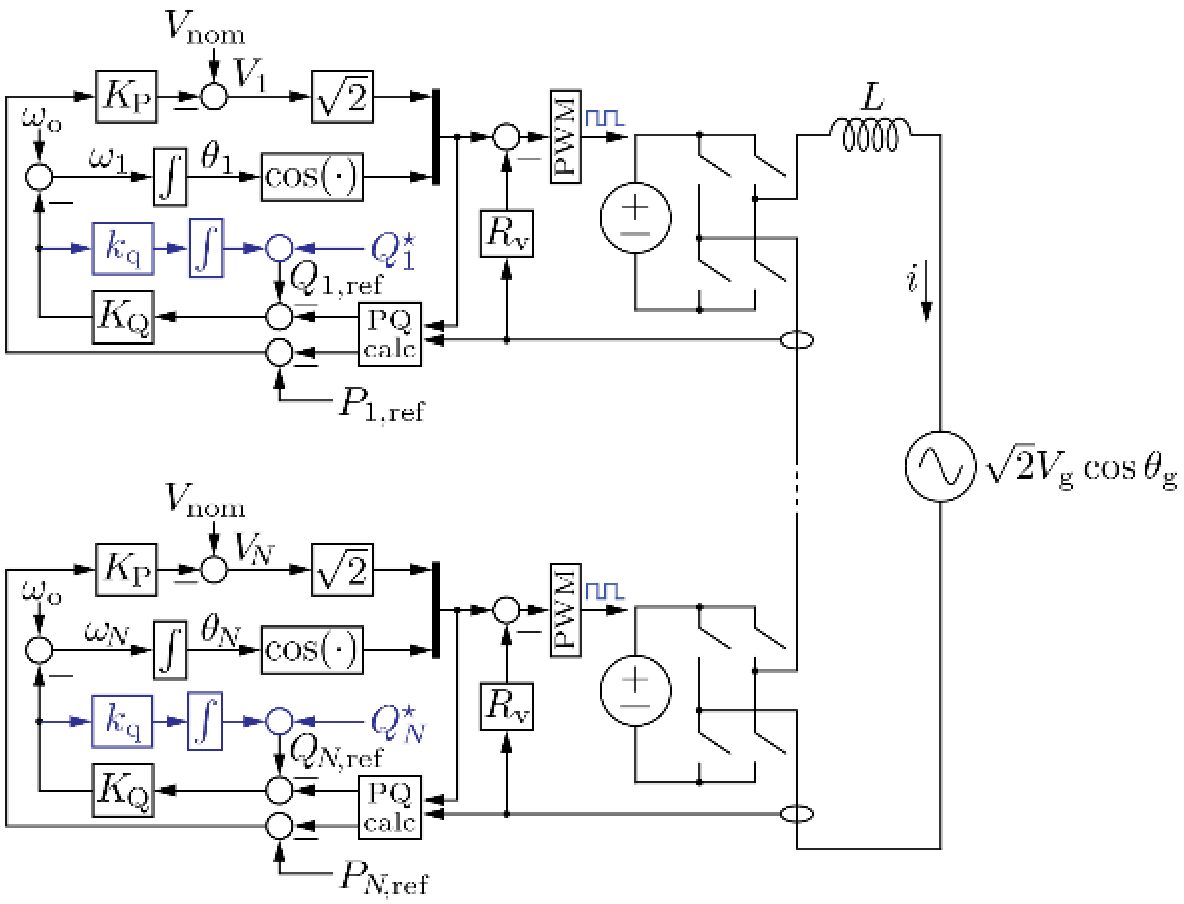
Choose diagonal F for decentralized implementation

$$F = -\frac{k_{\mathrm{q}}}{K_{\mathrm{Q}}}\begin{bmatrix} 1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & 1 \end{bmatrix}$$

New eigenvalues look like

$$\lambda_1(A) = -k_{\mathrm{q}} - KM\cos\theta_{\mathrm{o}},$$
$$\lambda_2(A) = \ldots = \lambda_N(A) = KN - k_{\mathrm{q}} - M\cos\theta_{\mathrm{o}},$$

Straightforward to pick stabilizing k_{q}. See [1] for details.

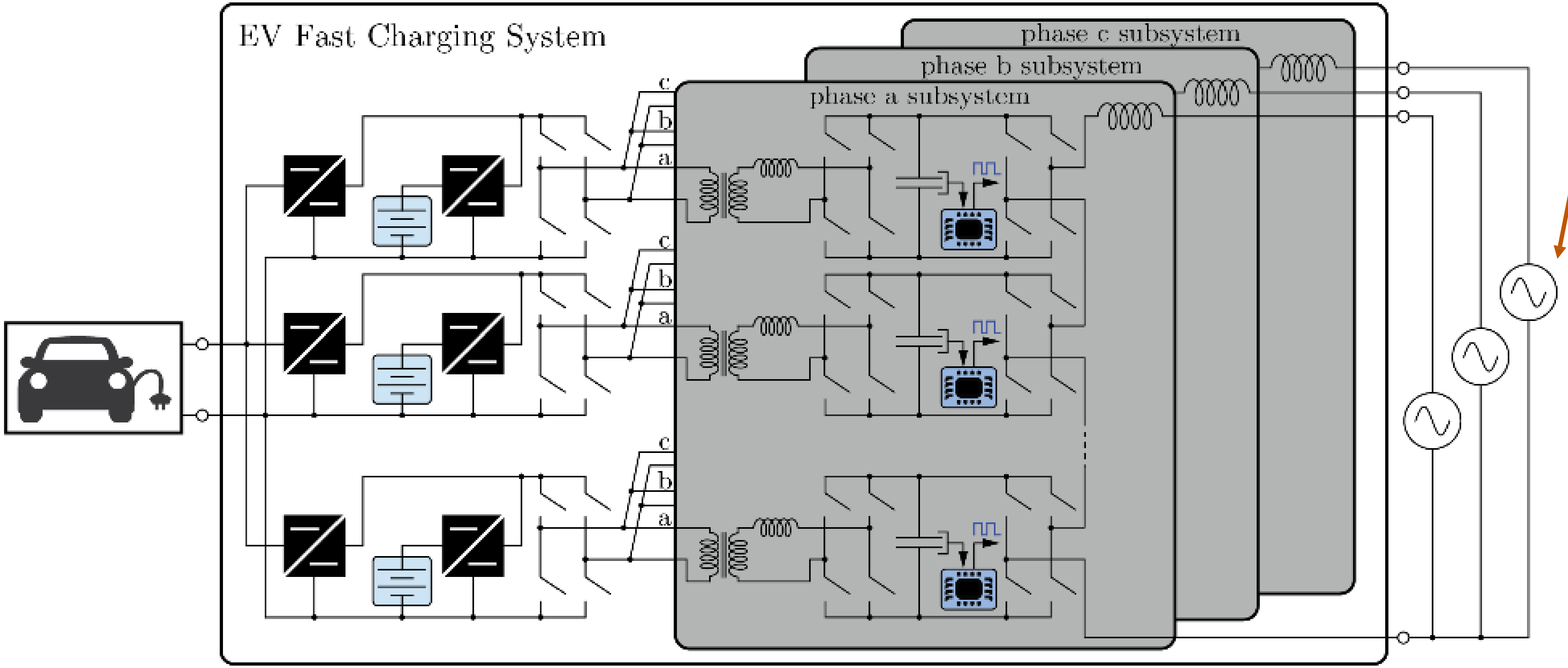


[1] Dutta, Lu, Mallik, Majmunovic, Mukherjee, Seo, Maksimovic, Johnson, "Decentralized control of cascaded H-bridge inverters for medium-voltage grid integration," COMPEL, 2020

Example Application

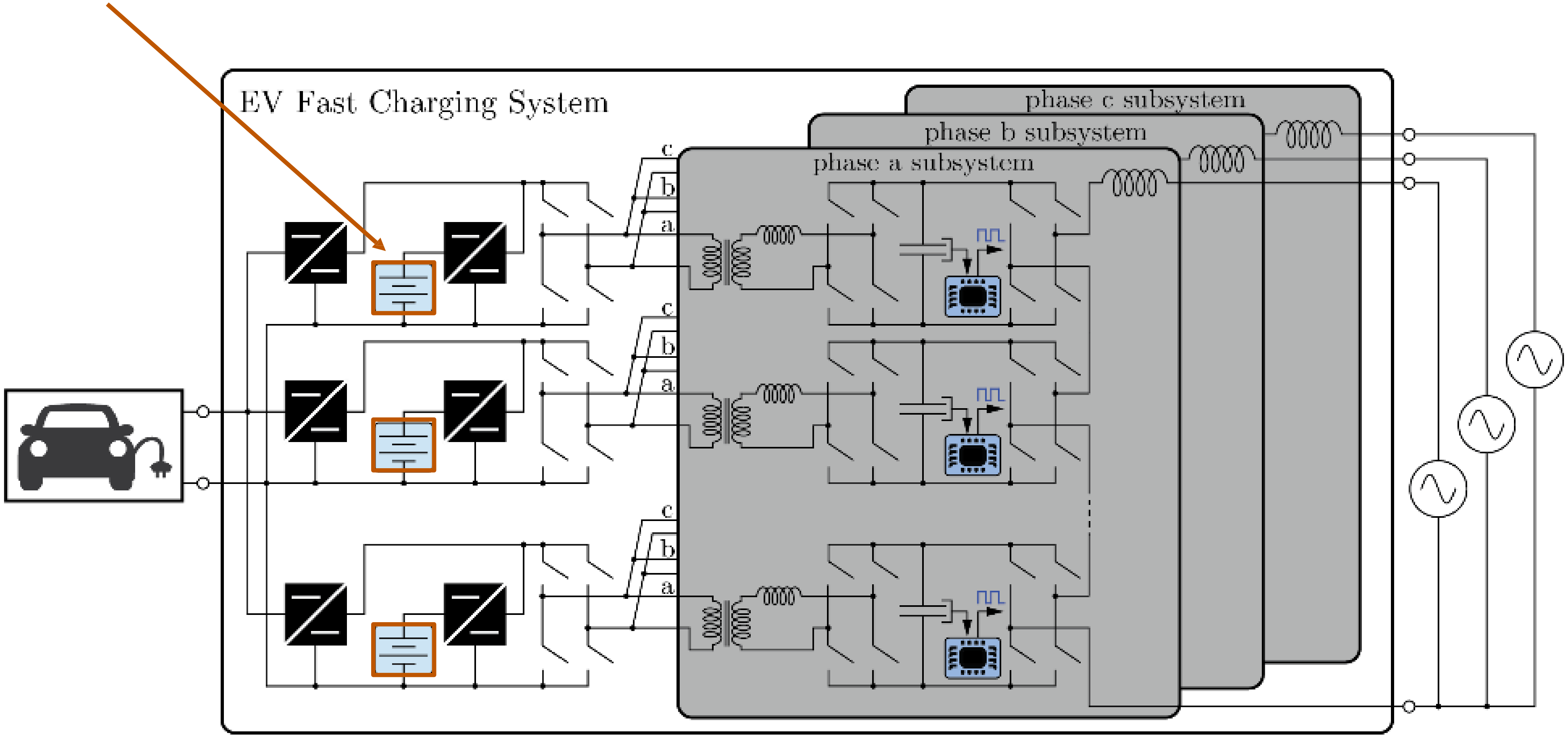
Proposed EV Fast-charging System With Grid Support Functions

- Direct medium-voltage interconnection



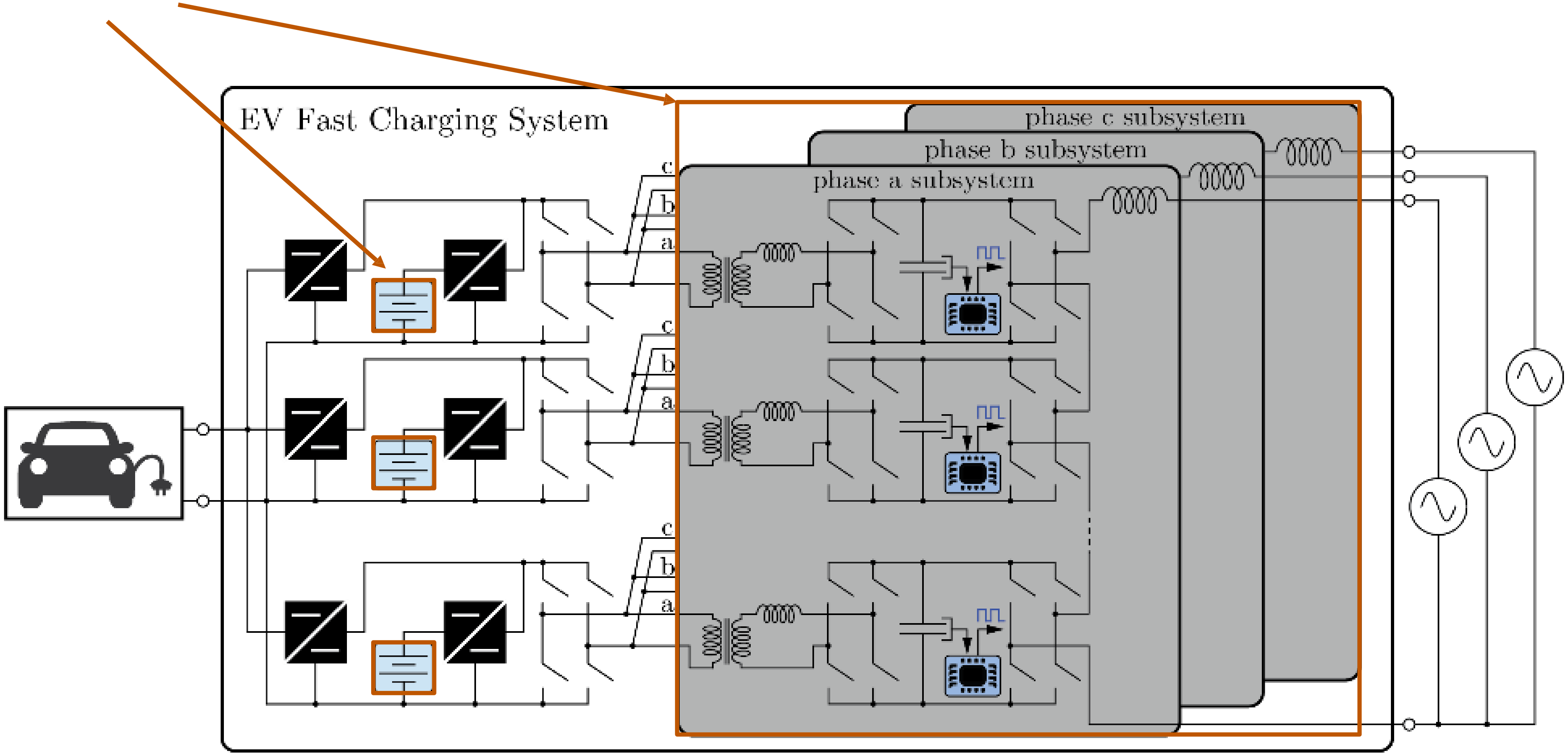
Proposed EV Fast-charging System With Grid Support Functions

- Distributed stationary storage to smooth out grid-side demand & reduce distribution capacity



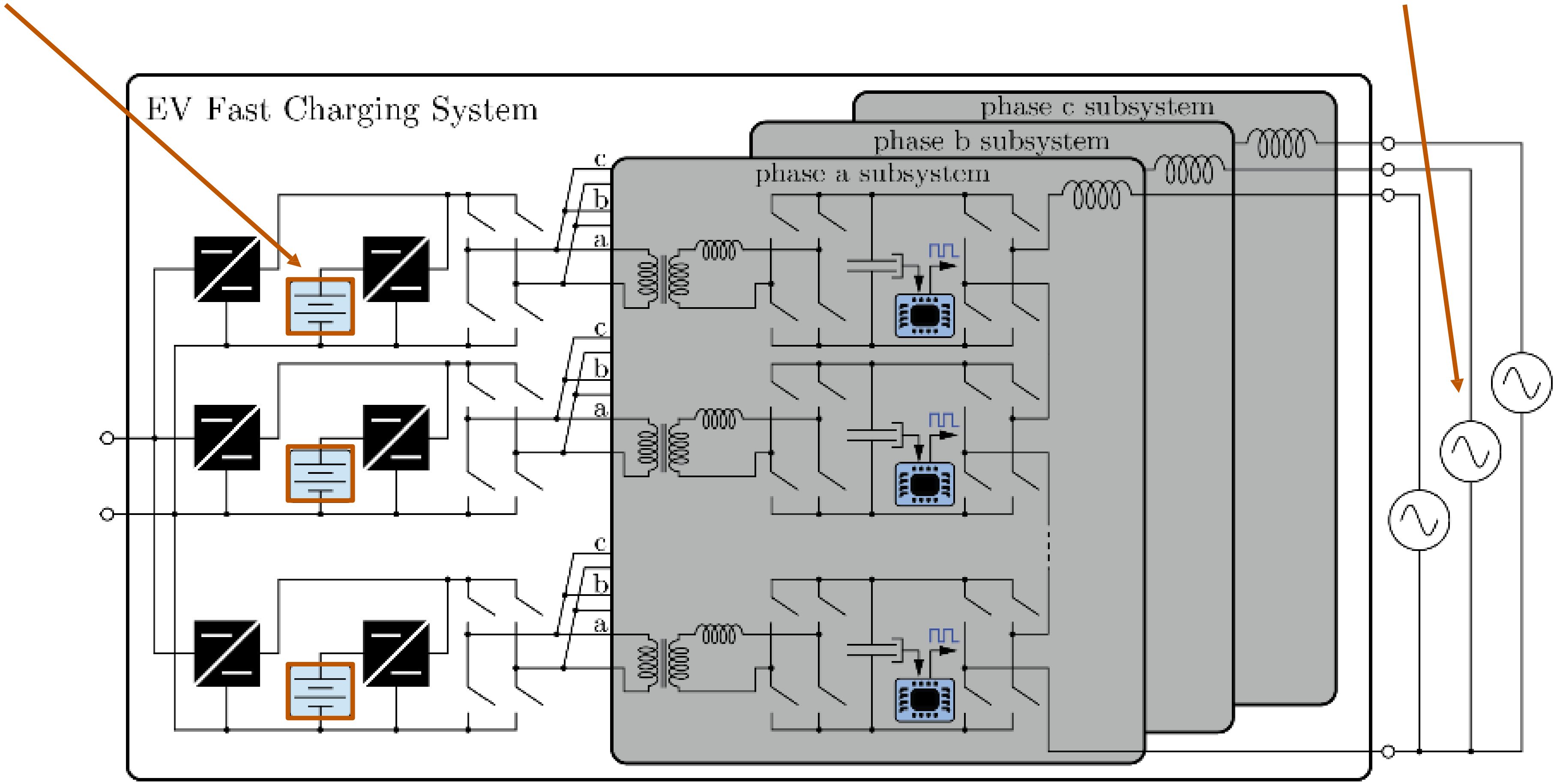
Proposed EV Fast-charging System With Grid Support Functions

- Dc and ac side controls work together and mimic power low pass filter from grid perspective



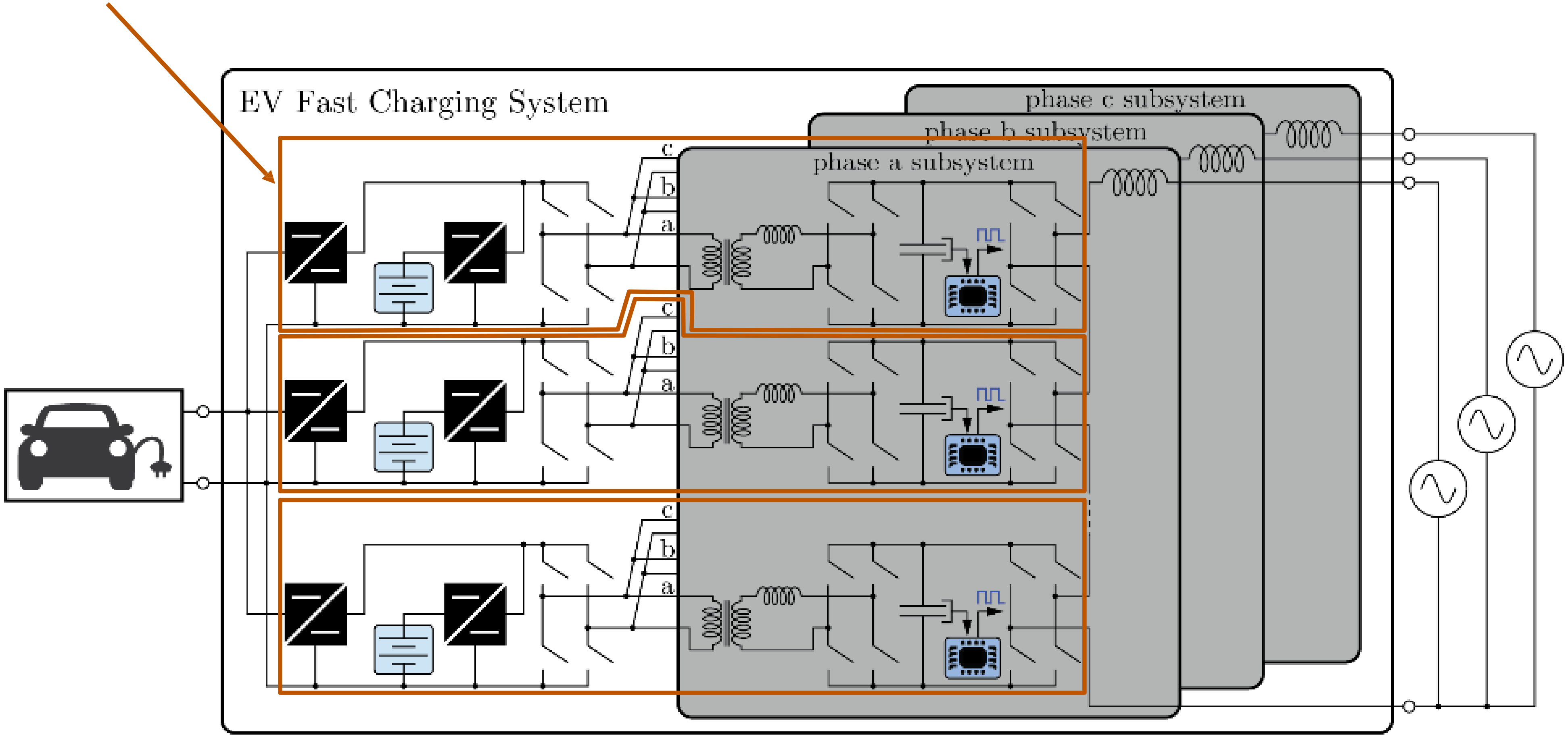
Proposed EV Fast-charging System With Grid Support Functions

- Distributed stationary storage to provide real/reactive power to support grid



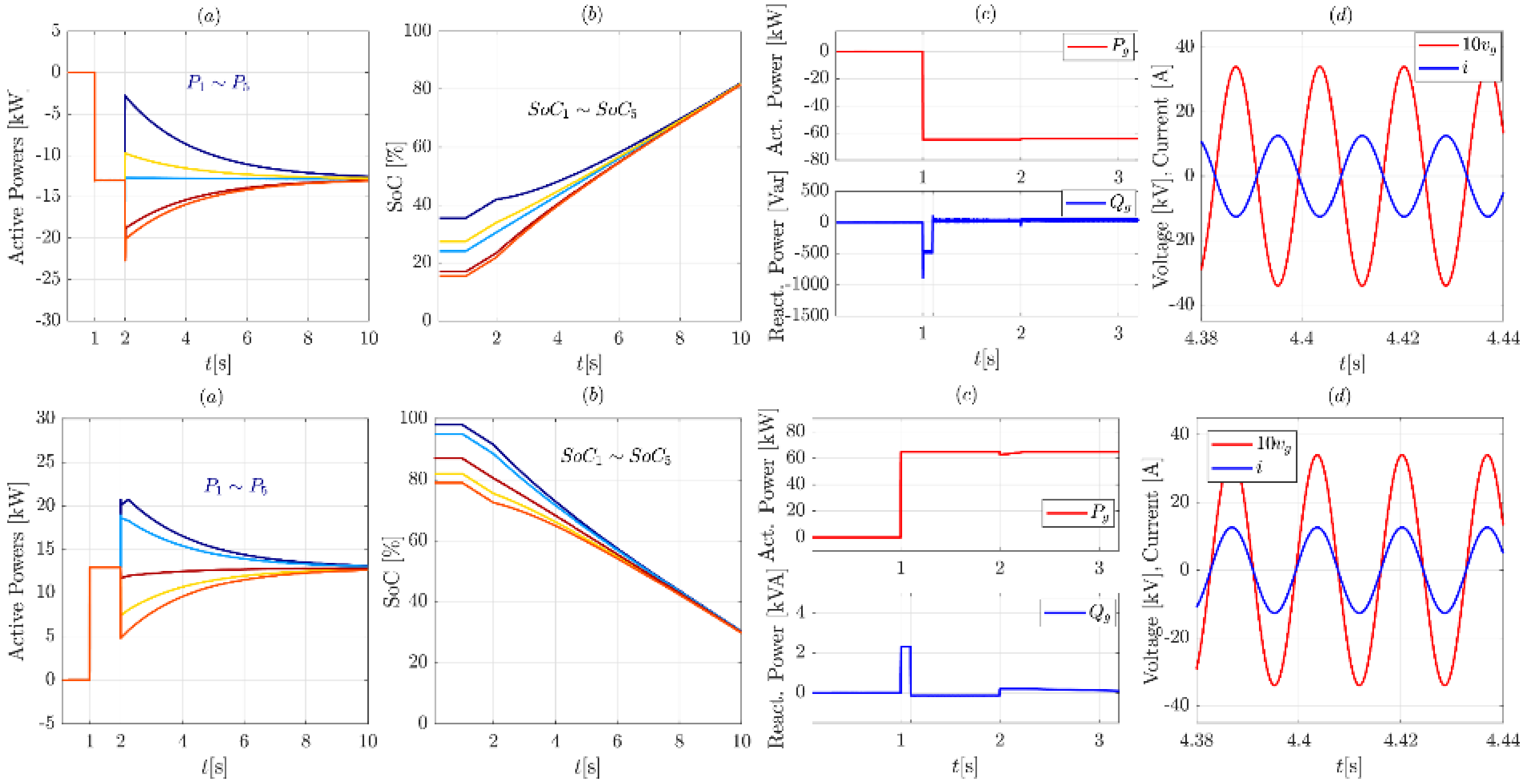
Proposed EV Fast-charging System With Grid Support Functions

- Modular physical structure and with mostly decentralized controls



Simulation of EV Fast-charging System

- Automatic battery balancing controls while charging/discharging stationary storage
- 5 units in series across 4.16 kV grid with total rating of 100 kVA



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3. Majmunović, Mukherjee, Martin, Mallik, Dutta, Seo, Johnson, Maksimović, Dragan, "1 kV, 10-kW SiC-based quadruple active bridge DCX stage in a DC to three-phase AC module for medium-voltage grid integration" TPEL, 2022.
4. Dutta, Lu, Majmunović, Mallik, Seo, Maksimović, Johnson, "Grid-connected self-synchronizing cascaded H-bridge inverters with autonomous power sharing" ECCE, 2021.
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Thanks for your attention!

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