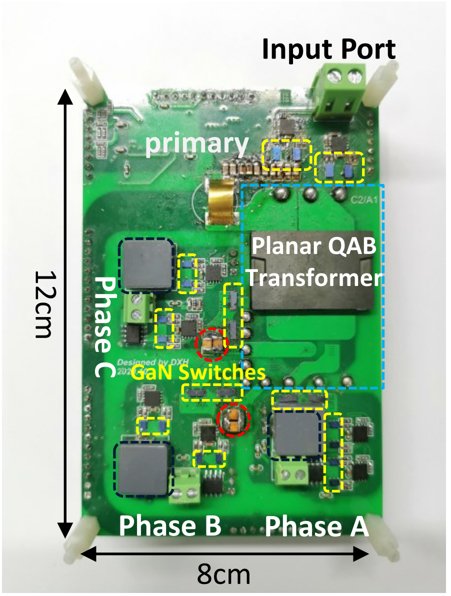
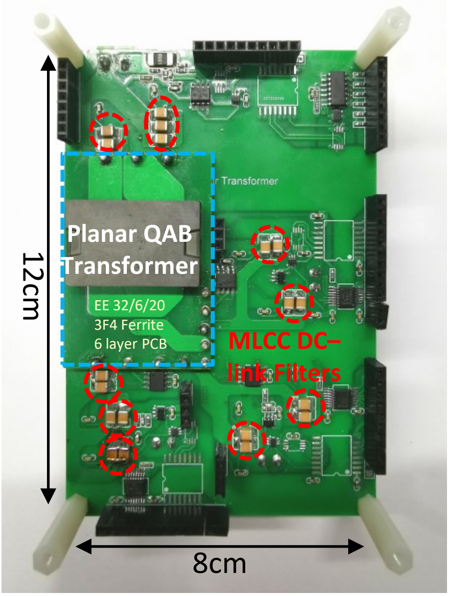
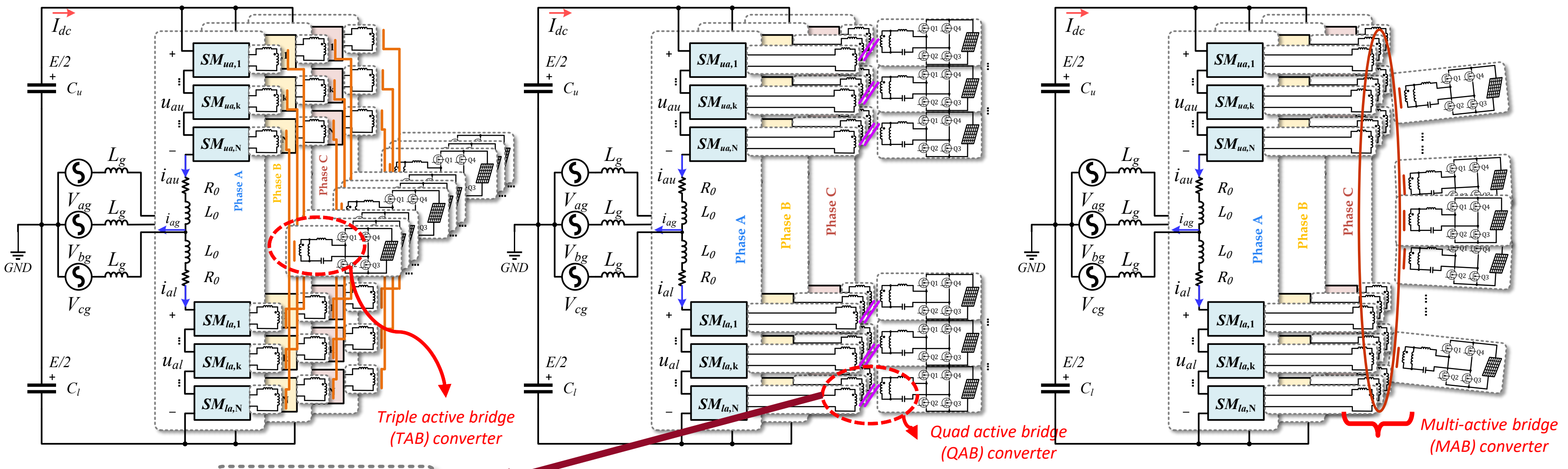
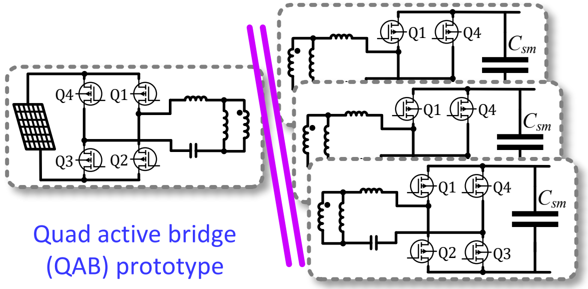
Research #2: Three-phase MMC PV inverter with Multi-Active Bridge

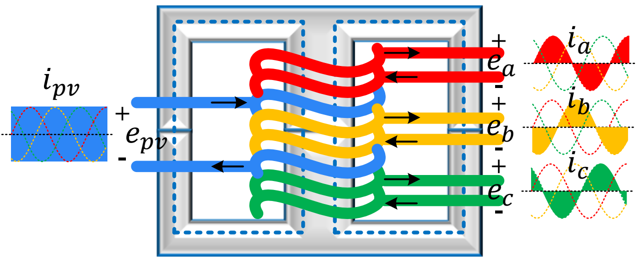




Magnetic Coupled Multilevel-modular Converter (MMC)

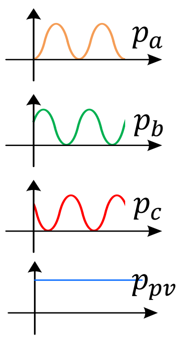






$$\begin{cases} p_a = P_a - p_{a2\omega} = \frac{UI}{2}[\cos\varphi - \cos(2\omega t - \beta)] = P_{p,a} - P_{a,b} + P_{c,a} \\ p_b = P_b - p_{b2\omega} = \frac{UI}{2}\left[\cos\varphi - \cos\left(2\omega t - \beta + \frac{2}{3}\pi\right)\right] = P_{p,b} + P_{a,b} - P_{b,c} \\ p_c = P_c - p_{c2\omega} = \frac{UI}{2}\left[\cos\varphi - \cos\left(2\omega t - \beta - \frac{2}{3}\pi\right)\right] = P_{p,c} + P_{b,c} - P_{c,a} \end{cases}$$

$$p_{pv} = p_a + p_b + p_c = \frac{3}{2}UI$$



- The fundamental and 2nd order harmonic frequency current components in the arm current are 120° phase shifted in three phases.
- From the perspective of instantaneous power, the constant PV power can be inherently distributed to three phases without power fluctuation.

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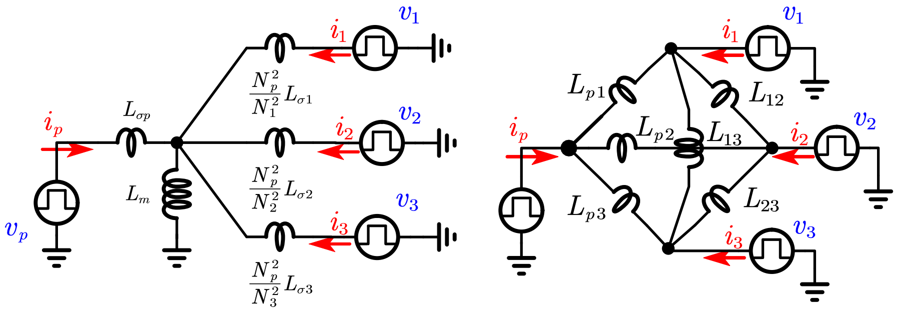
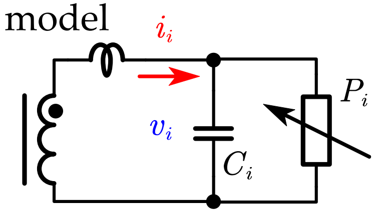
QAB model



$$I_i = \frac{-\sum_{j=1}^{n} P_{ij}}{V_i} = \sum_{j=1}^{n} \frac{V_j}{4fL_{ij}} d_{ij}(|d_{ij}|-1)$$

$$\hat{i}_i = \sum_{j=i}^{n} G_v(i,j)\hat{v}_j + \sum_{j=1}^{n} G_d(i,j)\hat{d}_j$$

Submodule model



$$i_i = \frac{v_i}{1/s\,C_i} + \frac{P_i}{v_i}(nonlinear\ constant\ power\ load)$$

$$i_i = \frac{V_i}{1/s\,C_i} + \frac{P_i}{V_{dc}} + \frac{P_i}{-V_{idc}^2}(v_i - V_{idc})(fourier\ expansion)$$

$$\hat{i}_i = \left(\frac{1}{1/s\,C_i} - \frac{P_i}{V_{idc}^2}\right)\hat{v}_i$$

Negative Resistance

Small-signal dynamics

$$G_v = \begin{bmatrix} 0 & \cdots & \frac{d_{1j}}{4fL_{1j}}(|d_{1j}|-1) & \cdots & \frac{d_{1j}}{4fL_{1j}}(|d_{1n}|-1) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{d_{i1}}{4fL_{i1}}(|d_{i1}|-1) & \cdots & \frac{d_{ij}}{4fL_{ij}}(|d_{ij}|-1)\ \forall[i\neq j] & \cdots & \frac{d_{ij}}{4fL_{in}}(|d_{in}|-1) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{d_{ij}}{4fL_{n1}}(|d_{n1}|-1) & \cdots & \frac{d_{ij}}{4fL_{nj}}(|d_{ij}|-1) & \cdots & 0 \end{bmatrix}$$

$$G_d = \begin{bmatrix} \sum_{k\neq 1} \frac{V_k}{4fL_{1k}}(2|d_{1k}|-1) & \cdots & \frac{V_j}{4fL_{1j}}(1-2|d_{1i}|) & \cdots & \frac{V_n}{4fL_{1n}}(1-2|d_{1n}|) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{V_i}{4fL_{i1}}(1-2|d_{i1}|) & \cdots & \frac{V_j}{4fL_{ij}}(1-2|d_{ij}|)\ \forall[i\neq j] & \cdots & \frac{V_n}{4fL_{in}}(1-2|d_{in}|) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \frac{V_i}{4fL_{n1}}(1-2|d_{n1}|) & \cdots & \frac{V_j}{4fL_{ni}}(1-2|d_{ni}|) & \cdots & \sum_{k\neq n} \frac{V_k}{4fL_{nk}}(2|d_{nk}|-1) \end{bmatrix}$$

$$G_z = G_v = diag\left[1/(\frac{1}{1/sC_1} - \frac{P_1}{V_{1dc}^2}) \ \cdots \ 1/(\frac{1}{1/sC_i} - \frac{P_i}{V_{idc}^2}) \ \cdots \ 1/(\frac{1}{1/sC_n} - \frac{P_n}{V_{ndc}^2})\right]$$

$$\begin{cases} \hat{i} = G_v \times \hat{v} + G_d \times \hat{d}, \\ \hat{v} = G_z \times \hat{i}. \end{cases}$$

$$\hat{v} = G_Z(I - G_v G_Z)^{-1} G_d \times \hat{d} = G_S \times \hat{d}$$

$$G_v(i,j) = \frac{d_{ij}}{4fL_{ij}}(|d_{ij}|-1)$$

$$G_d(i,j) = \begin{cases} \frac{V_j}{4fL_{ij}}(1-2|d_{ij}|) & j \neq i, \\ \sum_{k\neq i} \frac{V_k}{4fL_{ik}}(2|d_{ik}|-1) & j = i. \end{cases}$$

With system transfer function $G_S(s)$, it is possible to design the control system with power decoupling function to trace each phase power.

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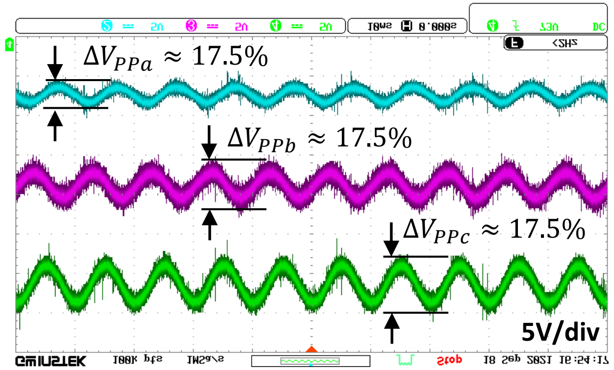
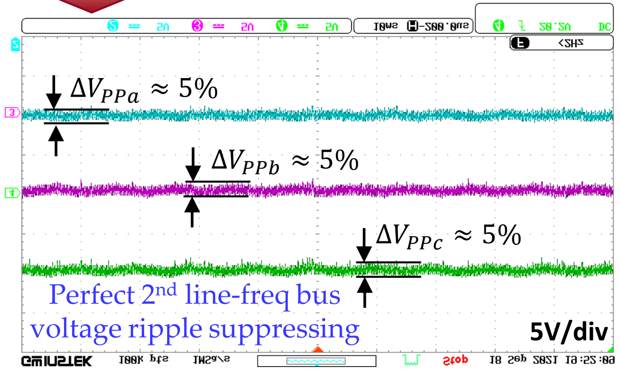
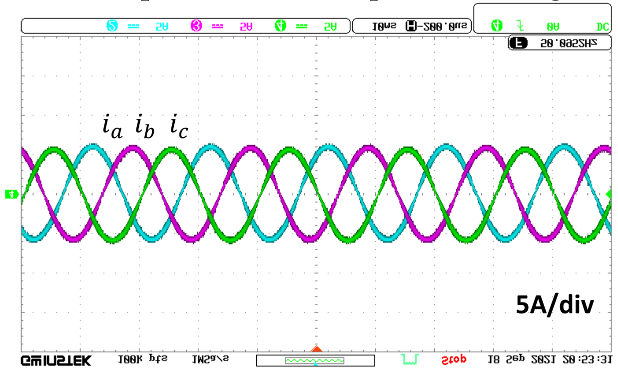


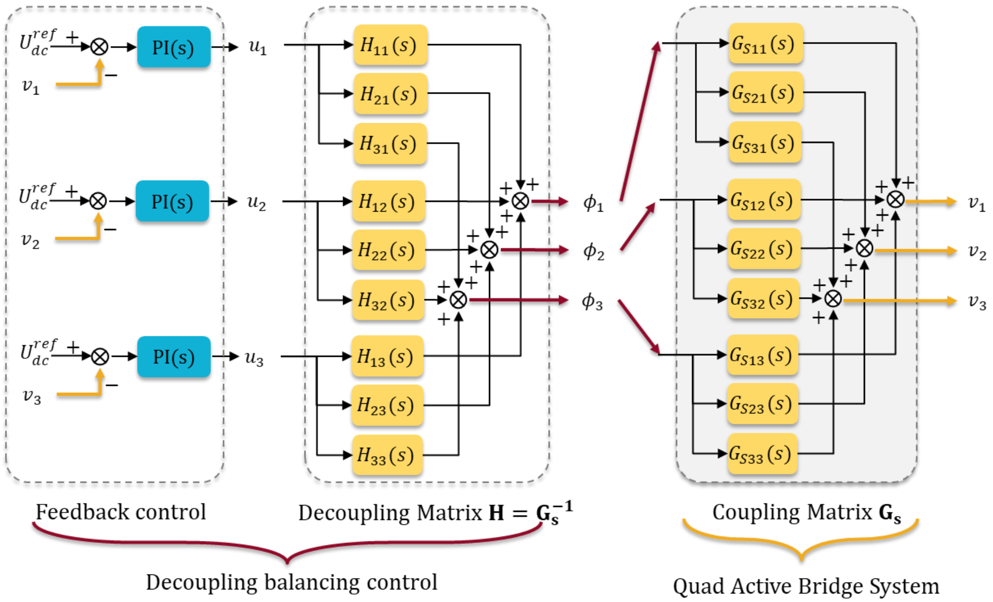
Enable QAB active phase-shift



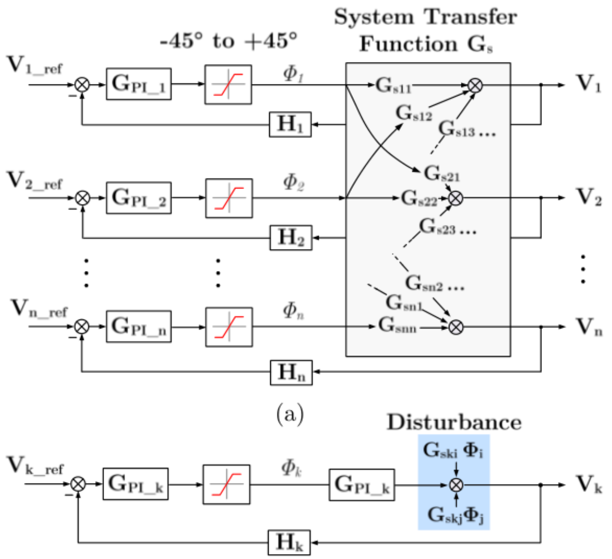
Three-phase dc-link capacitor voltage



Three-phase inverted grid current



Proposed decoupling phase-shifting control



Traditional coupled phase-shifting control

- Compared with non-phase shift QAB, the applying of voltage balancing phase shift have perfect 2nd line-frequency voltage ripple reduction.
- The decoupling is implemented by adopting inverse matrix of the system dynamic model $G_s(s)$, but the choice of decoupling matrix is not unique.
- Compared with traditional MAB coupled phase-shifting balancing control, the proposed decoupling phase shift control has perfect power distribution on each phase with desired inverted grid current.