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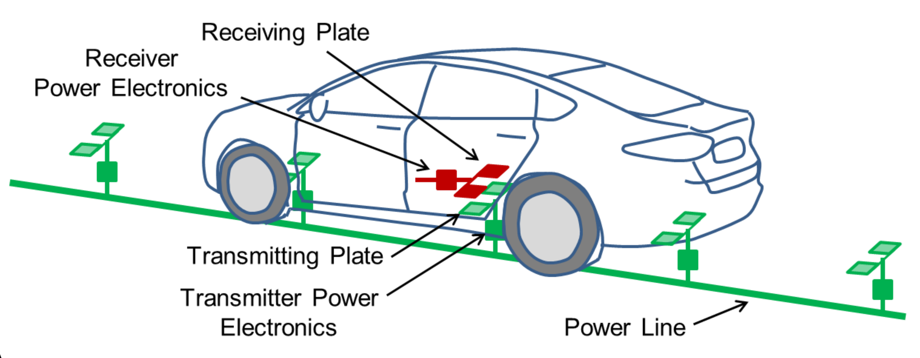
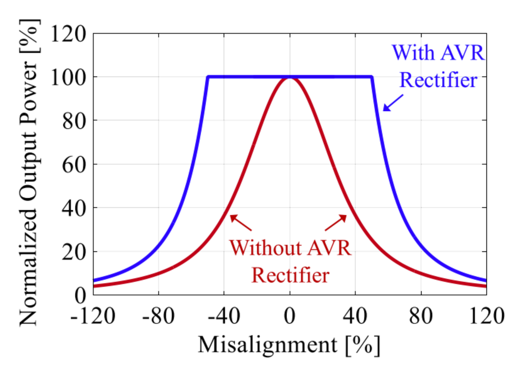
Full State Feedback Controller for Dynamic Capacitive Wireless Power Transfer Systems

Ben Liao, Sophia Lin, Dheeraj Etta, Khurram K. Afridi

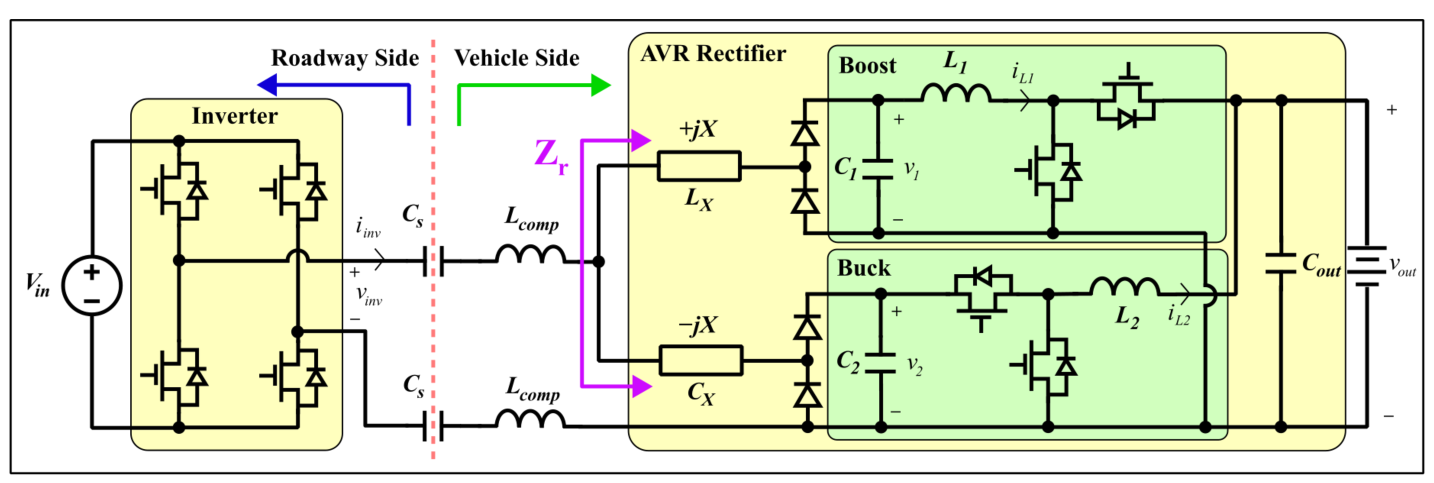
Motivation

- For wireless power transfer (WPT) systems:
  - **Capacitive**: cheaper, lighter, more robust
  - **Dynamic**: infinite range, zero down-time, small batteries
- Must compensate high-Q resonant systems for misalignment-induced variation in coupling capacitance
- Active Variable Reactance (AVR) rectifier has these properties

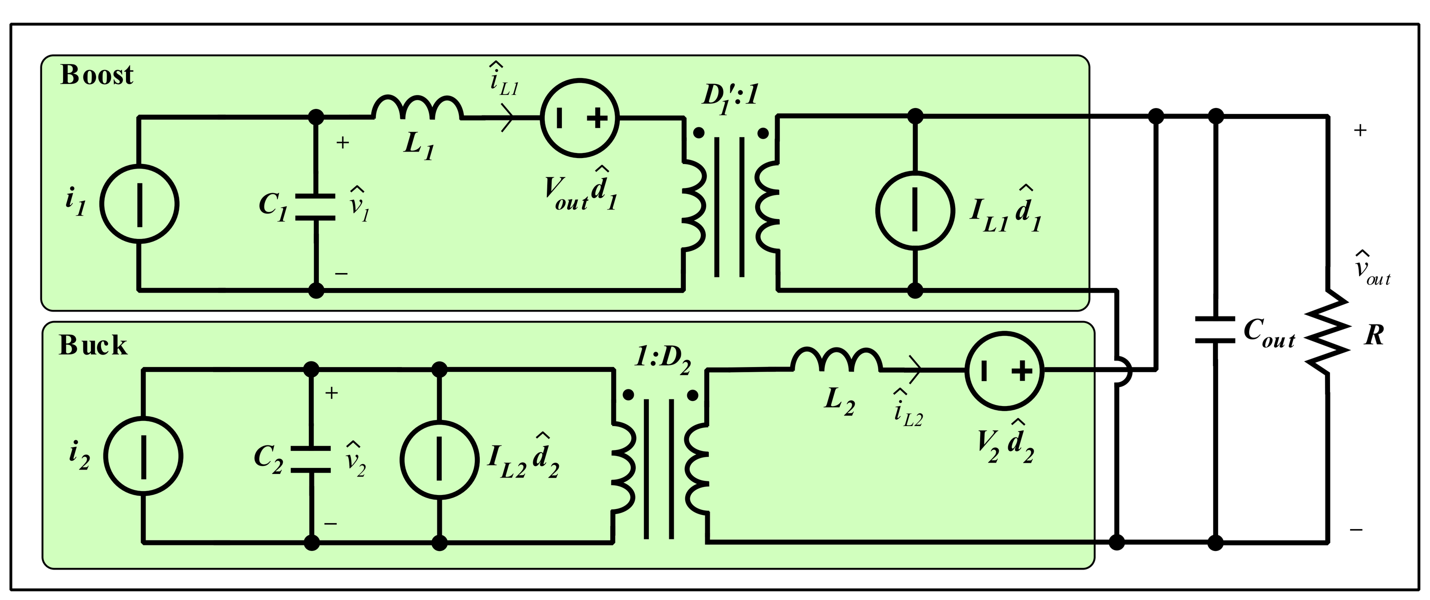




AVR Rectifier



- Provides continuously variable reactance while operating inverter at a fixed frequency
- Maintains constant output power and soft-switching of the inverter

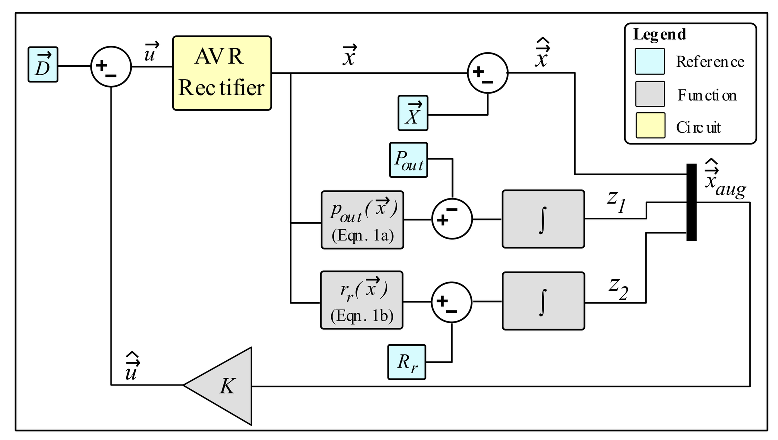


Linearized small-signal model of AVR rectifier

$$
\frac{d}{dt}\begin{bmatrix}\hat{v}_{out}\\ \hat{v}_1\\ \hat{v}_2\\ \hat{i}_{L1}\\ \hat{i}_{L2}\\ z_1\\ z_2\end{bmatrix} = \begin{bmatrix}
-\frac{1}{RC_{out}} & 0 & 0 & \frac{D_1'}{C_{out}} & \frac{1}{C_{out}} & 0 & 0\\
0 & 0 & 0 & -\frac{1}{C_1} & 0 & 0 & 0\\
0 & 0 & 0 & 0 & -\frac{D_2}{C_2} & 0 & 0\\
-\frac{D_1'}{L_1} & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0\\
-\frac{1}{L_2} & 0 & \frac{D_2}{L_2} & 0 & 0 & 0 & 0\\
-\frac{\partial p_{out}}{\partial v_{out}} & -\frac{\partial p_{out}}{\partial v_1} & -\frac{\partial p_{out}}{\partial v_2} & -\frac{\partial p_{out}}{\partial i_{L1}} & -\frac{\partial p_{out}}{\partial i_{L2}} & 0 & 0\\
-\frac{\partial r_r}{\partial v_{out}} & -\frac{\partial r_r}{\partial v_1} & -\frac{\partial r_r}{\partial v_2} & -\frac{\partial r_r}{\partial i_{L1}} & -\frac{\partial r_r}{\partial i_{L2}} & 0 & 0
\end{bmatrix}\begin{bmatrix}\hat{v}_{out}\\ \hat{v}_1\\ \hat{v}_2\\ \hat{i}_{L1}\\ \hat{i}_{L2}\\ z_1\\ z_2\end{bmatrix} + \begin{bmatrix}
-\frac{I_{L1}}{C_{out}} & 0\\
0 & 0\\
0 & -\frac{I_{L2}}{C_2}\\
\frac{V_{out}}{L_1} & 0\\
0 & \frac{V_2}{L_2}\\
0 & 0\\
0 & 0
\end{bmatrix}\begin{bmatrix}\hat{d}_1\\ \hat{d}_2\end{bmatrix}
$$

Augmented state-space model of AVR rectifier

Full State Feedback Controller



$$\vec{x} = \begin{bmatrix}V_{out}\\ V_1\\ V_2\\ I_{L1}\\ I_{L2}\end{bmatrix}$$

$\vec{X}$ = nominal values of $\vec{x}$

$$\hat{\vec{x}}_{aug} = \begin{bmatrix}\hat{\vec{X}}\\ z_1\\ z_2\end{bmatrix}$$

P_{out} = nominal P_{out}

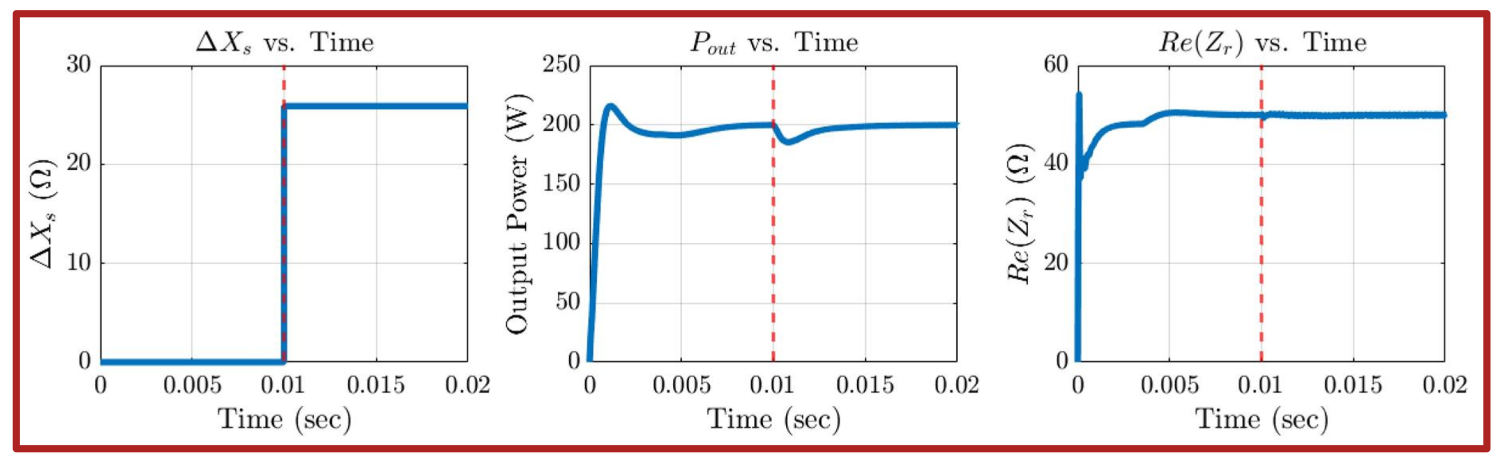
R_r = nominal $Re(Z_r)$

K = LQR gains

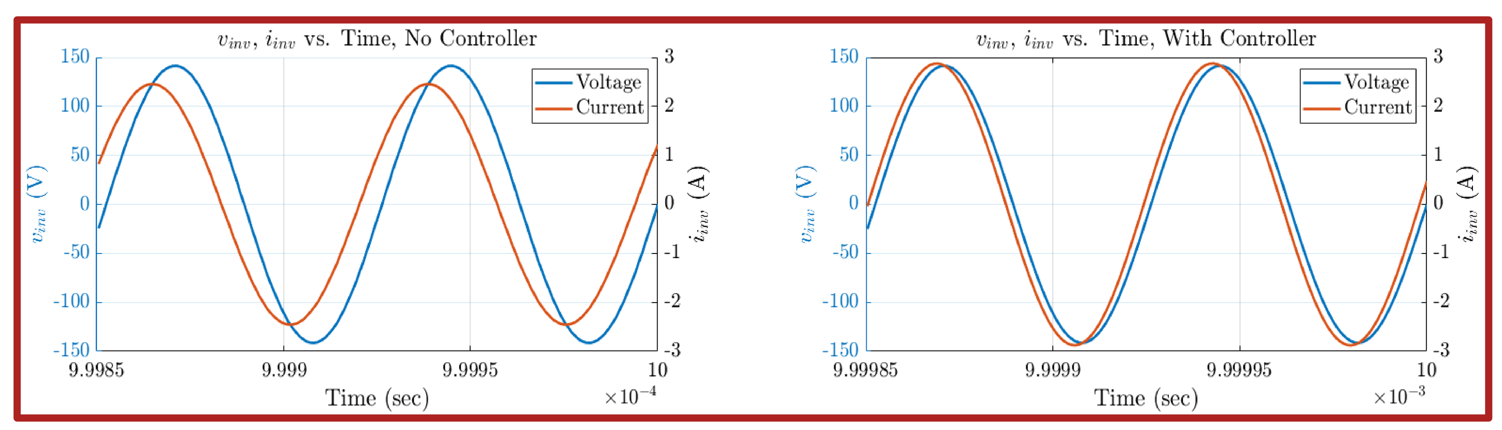
$\hat{\vec{u}} = K * \hat{\vec{x}}_{aug}$

$\vec{D} = \begin{bmatrix}1\\ 1\end{bmatrix}$

$\vec{u} = \begin{bmatrix}D_{Boost}\\ D_{Buck}\end{bmatrix}$

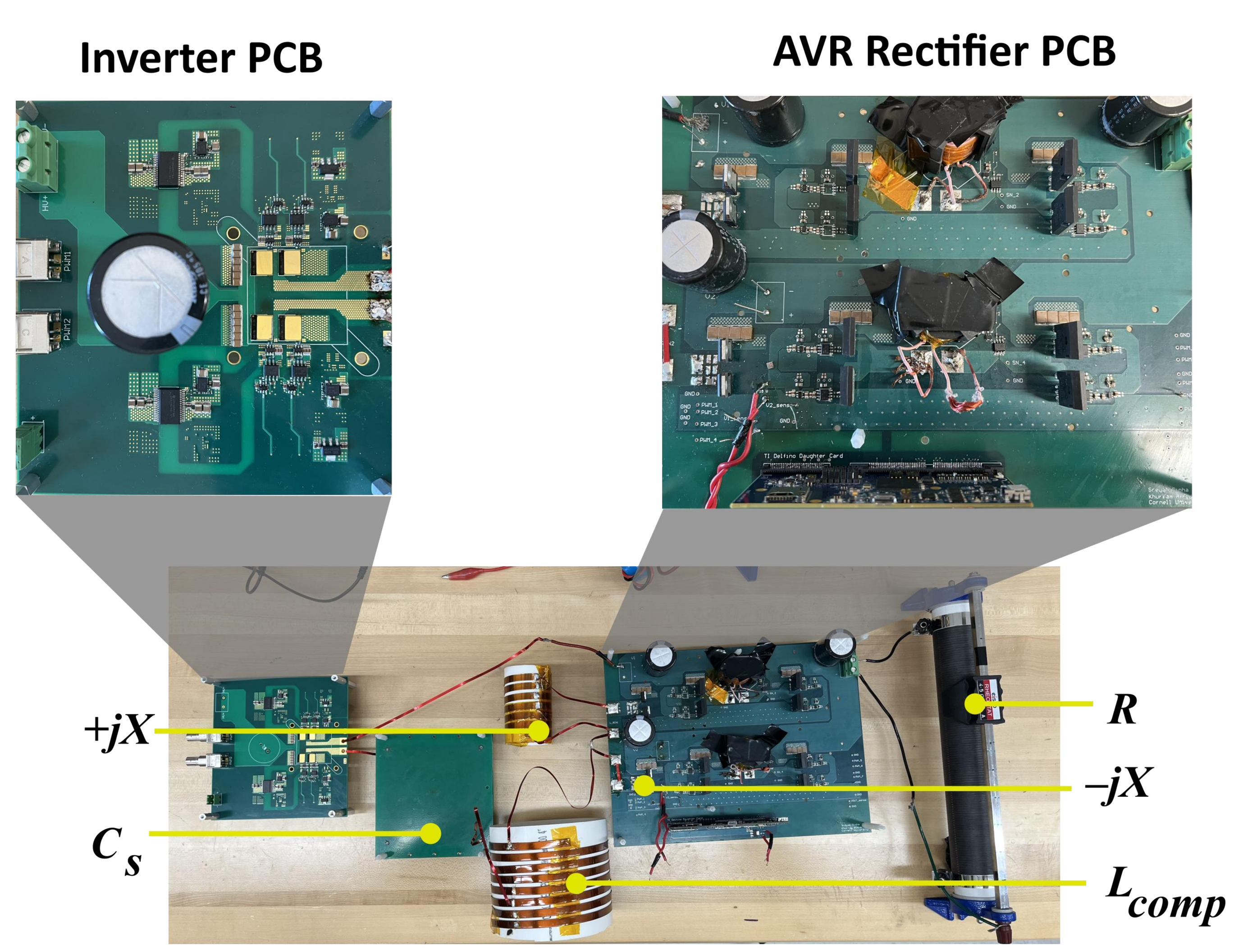


P_{out} and $Re(Z_r)$ Step Response

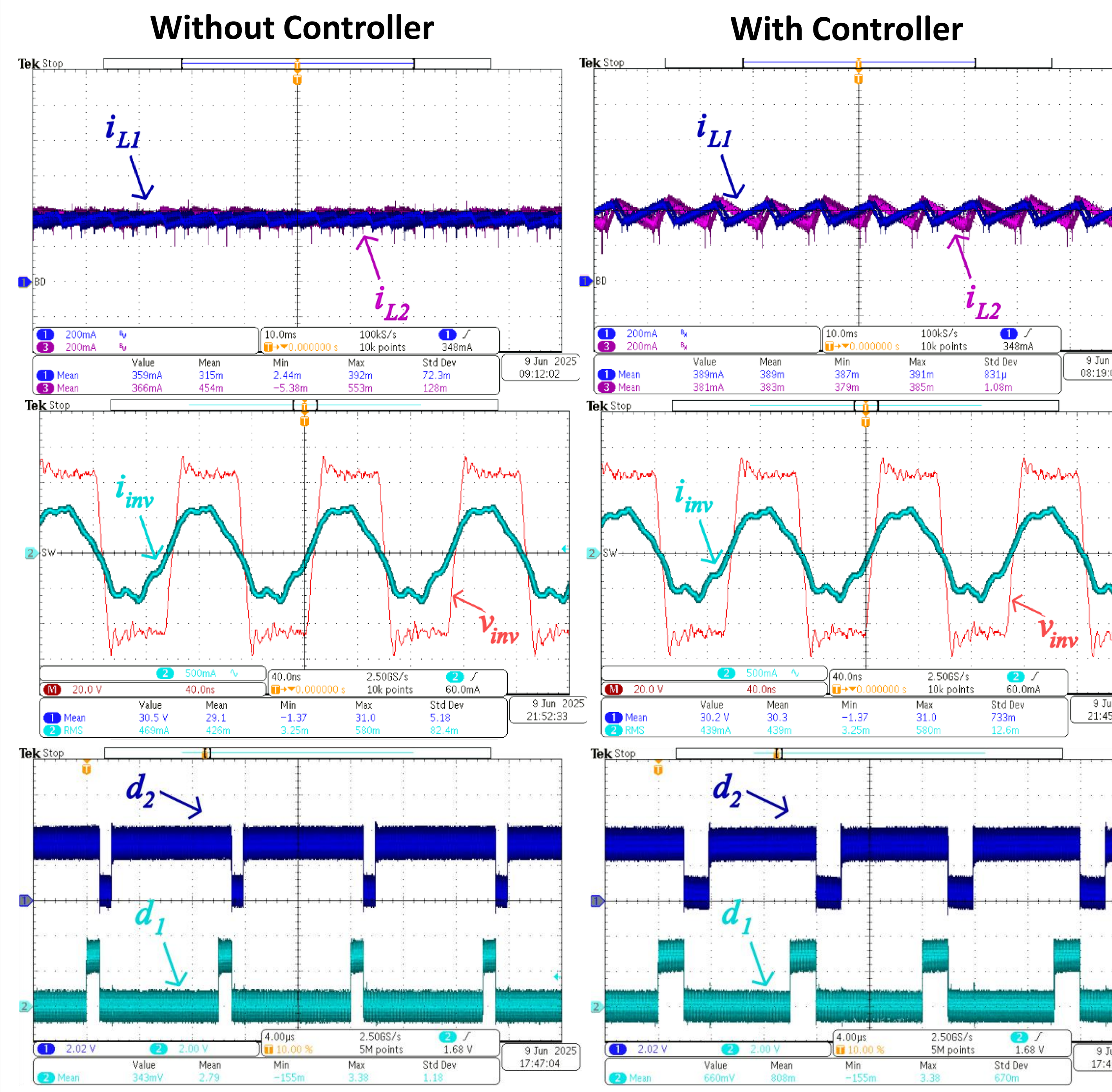


Phase shift between v_{inv} and i_{inv}

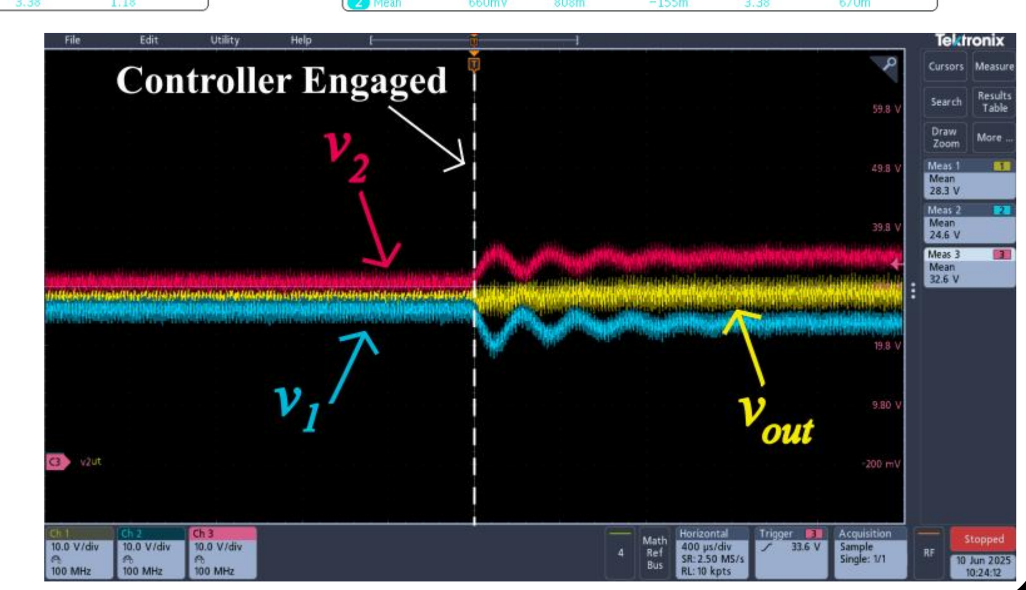
Hardware Prototype



Results



Voltage transients ~1ms settling time



Summary and Conclusions

- In dynamic settings, capacitive WPT systems will have variation in coupling capacitance, resulting in reduced overall power transfer
- AVR rectifier can be used to transfer nominal power at high efficiencies across changes in coupling capacitance
- Full-state feedback controller can adjust the duty ratios of the two dc-dc converters to regulate output power and enable ZVS
- Series-L-compensated capacitive WPT system with full-state feedback controller is tested in simulation
- 60 V, 25 W prototype used to validate proposed controller

Selected References

[1] S. Maji, D. Etta, and K. K. Afridi, “A high-power large air-gap multi-mhz dc-dc capacitive wireless power transfer system for electric vehicle charging,” in *2023 IEEE Wireless Power Technology Conference and Expo (WPTCE)*, pp. 1–6, 2023.

[2] S. Sinha, A. Kumar, B. Regensburger, and K. K. Afridi, “Active variable reactance rectifier—a new approach to compensating for coupling variations in wireless power transfer systems,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 8, no. 3, pp. 2022–2040, 2020.

[3] S. Sinha and K. K. Afridi, “Closed-loop control of a dynamic capacitive wireless power transfer system,” in *2019 20th Workshop on Control and Modeling for Power Electronics (COMPEL)*, pp. 1–6, 2019.

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