Full State Feedback Controller for Dynamic Capacitive Wireless Power Transfer Systems

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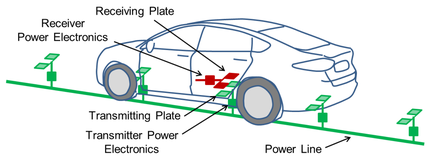
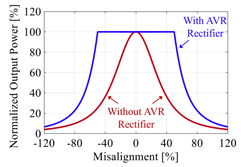
IEEE COMPEL 2025

CORNELL UNIVERSITY FOUNDED A.D. 1865

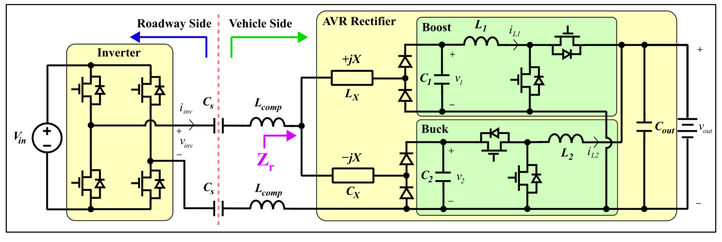
Motivation

- Dynamic wireless power transfer (WPT) to electric vehicles (EVs) enables unlimited range, zero charging time, and reduced EV cost
- Capacitive WPT can be less expensive, lighter, and more robust than inductive WPT
- Need mechanism to keep MHz-frequency capacitive WPT systems in resonance without changing frequency as coupling capacitance varies with vehicle motion
- Active Variable Reactance (AVR) rectifier can achieve this function

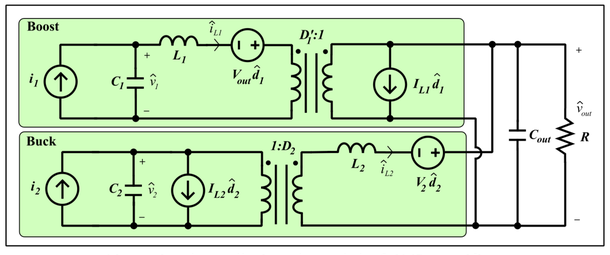




AVR Rectifier



- Provides continuously variable reactive compensation without changing operating frequency
- Maintains resonance and full output power by controlling input voltage of two dc-dc converters as coupling capacitance changes

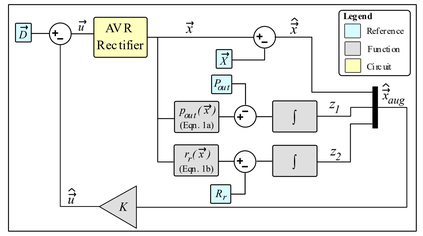


Linearized small-signal model of AVR rectifier

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

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 $\vec{x}$

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

P_{out} = nominal P_{out}

R_r = nominal $Re(Z_r)$

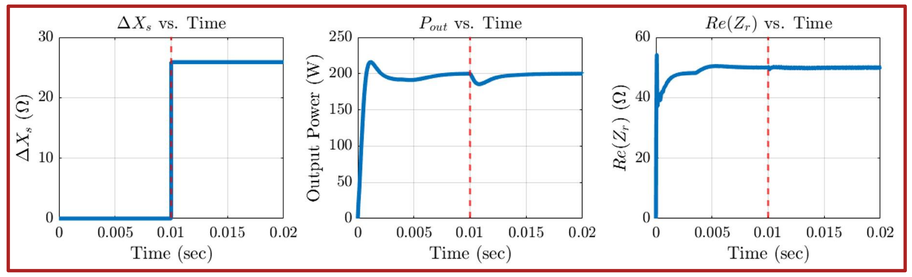
K = LQR gains

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

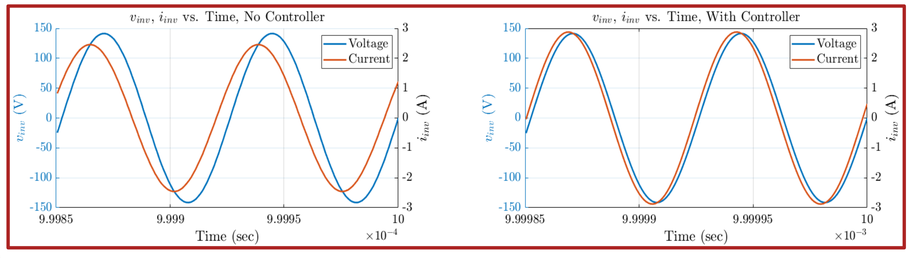
$$\vec{D} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

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

Simulation Results

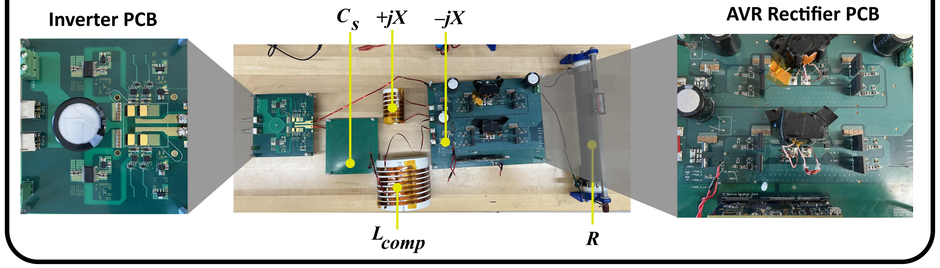


P_{out} and $Re(Z_r)$ Step Response

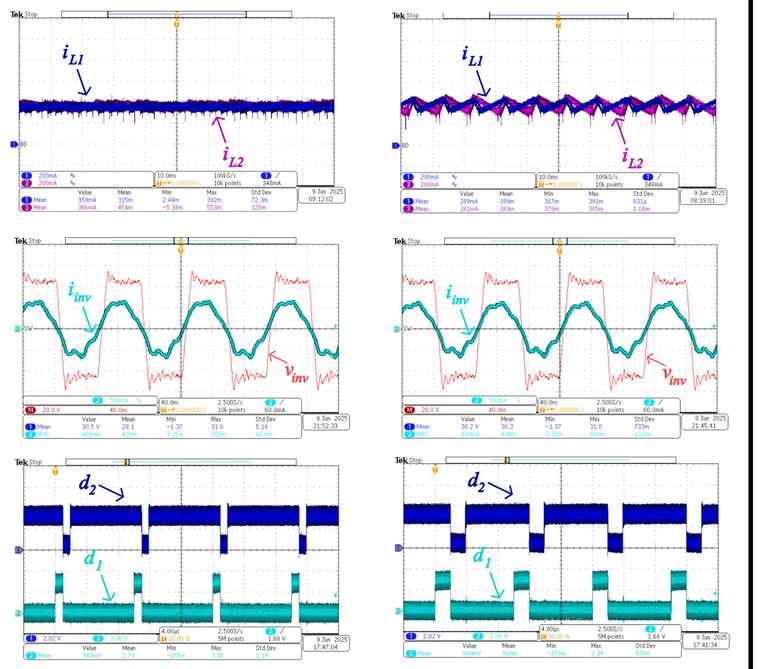


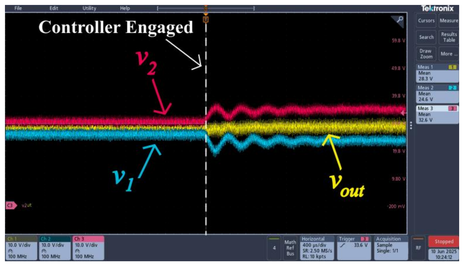
Phase shift between v_{inv} and i_{inv}

Hardware Prototype



Experimental Results





Transient settling time ≈ 1ms

Summary and Conclusions

- AVR rectifier can compensate for coupling variation in dynamic capacitive WPT systems by simply controlling two voltages
- Full-state feedback controller can adjust input voltages of two dc-dc converters to maintain resonance and regulate output power
- Capacitive WPT system with full-state feedback controller achieves fast dynamic response with about 1 ms settling time
- 25-W capacitive WPT prototype used to validate proposed controller

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Selected References

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[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, September 2020.
[3] S. Sinha and K. K. Afridi, "Closed-Loop Control of a Dynamic Capacitive Wireless Power Transfer System," *IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, Toronto, Canada, June 2019.
[4] J. C. Mayo-Maldonado et al., "State Space Modeling and Control of the DC-DC Multilevel Boost Converter," *IEEE International Conference on Electronics Communications and Computers (CONIELECOMP)*, Cholula, Mexico, February 2010.