Full State Feedback Controller for a Dynamic Capacitive Wireless Charging System

Abstract – This digest presents a novel state-space model and full state feedback (FSF) controller for the operation of capacitive wireless power transfer (WPT) systems in dynamic scenarios. This allows the system to transfer power efficiently as the coupling capacitance between the transmitter and receiver is varied. An Active Variable Reactance (AVR) rectifier is used to adjust the input reactance of the receiver dynamically in response to the change in coupling capacitance. The control of the AVR rectifier is not well-suited for frequency-based control methods due to significant nonlinearities and cross-coupling from its inputs to its outputs. A 6.78-MHz, 12-cm airgap capacitive WPT system with an AVR rectifier and a dynamically adjustable coupling capacitance was assembled. The proposed controller was validated in simulation and on the hardware prototype.

I. Introduction

Wireless power transfer is becoming increasingly important and has the potential to accelerate the widespread adoption of electric vehicles (EVs), especially amongst vehicles that routinely travel along fixed routes such as buses and warehouse forklifts. Capacitive WPT systems can be lighter, cheaper, and smaller than comparable inductive WPT systems due to the absence of ferrite cores. The ability of capacitive WPT systems to transfer high power at high efficiency has been demonstrated [1], thus proving the viability of this technology.

One main challenge of WPT is the extreme sensitivity to the value of the coupling capacitance or inductance between the receiver and the transmitter. This effect is magnified for capacitive WPT systems due to their high operating frequency, resulting in a precipitous drop in the system's efficiency and power transferring ability with the slightest deviation of the coupling capacitance from its nominal value. To increase the practicality of capacitive WPT systems, we must design and control the system to tolerate such deviations. In hardware, we replace the passive rectifier on the receiver with an Active Variable Reactance (AVR) rectifier [2]. This circuit allows us to dynamically adjust the reactive compensation of the resonant circuitry of the system in response to a change in the coupling capacitance. However, a robust controller is needed in order to perform this compensation automatically and with a sufficiently high bandwidth to allow for in-motion dynamic EV charging. In [3], a dual decoupled frequency-domain-based controller was designed, but the performance was not sufficient to operate the system dynamically. Moreover, the controller needed to be re-tuned at each misalignment condition.

This work presents a novel time-domain solution for the control of the AVR rectifier which has sufficiently high bandwidth and robustness to operate the system dynamically. First, a model of the AVR rectifier is derived in state space. Then, a state-space control strategy is proposed, and an optimal FSF linear quadratic regulator (LQR) controller is designed and validated in simulation. Finally, a prototype 6.78-MHz, 12-cm airgap capacitive WPT system with an AVR rectifier and a dynamically variable coupling capacitance is built and its operation demonstrated with the proposed control strategy.

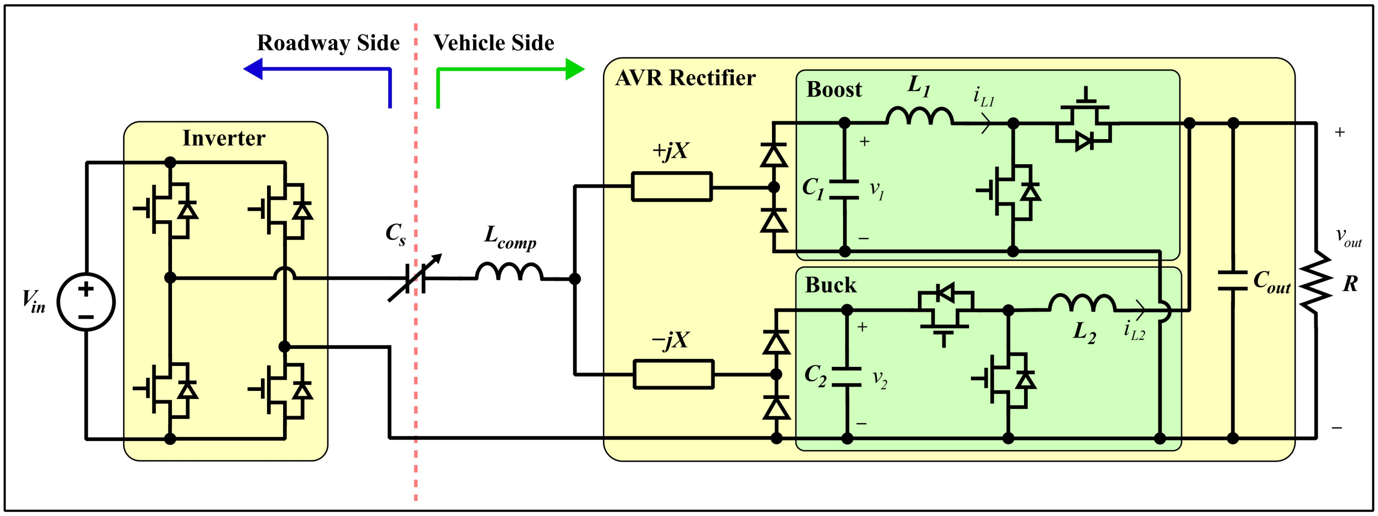

Fig. 1: Full capacitive WPT system with AVR rectifier schematic.

II. Dynamic Capacitive Wireless Charging System with an AVR Rectifier

Fig. 1 presents the full circuit schematic of the capacitive WPT system equipped with an AVR rectifier. A DC input bus is connected to a 6.78-MHz full-bridge inverter. Power then flows through the C_s-L_{comp} tank. C_s is the coupling capacitance between the roadway-side and vehicle-side coupling plates; L_{comp} is designed so that the impedance of the LC tank is zero when C_s assumes its nominal value. The AVR rectifier that follows has two branches that can process power:

1) The top branch, equipped with a boost converter, draws power through an inductive reactance $+jX$
2) The bottom branch, equipped with a buck converter, draws power through a capacitive reactance $-jX$

By controlling the total power processed across both branches, we can control the output power of the system. By controlling the proportion of the output power processed by the top branch relative to the bottom branch, we can vary the input impedance the AVR rectifier presents to the LC tank and, by extension, the inverter. Therefore, the AVR rectifier controller has two objectives: drive the output power and the real part of the input impedance to their nominal values [2].

III. State Space System Modeling

Fig. 2 contains the small-signal linearized model of the AVR rectifier. Of note is the inclusion of the input capacitance on both of the converters; these capacitors are necessary in modeling the dynamics of the converter as the input voltages v_1 and v_2 vary. A derivation of this model will be included in the full paper.

In general, a continuous-time state-space model can be written as $\frac{d}{dt}\vec{x} = A\vec{x} + B\vec{u}$, where $\vec{x}$ contains the system states, $\vec{u}$ contains the system inputs, A is the system dynamics matrix, and B is the input dynamics matrix. First, we choose the five capacitor voltages and inductor currents as the elements of our state vector $\vec{x}$: v_1, v_2, i_{L1}, i_{L2},

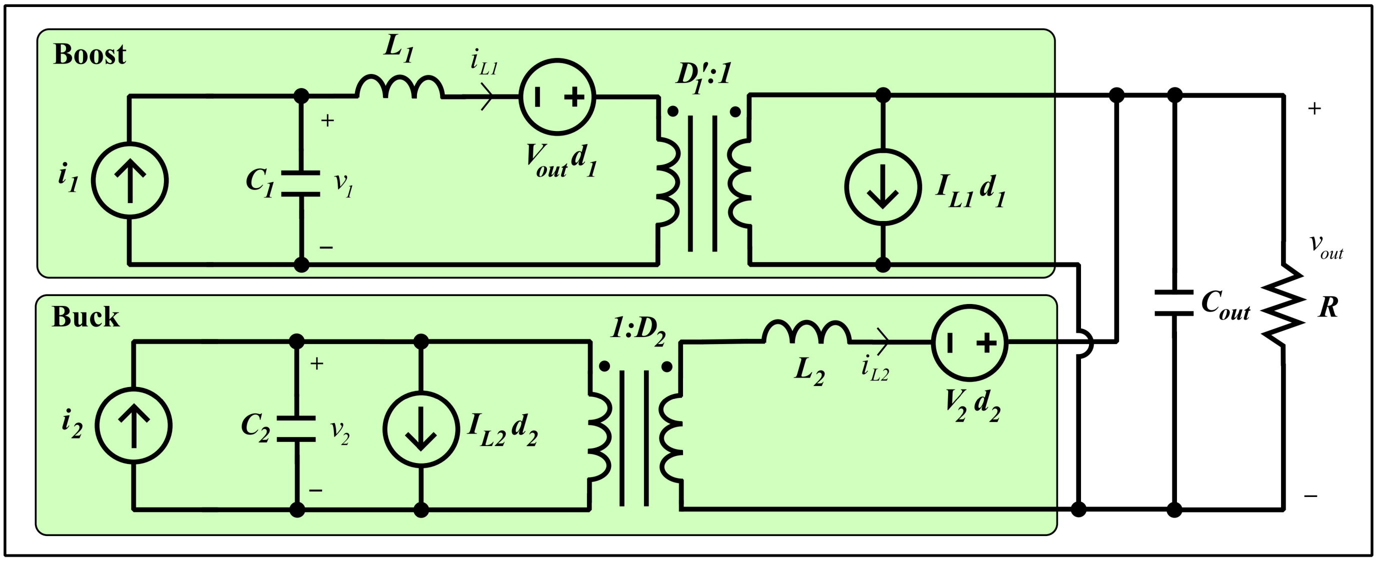

Fig. 2: Schematic of the AVR rectifier's linearized small-signal model.

and v_{out}. We further define our input vector $\vec{u}$ as having two elements corresponding to our two control handles: d_1' and d_2, the inverse duty cycle of the boost converter and the duty cycle of the buck converter, respectively.

Using time-domain circuit analysis, we can write first-order differential equations for $\frac{d}{dt}\vec{x}$ and arrange them into a matrix, resulting in a valid five-state un-augmented state space model of the AVR rectifier. However, the controller design requires us to augment the state space model with additional integral states z_1 and z_2 which track the integral of the error in output power p_{out} and error in input impedance $Re(z_r)$, respectively. Adding these two states to the model results in the complete seven-state state-space model (Eqn. 1) which we will use for designing the FSF controller. A derivation of Eqn. 1 will be presented in the full paper.

$$\frac{d}{dt}\begin{bmatrix} v_{out} \\ v_1 \\ v_2 \\ i_{L1} \\ i_{L2} \\ z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{RC_{out}} & 0 & 0 & \frac{D_1'}{C_{out}} & \frac{1}{C_{out}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{C_1} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{D_2}{C_2} & 0 & 0 \\ -\frac{D_1'}{L_1} & \frac{1}{L_1} & 0 & 0 & 0 & 0 & 0 \\ -\frac{1}{L_2} & 0 & \frac{D_2}{L_2} & 0 & 0 & 0 & 0 \\ -I_{L2} & -I_{L1} & 0 & -V_1 & -V_{out} & 0 & 0 \\ -\frac{\partial Re(z_r)}{\partial v_{out}} & -\frac{\partial Re(z_r)}{\partial v_1} & -\frac{\partial Re(z_r)}{\partial v_2} & -\frac{\partial Re(z_r)}{\partial i_{L1}} & -\frac{\partial Re(z_r)}{\partial i_{L2}} & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{out} \\ v_1 \\ v_2 \\ i_{L1} \\ i_{L2} \\ z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} -\frac{I_{L1}}{C_{out}} & 0 \\ 0 & 0 \\ 0 & -\frac{I_{L2}}{C_2} \\ \frac{V_{out}}{L_1} & 0 \\ 0 & \frac{V_2}{L_2} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \tag{1}$$

IV. Full State Feedback Controller Design and Simulation Validation

Fig. 3 shows the complete block diagram of the system under closed-loop control. The controller design consists of finding a gains matrix K such that when we set $\vec{u} = r - K\vec{x_{aug}}$, the system satisfies the two control objectives in response to disurbances in coupling capacitance. To find an optimal K, we use a linear quadratic regulator (LQR) with reasonable values for the diagonal elements of the Q and R cost-defining matrices. A discussion of how to choose appropriate Q and R for this control problem will be provided in the full paper. Then, we utilize the `lqr()` function in MATLAB to solve the corresponding Algebraic Riccati Equation for the optimal gains matrix K.

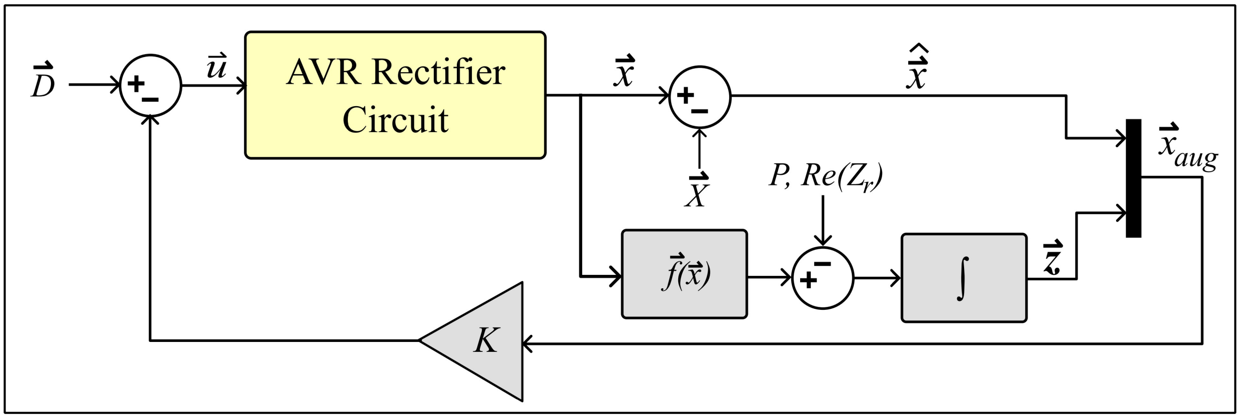

Fig. 3: Simplified block diagram of the state-space control loop. $\vec{f}(\vec{x})$ is a nonlinear function which computes p_{out} and $Re(Z_r)$ from the state vector $\vec{x}$. Capital letters denote dc values of the parameter at the nominal coupling capacitance. $x_{\vec{aug}}$ is the state vector after being augmented by $\vec{z}$.

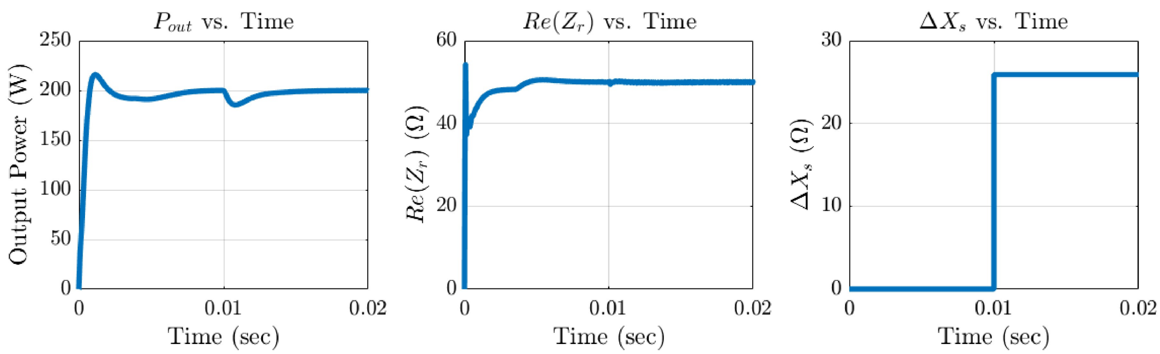

Fig. 4: P_{out} and $Re(Z_r)$ as a function of time, showing response to a step change in coupling reactance ΔX_s.

We build a model using Simulink and PLECS to validate the proposed controller. Fig. 4 shows the control objectives P_{out} and $Re(Z_r)$ being controlled to their target values of 200 W and 50 Ω, respectively, while we disturb the coupling capacitance by an amount ΔX_s. The impedance seen by the inverter must be near-resistive for the converter to operate at peak efficiency. Fig. 5 shows the input voltage and current waveforms at the inverter output under a misalignment condition with and without the controller. We see that the proposed controller is driving the input impedance effectively, as the voltage and current waveforms seen by the inverter are nearly in-phase.

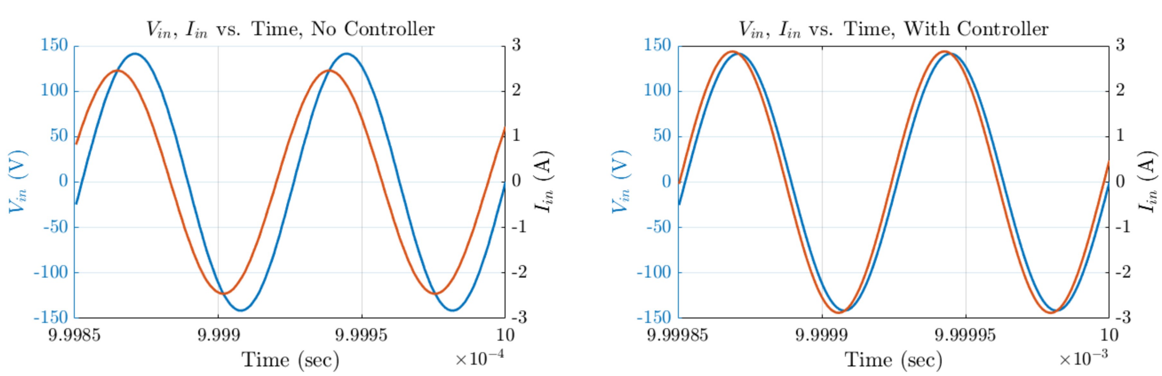

Fig. 5: V_{in} and I_{in} as functions of time, coupling reactance disturbed from nominal value by $\Delta X_s = 26\Omega$ in both cases.

V. Hardware and Experimental Results

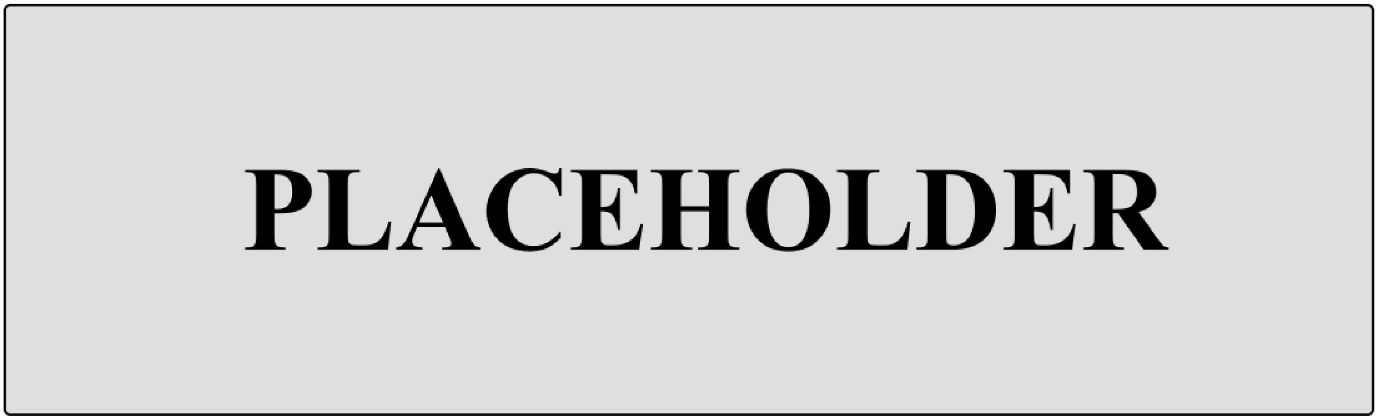

Fig. 6: Hardware result figures

The proposed controller was implemented on a prototype 6.78 MHz, 12-cm air gap capacitive WPT system equipped with an AVR rectifier and a dynamically adjustable coupling capacitance. The figure shows **what does it show? hopefully can get oscilloscope shot of controller running correctly and holding the power transfer and efficiency relatively as we make small changes to the coupling capacitance. perhaps we can also have an oscilloscope shot of the input current and voltage waveforms as well**.

VI. Conclusion and Future Work

This digest presents a novel state-space model and full state feedback (FSF) controller for capacitive WPT systems equipped with AVR rectifiers. The proposed controller allows the system to transfer power efficiently as the coupling capacitance between the transmitter and receiver is varied. A 6.78-MHz, 12-cm airgap capacitive WPT system with an AVR rectifier and a dynamically adjustable coupling capacitance was assembled. The proposed controller was validated in simulation and on the hardware prototype.

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.

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[3] S. Maji, Y. Cao, D. Etta, and K. K. Afridi, "An intelligent control methodology for in-motion dynamic capacitive wireless power transfer systems," in *2024 IEEE Workshop on Control and Modeling for Power Electronics (COMPEL)*, pp. 1–7, 2024.