Design of Voltage Stabilization with Semi-bridgeless Active Rectifier in Wireless Power Transfer System

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***Abstract*—Wireless Power Transfer technology is consistently the center of attention because of its wide range of applications. A control method that employs the primary-side phase shift H-bridge inverter and the secondary-side semi-active rectifier is presented in this paper to control the output voltage and maximize the system's efficiency under variable loads. The study suggests accurate system modeling for the secondary control loop. The proposed system is assessed through simulation and experiment. A stable 400 V on the load is achieved with 2.3% control error, and the transfer efficiency is improved up to 93%.**

Keywords—wireless power transfer, double-sided LCC compensation, voltage control, semi-bridgeless active rectifier, extended describing function

I. INTRODUCTION

The past few decades have witnessed the significant emergence of technologies on electric vehicles (EV) for their relatively environmental-friendliness, in which wireless power transfer (WPT) has received considerable attention. Principal WPT ideas in EV is charging the on-board battery [1], or wirelessly powering the motor [2]. Generally, the dc load (battery, motor, etc.) can be considered a resistor, simplifying the algorithm. Because this resistive load tends to vary during operation, maintaining the load voltage is necessary for further applications.

Some research makes use of the primary side inverter to control load voltage successfully [3]. However, in the case of multiple different loads being supplied simultaneously, the only feasible option is to control the secondary side. Typically, on the secondary side, some approaches employed a back-end DC/DC converter to control the output voltage [4]. The addition of a DC/DC converter is often not recommended because of space constraints and the system's efficiency. Moreover, rectifier, DC-DC converter and even var generator are neglected due to the innovation of active rectifier, which makes secondary-side control more attractive. Then, a semi-bridgeless active rectifier is most preferred. The accurate modeling of the rectifier is crucial to design a suitable performance controller. A small-signal modeling method was proposed in [5], but this method did not realize the dynamics of a resonant network because of the ideal AC source assumption to simplify the analysis. Therefore, to design the voltage controller, the mathematical and analytical modeling reflecting the dynamics of a compensation network and a semi-bridgeless active rectifier is required.

In this paper, a complete approach to accurately model a double-sided LCC compensation network and a semi-bridgeless active rectifier topology is introduced. Based on the model, a PI controller is finely designed to stabilize load voltage. Moreover, a primary phase-shift inverter is implemented to track the highest system efficiency.

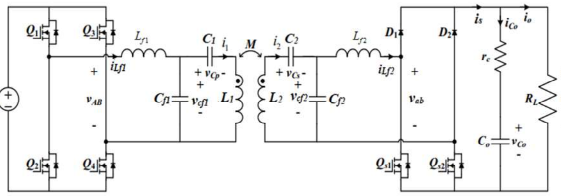

Fig. 1. Wireless power transfer system structure.

II. SYSTEM STRUCTURE

Fig. 1 shows the structure of the WPT system, which includes two separate sides. In the primary side, a battery-stored dc voltage is inverted to a high frequency by using a resonant inverter. Then, the electric energy is wirelessly transmitted to the secondary side through the magnetic resonance couplers. Designed in [6], the LCC resonance network has symmetrical primary and secondary circuits, including one compensation inductor and two compensation capacitors. The whole system operates at a resonant frequency of 40 kHz.

Assuming all the devices to be ideal and using fundamental harmonic approximation (FHA), all the harmonics are ignored, and the operating frequency of all the switches is fixed at 40 kHz. On the secondary equivalent circuit, the primary side is replaced with the induced voltage v_{sec} as follows:

$$v_{\sec} = \omega_s M I_1 \sin(\omega_s t) \qquad (1)$$

Q_{s1} and Q_{s2} operate with a phase difference of 180° from each other. For the semi-bridgeless active rectifier to operate normally, it is assumed that the duty ratio of Q_{s1} and Q_{s2} is always greater than 0.5. The operation of this topology can

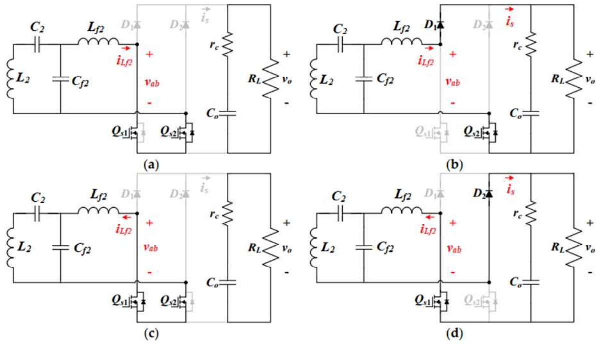

Fig. 2. Four operation modes of the proposed rectifier.

be divided into four modes as shown in Fig. 2.

III. MODELING AND DESIGN OF CONTROL LOOP

Because all the MOSFETs operate at a resonant frequency, the harmonics of compensation inductor currents and compensation capacitor voltages are greatly mitigated. Then, the resonant currents and voltages are quasi-sinusoidal.

By using Extended Describing Functions, the nonlinear components can be approximated to their fundamental harmonic and DC components. The small-signal model can be derived as follows:

$$\begin{cases}\dfrac{d\hat{x}}{dt} = A\hat{x} + B\hat{u} \\ \hat{y} = C\hat{x} + D\hat{u}\end{cases} \tag{2}$$

$$G_{vd}\left(s\right) = \frac{\hat{v}_0}{\hat{d}} = C\left(sI - A\right)^{-1} B + D \tag{3}$$

$G_{vd}(s)$ and a PI controller $G_c(s)$ for voltage stabilization is calculated as:

$$G_{vd}\left(s\right) \approx \frac{-1485.87}{1 + 0.047s} \tag{4}$$

$$G_{PI}\left(s\right) = -1184.8\frac{1 + 0.00028s}{s} \tag{5}$$

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. *Simualtion Results*

The system is simulated using PSIM software to verify the effectiveness of the proposed topology and control design method.

Fig. 3 represents the simulation results of the output voltage response and duty signal when the reference voltage V_{ref} changes from 300 V to 400 V at 0.02 s, to 500 V at 0.05 s, under a 20% load condition. Output voltage V_{ref} follows its reference voltage without overshoot and the settling time of the step response is approximately 0.0134 s, the steady-state error is about 0.0258 V.

Fig. 4 illustrates waveforms of switches' current and voltage. All switches achieve Zero Voltage Switch (ZVS) and Zero Current Switch (ZCS), reducing the proposed rectifier's switching loss.

B. *Experimental Results*

To verify the theory and simulation results, a prototype of the WPT system has been built.

A DC voltage of 40 is supplied to the inverter on the primary side, with a 33 Ω load on the secondary side. As shown in Fig. 5, the output voltage is stabilized at 61.4 V with an acceptable ripple of 2.3 %.

V. CONCLUSION

This paper proposes a novel method for modeling double-sided LCC compensation topology with the semi-active rectifier. The proposed modeling reflects the dynamics of the resonant network and rectifier, which facilitates control loop design. A simple PI controller is implemented to stabilize the output voltage. The proposed secondary control topology has fast response and high stability, which will be convenient for the secondary side control technology. Higher power experiments and better transient analysis will be realized in further research.

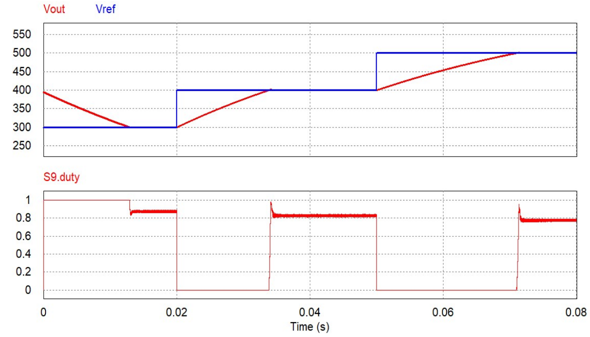

Fig. 5. Step respond of output voltage and duty signal at 20% load condition when reference output voltage.

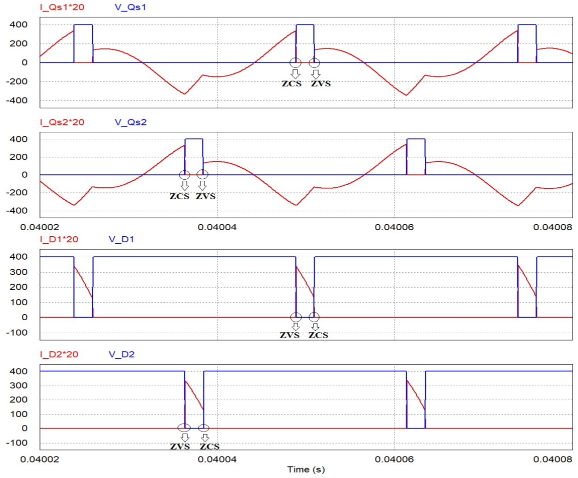

Fig. 4. Current and voltage through the rectifier switches.

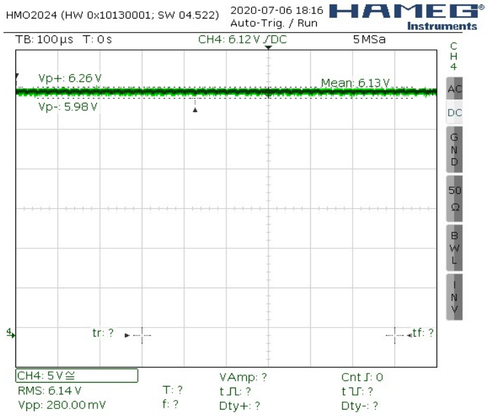

Fig. 3. Output voltage of open-loop control.

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