A Single-Stage Current-Mode Active Rectifier with Accurate Output-Current Regulation for IoT

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***Abstract*—This paper presents a single-stage wireless charger using a current-mode active rectifier with accurate output current regulation for efficient wireless charging. As we know, the rectifier processes an AC input voltage/current and a pulsing output current which are difficult to be accurately sensed on chip with small area and power overheads. The proposed current sensing technique uses a replica sensing stage in parallel with the main power stage. It consists of two small cross-connected sensing PMOS transistors, a small filtering capacitor, and a dynamic replica load. In addition, by adaptively tuning the delay of the power NMOS driving signal, the charging current is regulated precisely. This single-stage wireless charger operates at 6.78MHz, and is designed in a 0.35µm CMOS process. Simulation results show a minimum 97.5% current regulation accuracy over a 10× (from 100mA to 1A) output-current range. The peak efficiency of 94% is achieved with 4.2W output power.**

Keywords— AC-DC converter; current-mode active rectifier; current sensing; wireless charging; wireless power transfer (WPT)

I. INTRODUCTION

The growing number of Internet-of-Things (IoT) devices calls for convenient and efficient solutions for power delivery. Wireless battery charging via inductive coupling is an attractive solution, because it can deliver a wide range of power and helps the IoT devices to be water-/dust-proof. In addition, the requirements of small system volume and accessing a sealed space (like inside a tire) can also be satisfied by the inductive wireless charging.

In [1], a wireless power receiving unit was designed for the wireless charging, with a dc-dc buck converter following the rectifier. Therefore, a constant DC output voltage can be supplied. However, the dc-dc converter requires two large power transistors and one bulky off-chip inductor, demanding both chip and board areas. In addition, as a constant voltage supply cannot charge a battery directly, a post-stage charger between the wireless power receiving unit and the battery is necessary, which further increases the volume and cost of the system. Therefore, the charging scheme proposed in [1] is not suitable for IoT applications, where small volume and low cost is required. To remove the area-consuming dc-dc converter, a 3-mode reconfigurable resonant regulating rectifier was presented in [2]. By periodically switching the rectifier between different modes, like the pulse-width modulation (PWM) in a dc-dc converter, the output voltage can be regulated to a stable value, like for example 5V. However, a charger is still needed. In [3], a reconfigurable bidirectional wireless power transceiver with maximum-current charging mode was presented for battery-to-battery (B2B) charging. The battery is directly charged by the rectifier, eliminating a separate charger. Therefore, the charging efficiency can be improved, and the system volume can be reduced, both of which are favorable for IoT applications. However, unlike the B2B situation, the direct charging current may be larger than the maximum value that the battery of IoT devices can stand with. Therefore, a charging-current regulation scheme is necessary for low-capacity batteries.

In [4], an actively detuned wireless power receiver is proposed for the wireless charging of multiple IoT devices. The charging current is regulated by detuning the receiving coil. Thus, the battery is protected from the overcurrent, and the power allocation among multiple receivers is balanced. However, an auxiliary rectifier and auxiliary coil have to be adopted, which increase the chip and PCB area. Moreover, the charging current sensing is retrieved from a locally sensed peak voltage V_{peak}. But, because the charging current is the averaged value of the rectifier output current, V_{peak} cannot stand for the value of the charging current, especially when reverse current occurs during the rectification. As a result, the accuracy of the current regulation is limited.

The on-chip current sensing technique for dc-dc converters proposed in [5] can provide a high sensing accuracy with a small chip area. With this technique, a mirrored PMOS transistor matches a power PMOS transistor with a ratio of 1:1000. The mirrored transistor sources a fraction of current of the power transistor, and the sensing accuracy is determined by the matching performance of the current mirror. However, this technique cannot be directly applied to the full-wave rectifier in the wireless charging application, because the currents through its power transistors are AC currents.

In this paper, we present a single-stage current-mode active rectifier with accurate output current sensing and regulation. An on-chip averaged AC current sensing circuit is proposed with a pair of small replica cross-connected sensing PMOS transistors. And then, the charging current is regulated by adaptively tuning the delay of the driving signals of the power NMOS, with high accuracy and small chip area. Therefore, our single-stage active rectifier can directly charge the batteries of the IoT devices. Without a separate charger, small volume and high efficiency can be achieved. This paper is organized as follows. Section II describes the proposed single-stage active

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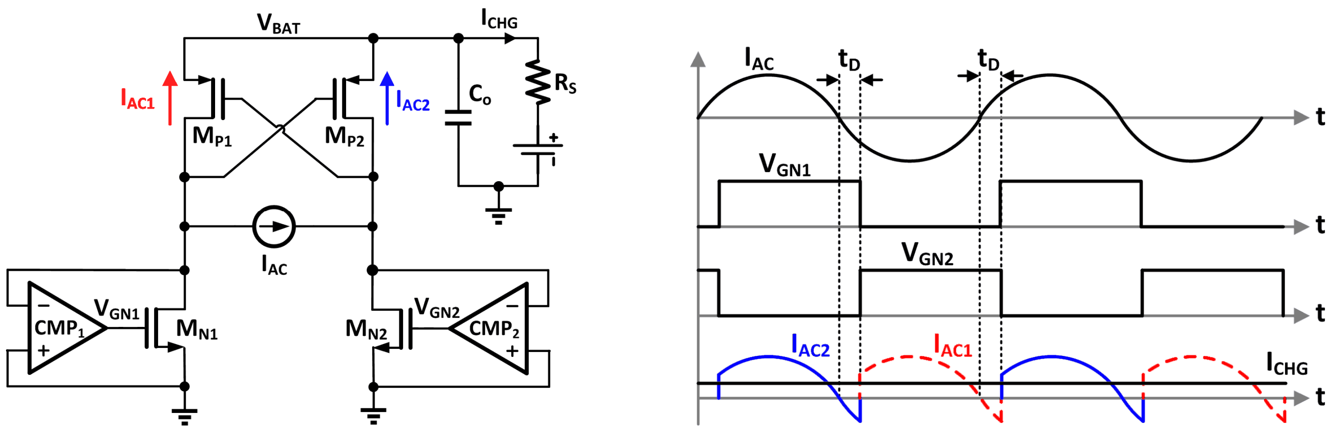

(a) (b)

Fig. 1. (a) Schematic of the active rectifier, and (b) its main waveforms.

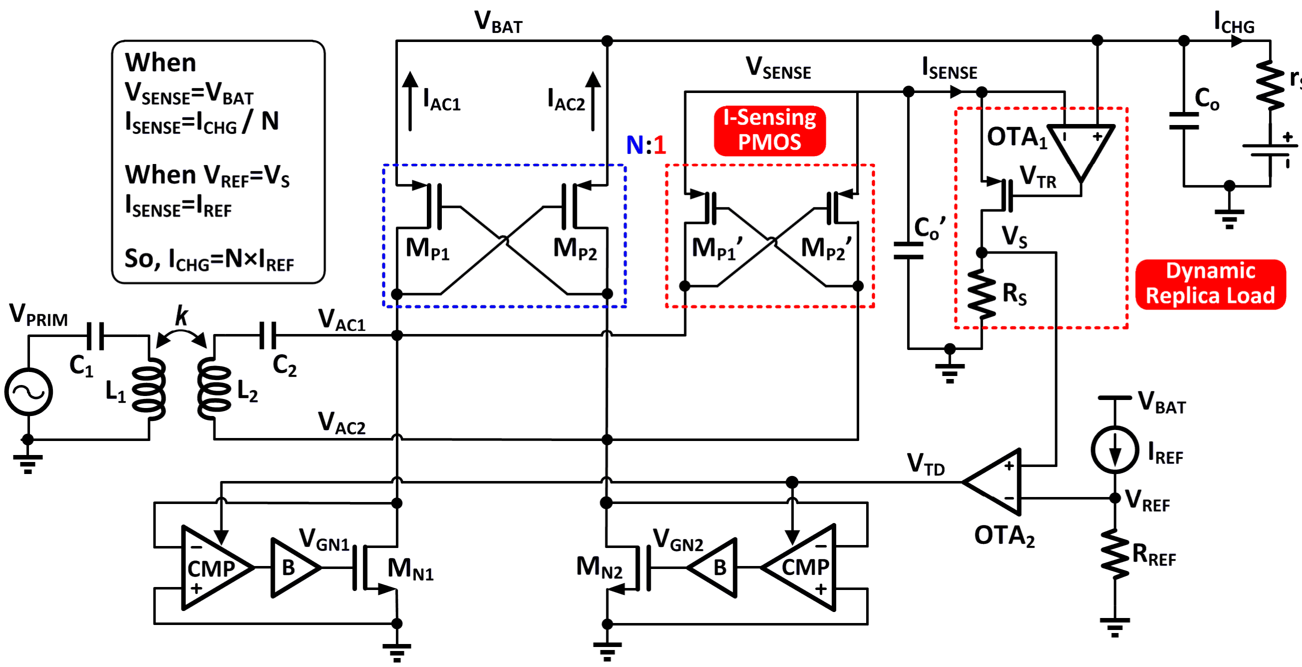

Fig. 2. Schematic of the proposed single-stage active rectifier with accurate output current regulation.

rectifier in detail. Then, the simulation results are given in Section III. Finally, we draw the conclusions in Section IV.

II. Proposed Current-Mode Active Rectifier With Accurate Output Current Regulation

Fig. 1(a) shows the schematic of a conventional active rectifier. M_{P1} and M_{P2} are the cross-connected power PMOS transistors for reducing the gate switching loss [6]. M_{N1} and M_{N2} are the power NMOS transistors driven by comparators, forming the active diodes. r_S is the inner resistance of the battery. I_{AC} is the received AC input current. After I_{AC} is rectified by the four power transistors and filtered by the output capacitor C_O, the averaged output current I_{CHG} is obtained. Fig. 1(b) exhibits the main waveforms of the active rectifier. Due to the active diode delay, t_D, caused by the comparators and buffers, M_{N1} and M_{N2} don't turn on/off at the zero crossing points of I_{AC}. Thus, reverse current exists in I_{AC1} and I_{AC2}. I_{CHG} is the averaged value of I_{AC1}+I_{AC2} and will be decreased by the reverse current. The relationship between t_D and I_{CHG} can be given by:

$$I_{CHG} = \frac{2}{\pi}\cos(2\pi\cdot\frac{t_D}{T})\cdot|I_{AC}|, \qquad (1)$$

where T is the period of I_{AC}. From (1), we find that I_{CHG} can be effectively regulated by continuously tuning the delay time t_D. Thus, we don't need any extra charger circuit between the rectifier and the battery, and direct charging can be realized, which significantly enhances the power conversion efficiency (PCE). Therefore, different from the previous active rectifier designs that try to minimize the active diode delay time, here, we are tuning the active diode delay for the output current regulation. In the following part of this section, we will introduce the accurate I_{CHG} sensing and the adaptive t_D tuning.

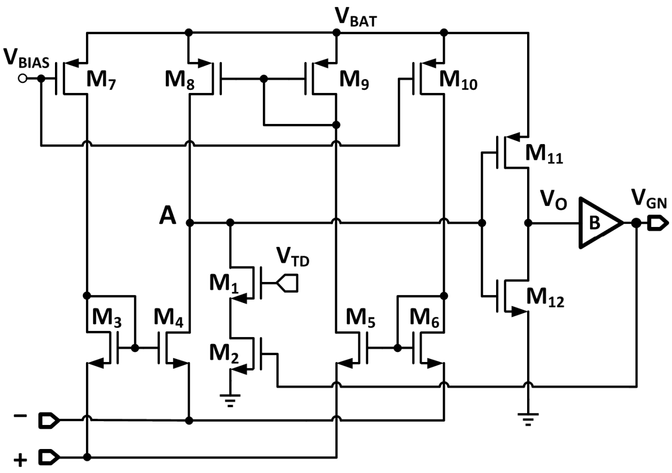

Fig. 3. Schematic of the comparator with adaptive offset control.

TABLE I. CRITICAL PARAMETERS

$M_{P1,2}$	$M_{N1,2}$	C_O	C_O’	N	R_S	r_S
100mm/0.5µm	**50mm/0.5µm**	**10µF**	**1nF**	**500**	**50Ω**	**0.2Ω**

A. Current Sensing Technique

Fig. 2 shows the schematic of the proposed single-stage active rectifier with output current regulation. The power receiving coil L_2 is connected in series with the resonant capacitor C_2 and acts as an AC current source. The current sensing circuit consists of a pair of cross-connected current sensing PMOS transistors M_{P1}’ and M_{P2}’, a filtering capacitor C_O’, and a dynamic replica load. M_{P1}’ and M_{P2}’ are the replica switches of M_{P1} and M_{P2}, respectively, which are scaled down in size by a ratio of N. The current through M_{P1} and M_{P2} is replicated first by M_{P1}’ and M_{P2}’, and then filtered to obtain the sensed DC current, I_{SENSE}. To make sure that $I_{SENSE}=I_{CHG}/N$, the source voltage of M_{P1}’ and M_{P2}’, V_{SENSE}, should be equal to V_{BAT}. Therefore, a negative feedback loop based on OTA_1 is added. If $V_{SENSE}>V_{BAT}$, the output of OTA_1, V_{TR}, will be lower to decease the impedance of the replica load. Then, V_{SENSE} will become smaller. If $V_{SENSE}<V_{BAT}$, V_{TR} will get larger to increase the impedance of the replica load. Then, V_{SENSE} will become larger. When the feedback loop gets into steady state, V_{SENSE} is regulated to be equal to V_{BAT}. Thus, the voltages on all the terminals of M_{P1} and M_{P2} are mirrored to that of M_{P1}’ and M_{P2}’, and $I_{SENSE}=I_{CHG}/N$ will be achieved. Meanwhile, I_{SENSE} is transformed to voltage V_S by R_S for regulating the charging current, which is going to be discussed next.

B. Adaptive Delay Tuning

Similar to I_{SENSE}, the reference current I_{REF} is transformed to voltage V_{REF} with the resistor R_{REF}. By making $V_S=V_{REF}$, an accurate current regulation of $I_{CHG}=N\times I_{REF}$ can be obtained. Thus, another negative feedback loop is added. As shown in Fig. 2, OTA_2 compares V_S and V_{REF}. If $V_S>V_{REF}$, which means I_{SENSE} is larger than I_{REF}, V_{TD} will be adjusted to increase the delay of the active diodes. Then, I_{CHG} and I_{SENSE} will decrease. On the other hand, if $V_S<V_{REF}$, the active diode delay will be decreased. Then, I_{CHG} and I_{SENSE} will increase. When the feedback loop gets settled, $I_{SENSE}=I_{REF}$ can be determined. Considering that $I_{SENSE}=I_{CHG}/N$, therefore, $I_{CHG}=N\times I_{REF}$.

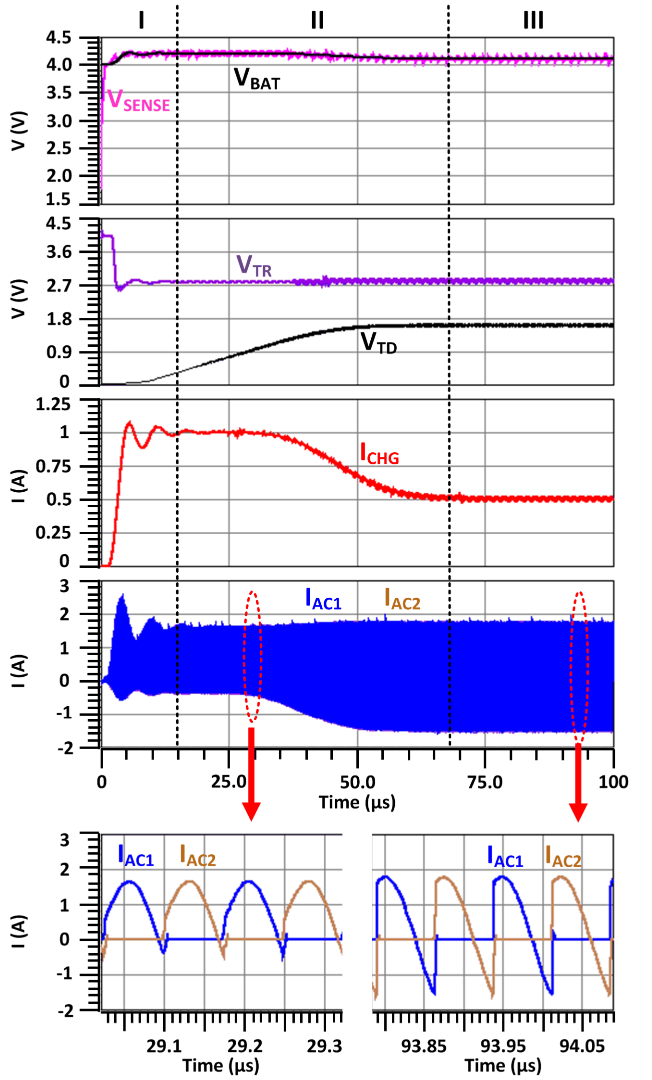

Fig. 4. The simulated operating waveforms of the proposed active rectifier when the targeted charging current is 500mA.

To control the active diode delay, a comparator with adaptively-controlled offset is adopted as shown in Fig. 3. The comparator is realized with the push-pull common-gate input stage. M_1 and M_2 are used to provide the switched offset current and to tune the off-delay of the comparator. The higher the V_{TD}, the larger the offset current, requiring more time to charge up node A. As a result, the off-delay will be increased. Meanwhile, other delay tuning methods, like the voltage-controlled delay line, can also be applied for the same purpose.

III. SIMULATION RESULTS

The proposed single-stage active rectifier with output-current regulation works at 6.78MHz, and is designed in a 0.35µm CMOS process. In the simulation, a capacitor of 10mF is used to emulate the battery. The critical parameters are listed in Table I. To drive the active rectifier, a power link supplied by a voltage source is applied, which can provide a peak

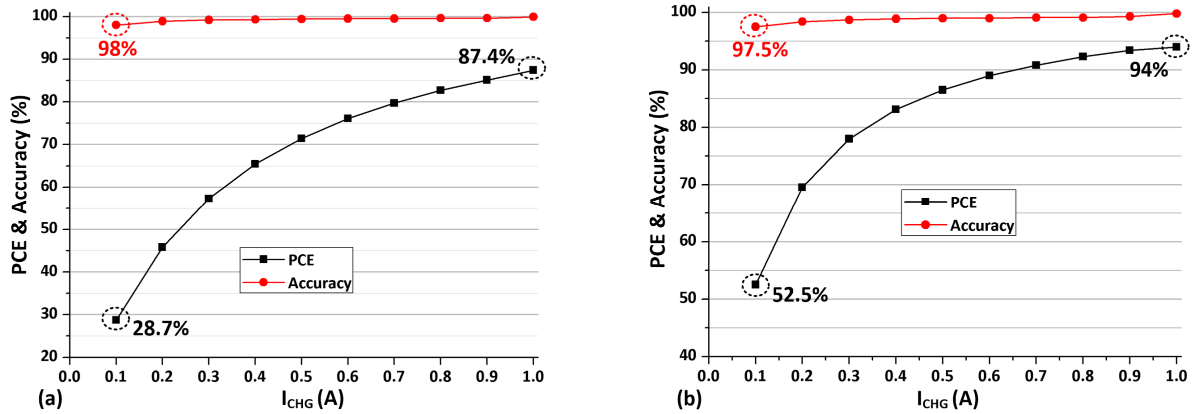

Fig. 5. Simulated PCE and current regulation accuracy under different charging currents at (a) V_{BAT}≈2.5V and (b) V_{BAT}≈4.2V.

TABLE II. COMPARISON WITH PRIOR WORKS

	[1] TPE 2016	[2] JSSC 2017	[3] ISSCC 2017	[4] ISSCC 2017	**This Work**
Process	0.18μm BCD	0.35μm CMOS	0.35μm CMOS	0.18μm CMOS	**0.35μm CMOS**
Regulation Type	Voltage Regulation	Voltage Regulation	No Regulation	Current Regulation	**Current Regulation**
Frequency (MHz)	6.78	6.78	6.78	6.78	**6.78**
PCE	80.86%	92.2%	91.5%	74%*	**94%****
$V_{OUT,MAX}$ (V)	5	5	4.2	4	**4.2**
$P_{OUT,MAX}$ (W)	6	6	1.65	0.52	**4.2****
Regulation Accuracy	N/A	N/A	N/A	N/A	**97.5%****
Off-Chip Components	1-Inductor, 3-Capacitors	1 Capacitor	1 Capacitor	1-PCB coil, 2-Capacitors	**1 Capacitor**

*End-to-end efficiency **Simulation results

charging current of 1A when the output voltage V_{BAT}≈4.2V. When V_{BAT}<4.2V, the peak I_{CHG} can be larger than 1A.

Fig. 4 shows the simulated waveforms of the proposed active rectifier when the targeted output current I_{CHG} is 500mA. The whole process can be divided into three stages. In stage I, V_{SENSE} is forced to be equal to V_{BAT} by the feedback loop, which is necessary for the accurate current sensing. In stage II, with an increased V_{TD}, the reverse current of I_{AC1} and I_{AC2} is increased, which reduces I_{CHG} gradually. At last, the circuit gets stable in stage III, and I_{CHG} is regulated to 500mA.

Fig. 5 shows the PCE and the current regulation accuracy of the proposed active rectifier with output current ranging from 0.1A to 1A. Because the battery is supposed to be charged from 2.5V to 4.2V, we select two cases, V_{BAT}≈2.5V and V_{BAT}≈4.2V, to demonstrate the results. From Fig. 5, we observe a minimum accuracy of 97.5% achieved when I_{CHG}=0.1A and V_{BAT}≈4.2V. The peak PCE is 94%, which is obtained when I_{CHG}=1A and V_{BAT}≈4.2V (when the output power is 4.2W). Table II shows the comparison with prior works. The proposed single-stage active rectifier achieves higher PCE and output current regulation accuracy.

IV. CONCLUSIONS

Charging current regulation in battery charging improves the battery health. In this paper, we present a current-mode active rectifier with accurate output current regulation serving as a single-stage wireless charger. Instead of minimizing the active diode delay, we employ the delay for an effective output current tuning. With two negative feedback loops, the output current is accurately sensed and regulated. The simulation results show a minimum current regulation accuracy of 97.5% over a 10× output-current range. The maximum PCE of 94% has been achieved when the output power is 4.2W.

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