International Journal of
Intelligent Engineering & Systems

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$2\times/3\times$ Step-Up Switched-Capacitor (SC) AC-DC Converters for RFID Tags

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Abstract: In signal processing circuits of a RDIF tag, the relaxation of restriction concerning operating voltage range enables us to develop various applications. In order to provide higher voltage to the signal processing circuit, two types of step-up AC-DC converters for RFID tags are proposed in this paper: the $3\times$ step-up converter and the $4\times$ step-up converter. To reduce ripple noise of output voltage, the proposed converters consist of 2 charge-pump type AC-DC converters with opposite polarities. Unlike conventional converters, the proposed converters can offer higher output voltages by realizing $3\times/4\times$ step-up conversion. Furthermore, as for the $3\times$ step-up converter, the circuit size of the proposed converter is almost the same as that of the Cockcroft-Walton type AC-DC converter. The properties of the proposed converters are clarified by theoretical analyses. The theoretical formulas can derive the equivalent circuits, output voltages, and power efficiency. Furthermore, SPICE simulations and the experiments showed the validity of theoretical formulas and circuit design.

Keywords: Power converters, AC-DC converters, Step-up converters, Switched-capacitor circuits, Charge-pump circuits, RFID

1. Introduction

Recently, RFID (Radio Frequency IDentification) systems [1]-[7] attract much attention as a basic technology of IT (Information Technology). The RFID system manages information with tags which embedded non-contact radio chips. In the RFID tag using RF electro-magnetic induction, AC-DC converters [1]-[10] are necessary to convert AC voltages provided by power receiving coils. For this reason, a half-wave rectifier or a full-wave rectifier has been used [4] as the AC-DC converter. However, due to their low power efficiency, these rectifiers are not efficient for low power conversion.

To solve this problem, Pan et al. [5] and Yakawa et al. [6, 7] proposed the Cockcroft-Walton type AC-DC converters for RFID tags. In the conventional converters, $2\times$ step-up AC-DC conversion is realized. First, in a pair of power receiving coils used in the conventional converter [6, 7], a pair of AC voltages V_{in+} and V_{in-} with opposite polarities is generated to reduce ripple noise of output voltage. In other words, input voltage V_{in} is stepped-down to $V_{in}/2$ by the power receiving coils. Next, in the conventional converter which consists of diode switches and capacitors, AC voltages V_{in+} and V_{in-} are converted to DC voltage $2(V_m - V_{th})$, where V_m denotes the amplitude of V_{in+} (or V_{in-}) and V_{th} denotes the threshold voltage of diode switch. Thus, although the conventional converter performs $2\times$ step-up conversion, the amplitude of DC output, $2(V_m - V_{th})$, is almost the same as that of input V_{in} due to the threshold drop of diode switches. For this reason, in signal processing circuits of a RDIF tag. the restriction concerning operating voltage range is caused by the low step-up ratio. In the conventional AC-DC converters, it is difficult to drive electric elements such as LEDs, piezoelectric buzzers, and so on.

In this paper, to drive electric elements which require higher voltages such as LEDs, piezoelectric buzzers, etc., a family of step-up AC-DC converters is proposed. By using switched-capacitor (SC) techniques [6]-[18], two types of step-up SC AC-DC converters are designed: the $3\times$ step-up converter and the $4\times$ step-up converter. Unlike conventional converters, the proposed converters can offer higher output voltages by realizing $3\times/4\times$ step-up conversion. In signal processing circuits of a RDIF tag, the relaxation of restriction concerning operating voltage range will enable us to develop various applications. Furthermore, as for the $3\times$ step-up converter, the circuit size of the proposed converter is almost the same as that of the Cockcroft-Walton type AC-DC converter.

The properties of the proposed converters are analyzed through theoretical analyses and simulations. Furthermore, to confirm the validity of circuit design, the experimental circuits are fabricated with commercially available diodes.

2. Circuit Structure

2.1 Conventional Converter

Figure 1 shows the Cockcroft-Walton type AC-DC converter proposed in [6, 7]. To realize small ripple noise, the conventional converter of Fig.1 consists of parallel-connected SC converters [19]-[21] with opposite polarities. In RFID systems, remote power feeding systems using RF electromagnetic induction are used. In the conventional converter, a pair of power receiving coils is modeled by a pair of AC voltage sources with opposite polarities (see Figs.1 (a) and (b)). Thus, as shown in Fig.1 (c), the amplitude of input voltages V_{in+} and V_{in-}, V_m, is the half of the amplitude of V_{in}. By converting V_{in+} and V_{in-}, the conventional converter offers the $2\times$ stepped-up DC voltage. After the AC-DC conversion, the output DC voltage is regulated by a regulator.

For easy understanding of the circuit operation of Fig.1, let us consider the converter block-1. When input V_{in+} is in $State-T2$ [1] (see in Fig.1 (c)), diode D_{2+} is turned on. Then the voltage of C_{1+} becomes about $V_m - V_{th}$, where V_m and V_{th} denote the amplitude voltage of AC input and the threshold voltage of the diode, respectively. Next, when input V_{in+} is in $State-T1$, diode D_{1+} is turned on. Then the output voltage of the converter becomes about $2(V_m - V_{th})$. However, the amplitude of DC output, $2(V_m - V_{th})$, is almost the same as that of input V_{in} which is $2V_m$. To drive LEDs, piezoelectric buzzers, etc., the stepped-up voltage is required.

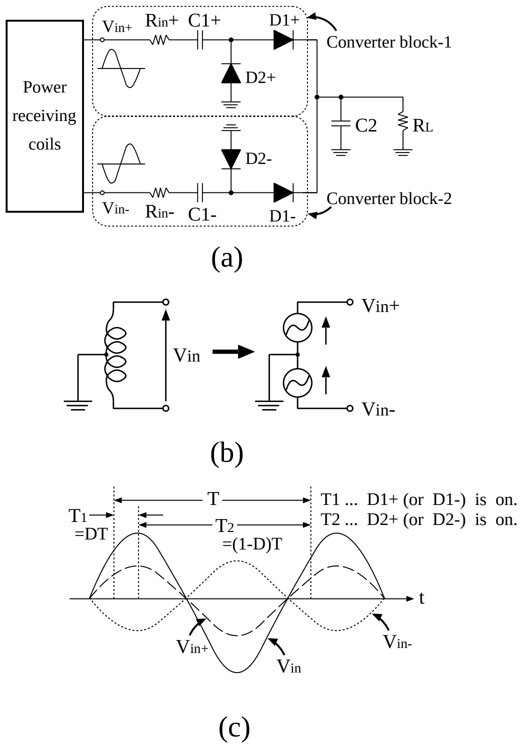

Figure 1. Conventional AC-DC converter. (a) Conventional circuit. (b) Power receiving coils. (c) Input AC wave.

2.2 Proposed Converter

Figure 2 shows the proposed AC-DC converters. To receive power by electromagnetic induction in the dozens MHz range, these converters are designed by using diode switches. To save space, only the operation of the proposed $3\times$ step-up converter is described in this section.

When input V_{in+} is in $State-T1$, the instantaneous equivalent circuit of Fig.2 (a) is expressed by the circuit shown in Fig.3 (a). In $State-T1$, the voltage of capacitor C_{1+} becomes $V_m - V_{th}$, because diode D_{1+} is turned on and D_{2+} is turned off. Next, when input V_{in+} is in $State-T2$, the stepped-up negative voltage $-2(V_m - V_{th})$ is provided to C_2 via D_{2+}, because diode D_{1+} is turned off and D_{2+} is turned on. At the same time, voltage $V_m - V_{th}$ is provided to C_3 via D_{3-}, because diode D_{3-} is turned on when

[1] In Fig.1, D denotes the duty factor.

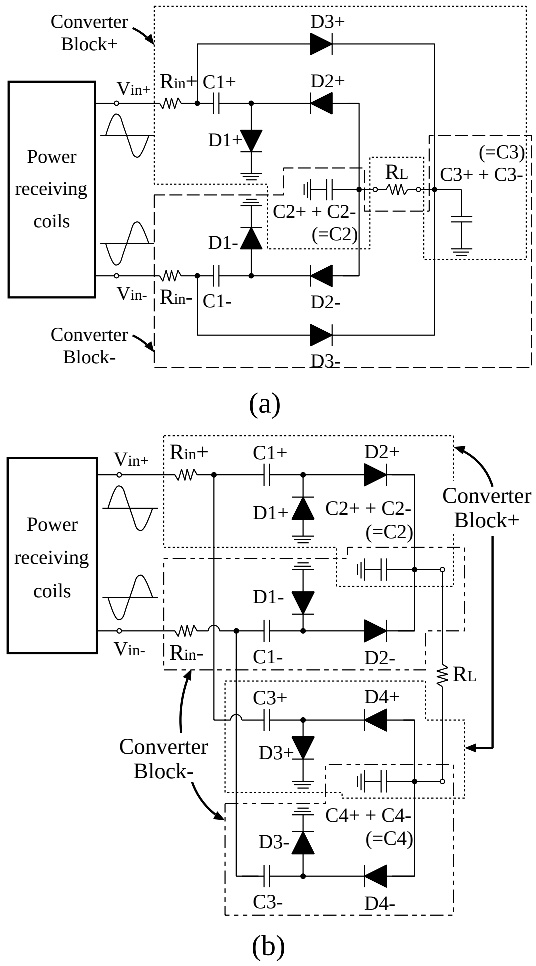

Figure 2. Proposed AC-DC converter. (a) 3× step-up. (b) 4× step-up.

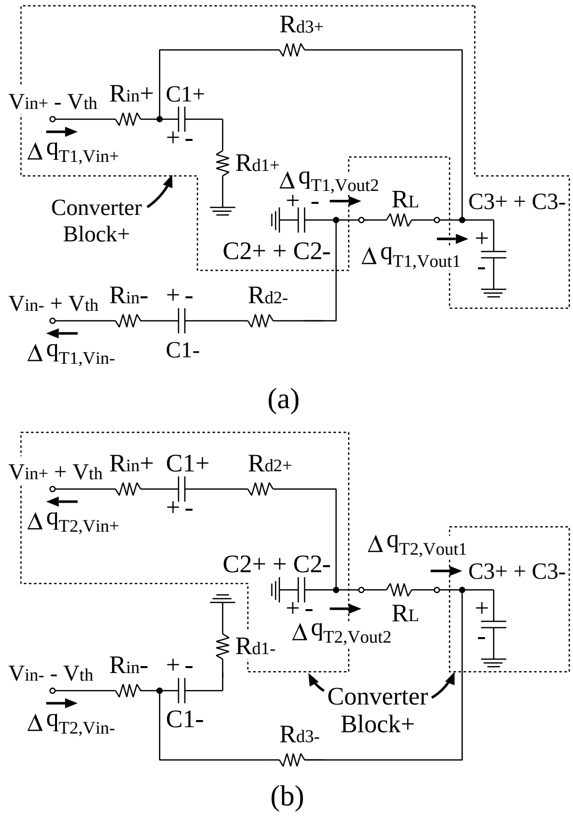

Figure 3. Instantaneous equivalent circuits of Fig.2 (a). (a) $State-T1$. (b) $State-T2$.

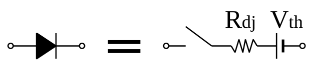

Figure 4. Diode model used in instantaneous equivalent circuits.

$State-T2$. Therefore, the voltage of output load R_L becomes about $3(V_m - V_{th})$ [2]. By iterating these operations, the proposed converter offers the $3\times$ stepped-up DC voltage.

3. Theoretical Analysis

In this section, the properties of the proposed converter shown in Fig.2 (a) is analyzed theoretically. To simplify the theoretical analysis, we assume that 1. parasitic elements are not effective, 2. the time constant is much larger than the period of input voltages, and 3. the waveform of inputs is a rectangular waveform.

First, the equivalent circuit of Converter Block+ (see in Fig.2 (a)) is derived. Figure 3 shows the instantaneous equivalent circuits of Fig.2 (a), where the diode switch is modeled by an ideal switch, a voltage source V_{th}, and a resistor R_{dj} $(j = \{1+, 1-, 2+, 2-, 3+, 3-\})$ as shown in Fig.4. In Fig.4, R_{dj} denotes the series resistance of diode.

In the steady state, the differential value of electric charges in C_{k+} $(k = \{1, 2, 3\})$ satisfies

$$\Delta q_{T1}^{k+} + \Delta q_{T2}^{k+} = 0, \tag{1}$$

where Δq_{T1}^{k+} and Δq_{T2}^{k+} denote electric charges when $State-T1$ and $State-T2$, respectively. In the case of $State-T1$, differential values of electric charges in the input terminal and the output terminals, $\Delta q_{T1,V_{in+}}$, $\Delta q_{T1,V_{out1+}}$, and $\Delta q_{T1,V_{out2+}}$, are given by

$$\begin{aligned} \Delta q_{T1,V_{in+}} &= \Delta q_{T1}^{1+} + \Delta q_{T1}^{3+} - \Delta q_{T1,V_{out1+}}, \\ \Delta q_{T1,V_{out1+}} &= \Delta q_{T1}^{1+} + \Delta q_{T1}^{3+} - \Delta q_{T1,V_{out1+}}, \\ \text{and} \quad \Delta q_{T1,V_{out2+}} &= \Delta q_{T1}^{2+}. \end{aligned} \tag{2}$$

In the case of $State-T2$, differential values of electric charges in the input terminal and the output terminals, $\Delta q_{T2,V_{in+}}$, $\Delta q_{T2,V_{out1+}}$, and $\Delta q_{T2,V_{out2+}}$, are

[2]The range of the output voltage is $[-2(V_m - V_{th}), V_m - V_{th}]$.

given by

$$\begin{aligned} \Delta q_{T2,V_{in+}} &= -\Delta q_{T2}^{1+}, \\ \Delta q_{T2,V_{out1+}} &= \Delta q_{T2}^{3+}, \\ \text{and} \qquad \Delta q_{T2,V_{out2+}} &= \Delta q_{T2}^{1+} + \Delta q_{T2}^{2+}. \end{aligned} \quad (3)$$

Here, averaged input current $\overline{I_{in+}}$ and averaged output currents $\overline{I_{out+}}$ $(= \overline{I_{out1+}} = \overline{I_{out2+}})$ are given by

$$\begin{aligned} \overline{I_{in+}} &= (\Delta q_{T1,V_{in+}} + \Delta q_{T2,V_{in+}})/T \\ &\equiv \Delta q_{V_{in+}}/T \\ \overline{I_{out1+}} &= (\Delta q_{T1,V_{out1+}} + \Delta q_{T2,V_{out1+}})/T \\ &\equiv \Delta q_{V_{out1+}}/T \ \ (= \Delta q_{V_{out+}}/T), \\ \text{and} \quad \overline{I_{out2+}} &= (\Delta q_{T1,V_{out2+}} + \Delta q_{T2,V_{out2+}})/T \\ &\equiv \Delta q_{V_{out2+}}/T \ \ (= \Delta q_{V_{out+}}/T), \end{aligned} \quad (4)$$

where $\Delta q_{V_{in+}}$, $\Delta q_{V_{out1+}}$, and $\Delta q_{V_{out2+}}$ are electric charges in the input and the outputs, respectively. From Eqs.(1) $\sim$ (4), the following equation is derived:

$$\overline{I_{in+}} = -3\,\overline{I_{out+}}. \quad (5)$$

In Converter Block+ of Fig.3 (a), the energy consumed by resistors in one period, W_T^+, can be expressed as

$$W_T^+ = W_{T1}^+ + W_{T2}^+, \quad (6)$$

where

$$\begin{aligned} W_{T1}^+ &= R_{in+}\left(\frac{\Delta q_{T1}^{1+} + \Delta q_{T1}^{3+} - \Delta q_{T1,V_{out1+}}}{T1}\right)^2 \cdot T_1 \\ &+ R_{d1+}\left(\frac{\Delta q_{T1}^{1+}}{T1}\right)^2 \cdot T_1 \\ &+ R_{d3+}\left(\frac{\Delta q_{T1}^{3+} - \Delta q_{T1,V_{out1+}}}{T1}\right)^2 \cdot T_1 \end{aligned}$$

and

$$W_{T2}^+ = R_{in+}\left(\frac{\Delta q_{T2}^{1+}}{T2}\right)^2 \cdot T_2 + R_{d2+}\left(\frac{\Delta q_{T2}^{1+}}{T2}\right)^2 \cdot T_2.$$

From Eqs.(1) $\sim$ (4), Eq.(6) can be rewritten as

$$\begin{aligned} W_T^+ &= \frac{4R_{in+}}{DT}(\Delta q_{V_{out+}})^2 + \frac{R_{d1+}}{DT}(\Delta q_{V_{out+}})^2 \\ &+ \frac{R_{d3+}}{DT}(\Delta q_{V_{out+}})^2 + \frac{R_{in+}}{(1-D)T}(\Delta q_{V_{out+}})^2 \\ &+ \frac{R_{d2+}}{(1-D)T}(\Delta q_{V_{out+}})^2, \end{aligned} \quad (7)$$

where D denotes the duty factor. Furthermore, Eq.(7) can be expressed as

$$W_T^+ = \frac{(4-3D)R_{in+} + (2-D)R_d}{D(1-D)T}(\Delta q_{V_{out+}})^2 \quad (8)$$

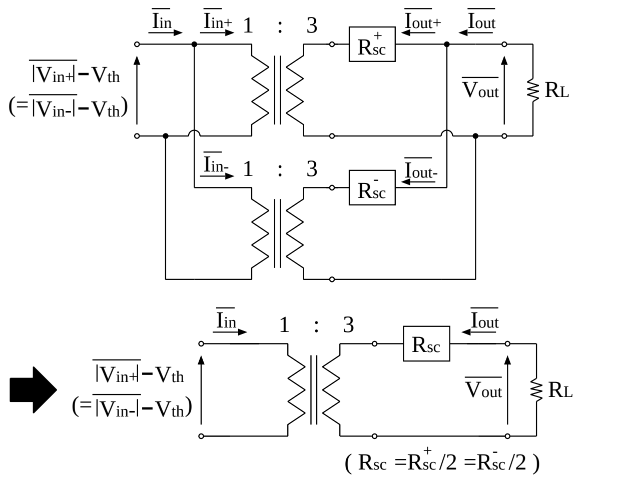

Figure 5. Equivalent circuit of 3× step-up AC-DC converter.

when $R_d \equiv R_{d1+} = R_{d2+} = R_{d3+}$.

Here, it is known that a general equivalent circuit of SC power converters can be expressed by the determinant using the Kettenmatrix [16]-[18]. In the general equivalent circuit of SC power converters, consumed energy W_T is defined by

$$\begin{aligned} W_T^+ &= W_{T1}^+ + W_{T2}^+ \\ &\equiv \left(\frac{\Delta q_{V_{out+}}}{T}\right)^2 \cdot R_{SC}^+ \cdot T, \end{aligned} \quad (9)$$

where R_{SC}^+ is called the SC resistance. From Eqs.(8) and (9), the SC resistance R_{SC}^+ is given by

$$R_{SC}^+ = \frac{(4-3D)R_{in+} + (2-D)R_d}{D(1-D)}. \quad (10)$$

Therefore, by using Eqs.(5) and (10), the equivalent circuit of Converter Block+ is given by the following determinant:

$$\begin{bmatrix} \overline{|V_{in+}|} - V_{th} \\ \overline{I_{in+}} \end{bmatrix} = \begin{bmatrix} 1/3 & 0 \\ 0 & 3 \end{bmatrix} \begin{bmatrix} 1 & R_{SC}^+ \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{V_{out+}} \\ -\overline{I_{out+}} \end{bmatrix}. \quad (11)$$

The equivalent circuit of Converter Block- (see in Fig.2 (a)) can also be analyzed by the same method. Thus, from Eq.(11), the equivalent circuit of the 3× step-up converter can be expressed by the circuit shown in Fig.5.

In Fig.5, by using Thevenin's theorem, output voltage $\overline{V_{out}}$ is obtained by

$$\overline{V_{out}} = 3(\overline{|V_{in+}|} - V_{th}) \times \frac{R_L}{R_L + R_{SC}^+/2}. \quad (12)$$

Table 1 Theoretical results of proposed converters.

	Step-Up Ratio	SC Resistance R_{SC}
$3\times$ Step-Up AC-DC Converter	$3\times$	$\frac{(4-3D)R_{in+}+(2-D)R_d}{2D(1-D)}$
$4\times$ Step-Up AC-DC Converter	$4\times$	$\frac{2R_{in+}+R_d}{D(1-D)}$
Conventional $2\times$ Step-Up Converter	$2\times$	$\frac{R_{in+}+R_d}{2D(1-D)}$

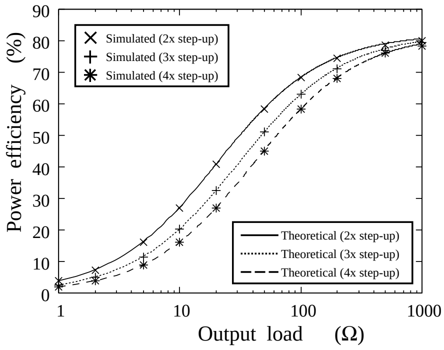

Figure 6. Power efficiency of proposed converters.

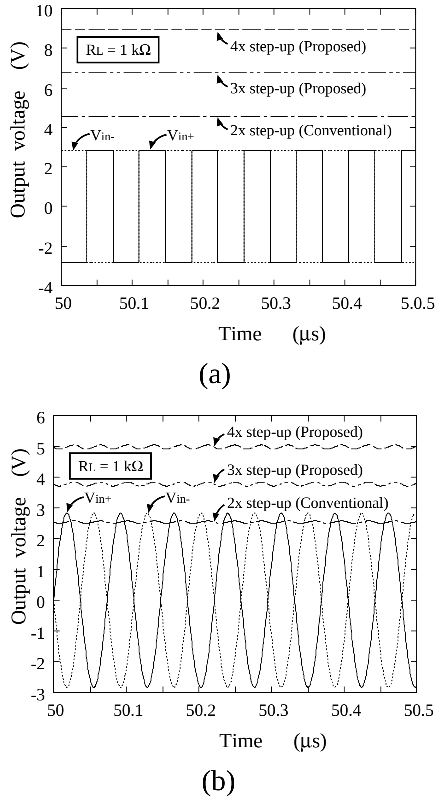

Figure 7. AC-DC signals obtained by simulations when output load R_L= 1 kΩ. (a) Rectangular waveform. (b) Sinusoidal waveform.

From Fig.5, the power efficiency [3] of the $3\times$ step-up converter, η, can be expressed by

$$\eta = \frac{\overline{|V_{in+}|}-V_{th}}{\overline{|V_{in+}|}} \times \frac{(\overline{I_{out}})^2 R_L}{(\overline{I_{out}})^2 R_L + (\overline{I_{out}})^2 R_{SC}^{+}/2}$$

$$= \frac{\overline{|V_{in+}|}-V_{th}}{\overline{|V_{in+}|}} \times \frac{R_L}{R_L + R_{SC}^{+}/2}. \quad (13)$$

To save space, the theoretical analysis of the $4\times$ step-up converter [4] is omitted in this section. However, the $4\times$ step-up converter can also be analyzed by the same method. Table 1 shows the summary of the theoretical results. As Table 1 shows, the SC resistance becomes large according to the step-up ratio. Concretely, when $D = 0.5$, the SC resistance of $2\times$, $3\times$, and $4\times$ step-up converters are $R_{SC} = 2R_{in+}+2R_d$, $5R_{in+}+3R_d$, and $8R_{in+} + 4R_d$, respectively. Thus, from Table 1 and Eq.(13), the power efficiency decreases according to the increase of step-up ratio. However, the decrease of efficiency according to the increase of step-up ratio is generally caused in other power converters.

4. Simulation

To confirm the validity of the theoretical analysis, SPICE simulations were performed concerning the circuits shown in Fig.2.

Figure 6 shows the simulated power efficiency, where we assumed that the waveform of inputs is a rectangular waveform and the diode is modeled as shown in Fig.4. The SPICE simulations of Fig.6 were performed under conditions where $V_{in+} = -V_{in-}$ = 2V@ 13.56MHz, $C_{1+} = C_{1-} = \cdots = C_{4+} = C_{4-}$ = 10nF, R_d = 10 Ω, V_{th} = 0.5 V, R_{in} = 0.1 Ω, and $D = 0.5$. As Fig.6 shows, the obtained formulas are useful for designing the proposed converter, because the theo-

[3] The consumed energy of peripheral circuits such as pulse generators, regulators, etc. is disregarded in power efficiency.

[4] The theoretical analysis of the $4\times$ step-up converter is described in Appendix.

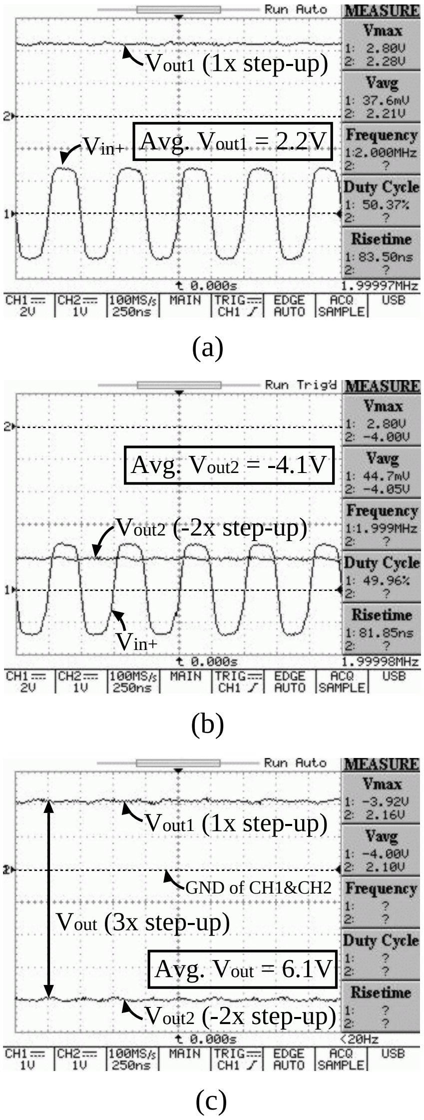

Figure 8. AC-DC signals obtained by $3\times$ step-up converter when output load R_L= 1 kΩ. (a) V_{out1}. ($1\times$ step-up) (b) V_{out2}. ($-2\times$ step-up) (c) Output voltage. V_{out} (= V_{out1} + V_{out2})

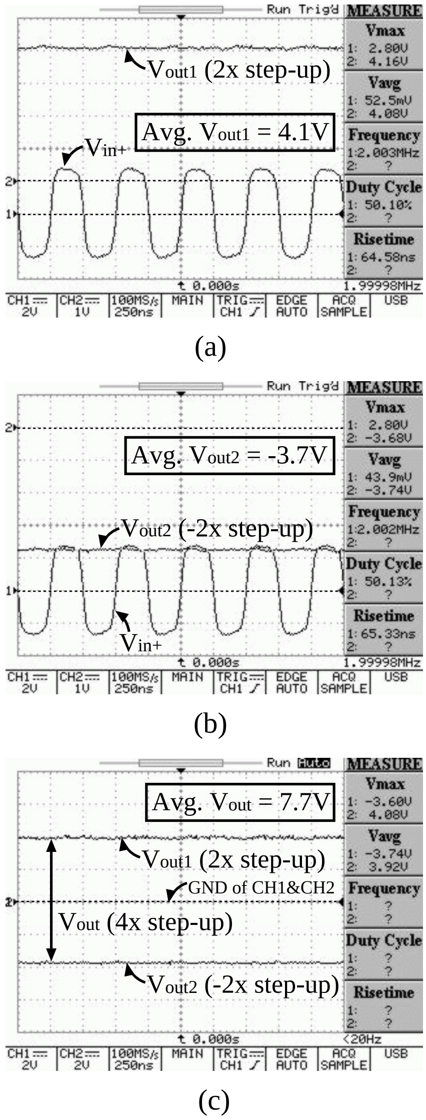

Figure 9. AC-DC signals obtained by $4\times$ step-up converter when output load R_L= 10 kΩ. (a) V_{out1}. ($2\times$ step-up) (b) V_{out2}. ($-2\times$ step-up) (c) Output voltage. V_{out} (= V_{out1} + V_{out2})

retical results agree well with the simulation results [5]
.

Figure 7 shows the results of AC-DC conversion obtained by SPICE simulations. As Fig.7 shows, the proposed converters can realize step-up AC-DC conversion even if the input voltage is a sinusoidal voltage. In Fig.7, the main reasons for reduction of output voltage are the influences of threshold voltage V_{th} of diode switches.

[5]Of course, the power efficiency decreases when the input is a sinusoidal voltage. Thus, the theoretical formulas obtained in this paper will give the maximum power efficiency of converters.

5. Experiment

To confirm the validity of circuit design, the experiments were performed regarding to the proposed converters. The experimental circuits were built with a FCZ1.9-type coil and commercially available diodes 1S2075K-E [6] on a bread board.

Figures 8 and 9 show the experimental results of $3\times$ and $4\times$ AC-DC conversion, respectively. The experiments of Figs.8 and 9 were performed under conditions where $V_{in+} = -V_{in-}$ = 2V@2 MHz, capacitors $C_{1+} = C_{1-} = \cdots = C_{3+} = C_{3-}$ = 10nF, and R_L = 1 kΩ. As Figs.8 and 9 show, the circuit design of the

[6]The forward voltage of 1S2075K-E is 0.8 V.

proposed converters is appropriate, because $3\times$ and $4\times$ step-up AC-DC conversion [7] can be confirmed.

6. Conclusion

In this paper, a family of step-up SC AC-DC converters for RFID tags has been proposed. Concerning the proposed $3\times$ and $4\times$ step-up converters, SPICE simulations, theoretical analyses, and experiments were performed to confirm the validity of circuit design.

The SPICE simulations, theoretical analyses, and experiments showed: 1. Unlike conventional converters, the proposed converter can offer $3\times$ or $4\times$ stepped-up voltages. 2. The formulas obtained by the theoretical analyses are useful for designing the proposed converter, because the theoretical results agreed well with the simulation results.

The proposed converters will enable us to develop various applications, because the relaxation of restriction concerning operating voltage range can be realized in signal processing circuits of a RDIF tag.

The IC implementation is left to a future study.

Appendix

In this section, the properties of the proposed $4\times$ step-up converter is analyzed theoretically. The conditions of this theoretical analysis are the same as that shown in Sect.3.

First, the equivalent circuit of Converter Block+ (see in Fig.2 (b)) is derived. Figure 10 shows the instantaneous equivalent circuits of $4\times$ step-up converter. In the steady state, the differential value of electric charges in C_{k+} $(k = \{1, 2, 3\})$ satisfies Eq.(1). In the case of $State-T1$, differential values of electric charges in the input terminal and the output terminals, $\Delta q_{T1,V_{in+}}$, $\Delta q_{T1,V_{out1+}}$, and $\Delta q_{T1,V_{out2+}}$, are given by

$$\begin{aligned} &\Delta q_{T1,V_{in+}} = \Delta q_{T1}^{3+} - \Delta q_{T1}^{1+}, \\ &\Delta q_{T1,V_{out1+}} = \Delta q_{T1}^{1+} + \Delta q_{T1}^{2+}, \\ \text{and} \quad &\Delta q_{T1,V_{out2+}} = \Delta q_{T1}^{4+}. \end{aligned} \tag{14}$$

In the case of $State-T2$, differential values of electric charges in the input terminal and the output terminals, $\Delta q_{T2,V_{in+}}$, $\Delta q_{T2,V_{out1+}}$, and $\Delta q_{T2,V_{out2+}}$, are

[7] In the experiment, the circuit properties such as power efficiency, ripple noise, etc. were not examined, because the experimental circuit was built with commercially available transistors on the bread board. Therefore, only the circuit design was verified through this experiment. The IC implementation is left to a future study.

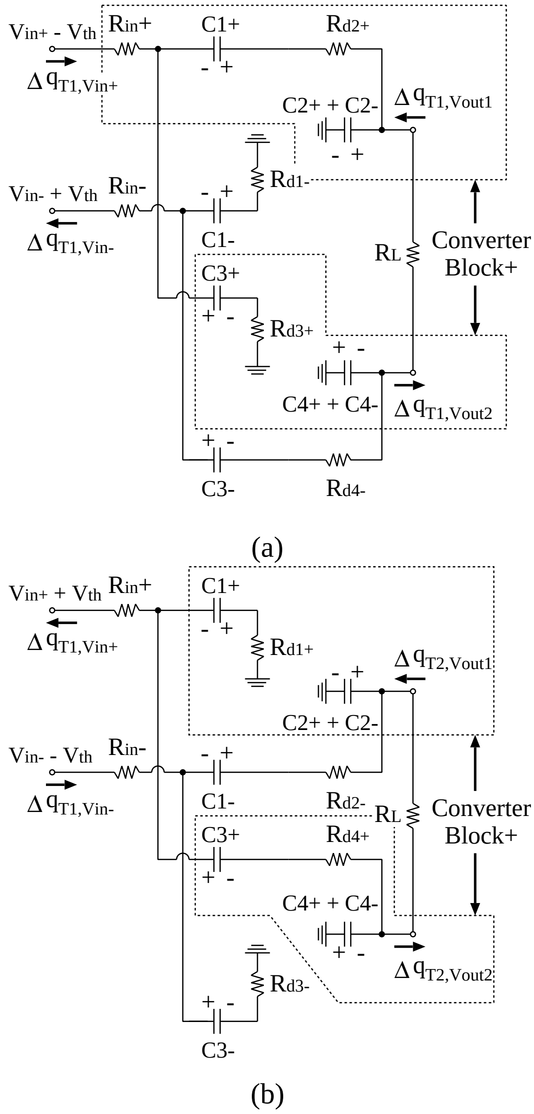

Figure 10. Instantaneous equivalent circuits of $4\times$ step-up converter. (a) $State-T1$. (b) $State-T2$.

given by

$$\begin{aligned} &\Delta q_{T2,V_{in+}} = \Delta q_{T2}^{1+} - \Delta q_{T2}^{3+}, \\ &\Delta q_{T2,V_{out1+}} = \Delta q_{T2}^{2+}, \\ \text{and} \quad &\Delta q_{T2,V_{out2+}} = \Delta q_{T2}^{3+} + \Delta q_{T2}^{4+}. \end{aligned} \tag{15}$$

By substituting Eqs.(1), (14), and (15) into Eq.(4), the following equation is derived:

$$\overline{I_{in+}} = -4\,\overline{I_{out+}}. \tag{16}$$

In Converter Block+ of Fig.10 (a), the energy consumed by resistors in one period, W_T^+, can be expressed as

$$W_T^+ = W_{T1}^+ + W_{T2}^+, \tag{17}$$

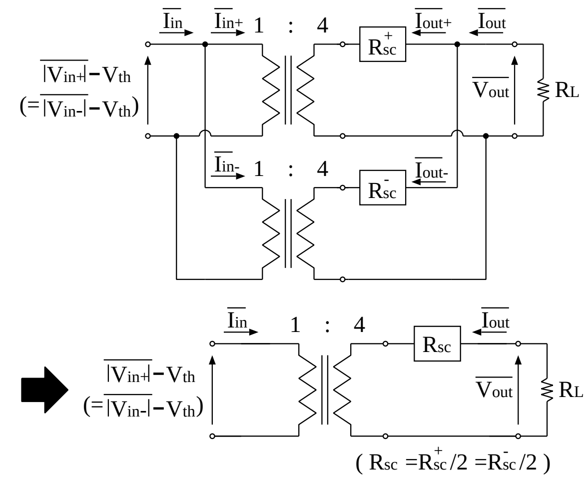

Figure 11. Equivalent circuit of 3× step-up AC-DC converter.

where

$$W_{T1}^{+} = R_{in+}(\frac{\Delta q_{T1}^{3+} - \Delta q_{T1}^{1+}}{T1})^2 \cdot T_1 + R_{d2+}(\frac{\Delta q_{T1}^{1+}}{T1})^2 \cdot T_1 + R_{d3+}(\frac{\Delta q_{T1}^{3+}}{T1})^2 \cdot T_1$$

and

$$W_{T2}^{+} = R_{in+}(\frac{\Delta q_{T2}^{1+} - \Delta q_{T2}^{3+}}{T2})^2 \cdot T_2 + R_{d1+}(\frac{\Delta q_{T2}^{1+}}{T2})^2 \cdot T_2 + R_{d4+}(\frac{\Delta q_{T2}^{3+}}{T2})^2 \cdot T_2.$$

From Eqs.(1), (4), (14), and (15), Eq.(17) can be rewritten as

$$\begin{aligned} W_T^{+} &= \frac{4R_{in+}}{DT}(\Delta q_{V_{out+}})^2 + \frac{R_{d2+}}{DT}(\Delta q_{V_{out+}})^2 \\ &+ \frac{R_{d3+}}{DT}(\Delta q_{V_{out+}})^2 + \frac{4R_{in+}}{(1-D)T}(\Delta q_{V_{out+}})^2 \\ &+ \frac{R_{d1+}}{(1-D)T}(\Delta q_{V_{out+}})^2 \\ &+ \frac{R_{d4+}}{(1-D)T}(\Delta q_{V_{out+}})^2. \end{aligned} \quad (18)$$

Furthermore, Eq.(18) can be expressed as

$$W_T^{+} = \frac{(4R_{in+} + 2R_d)}{D(1-D)T}(\Delta q_{V_{out+}})^2 \quad (19)$$

when $R_d \equiv R_{d1+} = R_{d2+} = R_{d3+} = R_{d4+}$. Thus, from Eqs.(9) and (19), the SC resistance R_{SC}^{+} is given by

$$R_{SC}^{+} = \frac{4R_{in+} + 2R_d}{D(1-D)} \quad (20)$$

Therefore, by using Eqs.(16) and (20), the equivalent circuit of Converter Block+ is given by the following determinant:

$$\begin{bmatrix} \overline{|V_{in+}|} - V_{th} \\ \overline{I_{in+}} \end{bmatrix} = \begin{bmatrix} 1/4 & 0 \\ 0 & 4 \end{bmatrix} \begin{bmatrix} 1 & R_{SC}^{+} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \overline{V_{out+}} \\ -\overline{I_{out+}} \end{bmatrix}. \quad (21)$$

The equivalent circuit of Converter Block- (see in Fig.2 (b)) can also be analyzed by the same method. Thus, by using Eq.(21), the equivalent circuit of the $4\times$ step-up converter can be expressed by the circuit shown in Fig.11.

In Fig.11, by using Thevenin's theorem, output voltage $\overline{V_{out}}$ is obtained by

$$\overline{V_{out}} = 4(\overline{|V_{in+}|} - V_{th}) \times \frac{R_L}{R_L + R_{SC}^{+}/2}. \quad (22)$$

From Fig.11, the power efficiency of the $4\times$ step-up converter, η, can be expressed by

$$\eta = \frac{\overline{|V_{in+}|} - V_{th}}{\overline{|V_{in+}|}} \times \frac{R_L}{R_L + R_{SC}^{+}/2}.$$

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