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Analysis of Charge Pump Circuits with Threshold-Controlled Switching

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Abstract

This paper studies basic dynamics of charge pump circuits with threshold-controlled switching. Adjusting the threshold value, the circuit can realize fast transient and robust operation. Applying a piecewise linear modeling, the circuit dynamics can be analyzed by exact piecewise solutions. Performing basic numerical experiments, the fast and robust operation are confirmed.

Keywords: Charge-pump, Threshold-controlled switching

1. Introduction

Switched capacitor (SC) techniques are widely used in the power electronics.[1]. As compared with the inductor-based power supplies, the SC-based power supplies are suitable for feature miniaturization, lighter weight and lower noise [2]-[3]. The technology is a kind of switch capacitor technology. and the CP circuit is a typical example of the SC-based power converters. The CP circuit is used mainly as a low power dc-dc converter for power management of integrated circuits. The CP circuit is currently used to generate a voltage higher than the supply voltage and wider output range is possible. In the design of the CP, transient and stability are key points, however, their analysis is not sufficient [4]-[8].

This paper studies a basic charge pump circuit where the switching depends not only on periodic clock but also on state variable. The state-dependent switching uses a voltage-mode threshold-controlled switching (TCS) and is effective for robust and fast operation. Applying a simple piecewise linear modeling, the stability and transient characteristics can be analyzed precisely. Performing basic numerical experiments, the circuit performance is investigated.

2. The Charge Pump Circuit

Fig. 1 shows the circuit: the dc input V_{DD} is applied to the load resistor R_L via the basic charge pump consisting of two capacitors and three switches with inner resistors R_1 and R_2. The three switches can be either of the three states:

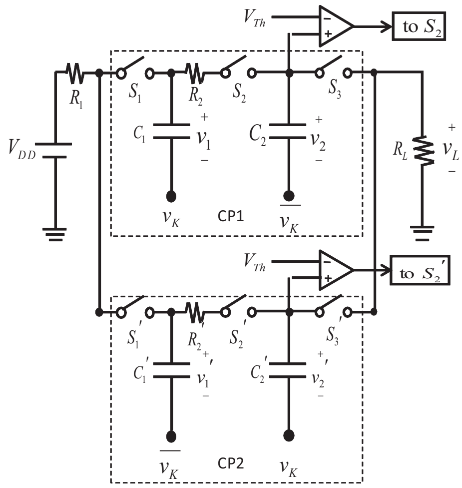

Figure 1: Paralleled 2-Stage Charge pump circuit with Threshold-Controlled Switching

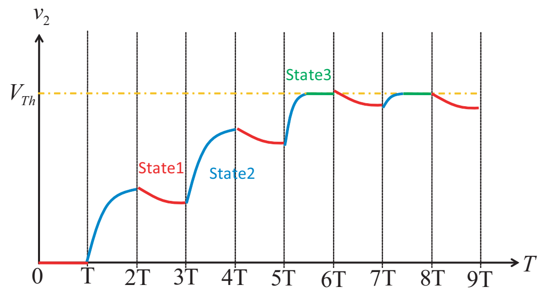

Figure 2: Typical waveform

CP1

State 1: (S_1, S_2, S_3)=(on, off, on), $V_K = 0$
State 2: (S_1, S_2, S_3)=(off, on, off), $V_K = V_{DD}$
State 3: (S_1, S_2, S_3)=(off, off, off), $V_K = V_{DD}$

CP2

State 4: (S'_1, S'_2, S'_3)=(on, off, on), $V_K = V_{DD}$
State 5: (S'_1, S'_2, S'_3)=(off, on, off), $V_K = 0$
State 6: (S'_1, S'_2, S'_3)=(off, off, off), $V_K = 0$

The switching among these state is defined by

$$\begin{array}{l} CP1 \\ \\ \text{State 1} \rightarrow \text{State 2 at } t = (2n-1)T \\ \text{State 2} \rightarrow \text{State 3 if } v_2 = V_{Th} \\ \text{State 2 or 3} \rightarrow \text{State 1 at } t = 2nT \end{array} \tag{1}$$

$$\begin{array}{l} CP2 \\ \\ \text{State 4} \rightarrow \text{State 5 at } t = (2n-1)T \\ \text{State 5} \rightarrow \text{State 6 if } v_2 = V_{Th} \\ \text{State 5 or 6} \rightarrow \text{State 4 at } t = 2nT \end{array} \tag{2}$$

where n denote positive integers. Basically, the sub-circuit CP2 operates in phase shift T to the sub-circuit CP1 where T is the period of the clock signal. The switching depends not only on the periodic clock but also on comparator of the capacitor voltage the threshold V_{Th}. Fig. 2 shows the typical waveform. This threshold control is effective to realize fast transient and strong stability.

3. Stability Analysis

Since the operation of sub-circuit CP2 is phase shift T to the sub-circuit CP1, we consider the sub-circuit CP1 only. The circuit dynamics is described by the following equation and the switching rule (1).

$$\begin{array}{l} \text{State 1} \\ \dot{v}_1 = -\frac{1}{C_1R_1}(v_1 - V_{DD}), \\ \dot{v}_2 = -\frac{1}{C_2R_L}(v_2 + V_{DD}) \\ \text{State 2} \\ \dot{v}_1 = -\frac{1}{C_1R_2}(v_1 - v_2 + V_{DD}), \\ \dot{v}_2 = -\frac{1}{C_2R_2}(-v_1 + v_2 - V_{DD}) \\ \text{State 3} \\ \dot{v}_1 = 0,\ \dot{v}_2 = 0 \end{array} \tag{3}$$

where $\dot{x} \equiv \frac{dv}{dt}$ and R_1 is the internal resistance of the input voltage source V_{DD}. v_L is a output voltage across the load resister R_L. These three states are switched by the rule (1). Using the following dimensionless variables and parameters:

$$\begin{array}{l} \tau = \frac{t}{T},\ x_1 = \frac{v_1}{V_{DD}},\ x_2 = \frac{v_2}{V_{DD}},\ x_L = \frac{v_L}{V_{DD}} \\ X_{Th} = \frac{V_{Th}}{V_{DD}},\ \dot{x} = \frac{dx}{d\tau},\ \alpha = \frac{C_1R_1}{T} \\ \beta_1 = \frac{C_1R_2}{T},\ \beta_2 = \frac{C_2R_2}{T},\ \gamma = \frac{C_2R_L}{T} \end{array} \tag{4}$$

Eq. (3) and the switching rule (1) are transformed into

$$\begin{array}{l} \text{State 1} \\ \dot{x}_1 = -\alpha^{-1}(x_1 - 1), \\ \dot{x}_2 = -\gamma^{-1}(x_2 + 1) \\ \text{State 2} \\ \dot{x}_1 = -\beta_1^{-1}(x_1 - x_2 + 1), \\ \dot{x}_2 = -\beta_2^{-1}(-x_1 + x_2 - 1) \\ \text{State 3} \\ \dot{x}_1 = 0,\ \dot{x}_2 = 0 \end{array} \tag{5}$$

$$\begin{array}{l} \text{State 1} \rightarrow \text{State 2 at } \tau = 2n-1 \\ \text{State 2} \rightarrow \text{State 3 if } x_2 = X_{Th} \\ \text{State 2 or 3} \rightarrow \text{State 1 at } \tau = 2n \end{array} \tag{6}$$

where $\dot{x} \equiv \frac{dx}{d\tau}$. The exact piecewise solutions for initial value $(x_1(0), x_2(0))$ are given by

$$\begin{array}{l} \text{State 1} \\ x_1 = (x_1(0) - 1)e^{-\alpha^{-1}\tau} + 1 \\ x_2 = (x_2(0) + 1)e^{-\gamma^{-1}\tau} - 1 \\ \text{State 2} \\ x_1 = \frac{1}{\beta_1+\beta_2}((\beta_1 + \beta_2 e^{-\Lambda\tau})x_1(0) + (\beta_2 - \beta_2 e^{-\Lambda\tau})x_2(0) \\ -\beta_2 + \beta_2 e^{-\Lambda\tau}) \\ x_2 = \frac{1}{\beta_1+\beta_2}((\beta_1 - \beta_1 e^{-\Lambda\tau})x_1(0) + (\beta_2 + \beta_1 e^{-\Lambda\tau})x_2(0) \\ +\beta_1 - \beta_1 e^{-\Lambda\tau}) \\ \text{State 3} \\ x_1 = x_1(0),\ x_2 = X_{Th} \end{array} \tag{7}$$

where $\Lambda \equiv 1/\beta_1 + 1/\beta_2$. By using these solutions, voltage waveforms can be calculated exactly. Figures 3 and 4 show typical waveforms. In Fig. 3, the state variable x can reach the threshold X_{Th} and the threshold effect can realize fast and robust operation. Varying the value of the threshold, we can adjust the output voltage flexibly. In Fig. 4, the x can not reach the threshold and the robust operation is hard. Figures 5 and 6 show waveforms for $R_2 \rightarrow 0$ corresponding to Figs 3 and 4, respectively. In this case, the analysis can be simplified and the global stability can be guaranteed theoretically [9]. These figures suggest that the simplified model of $R_2 \rightarrow 0$ can approximate waveforms for $\beta_2 < 0.4$

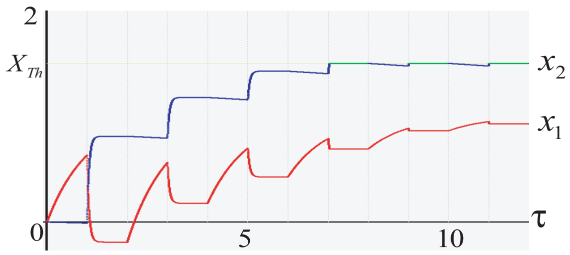

Figure 3: Typical waveform of capacitor voltages for (α, $\beta_1, \beta_2, \gamma, X_{th}$) = (1, 0.1, 0.1, 100, 1.5).

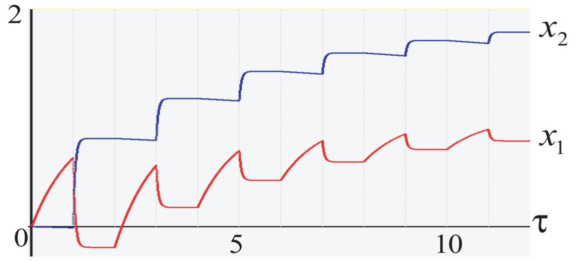

Figure 4: Typical waveform of capacitor voltages for (α, β_1, β_2, γ) = (1, 0.1, 0.1, 100), $X_{th} \geq 2$

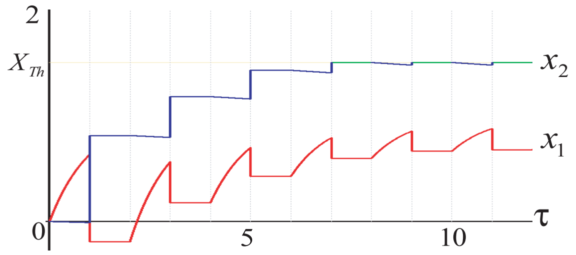

Figure 5: Typical waveform of capacitor voltages for (α, γ, X_{th}) = (1, 100, 1.5), $R_2 \to 0$

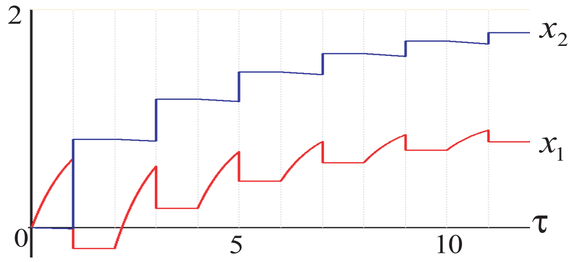

Figure 6: Typical waveform of capacitor voltages for (α, γ) = (1, 100), $X_{th} \geq 2$, $R_2 \to 0$

4. Transient response time

In order to analyze the stability, we define steady state. Let us consider the state variable x_2 that is proportional to the output voltage. Since the system is period 2, we consider $x_2(n)$ and $x_2(n+2)$. If $x_2(n) \to x_2(n+2)$, we can consider that x_2 approaches to a stable steady state. If $R_2 \to 0$, we can guarantee that the steady state has strong stability [9]. Using the exact piecewise solution the transient response time can be expressed explicitly. Figure 7 shows transient response time. The state variable x_2 can reach the threshold for $X_{Th} < 1.95$. If x_2 can reach a threshold X_{Th}, transient response time will be shortened. It is shown that TCS can realize fast transient characteristic.

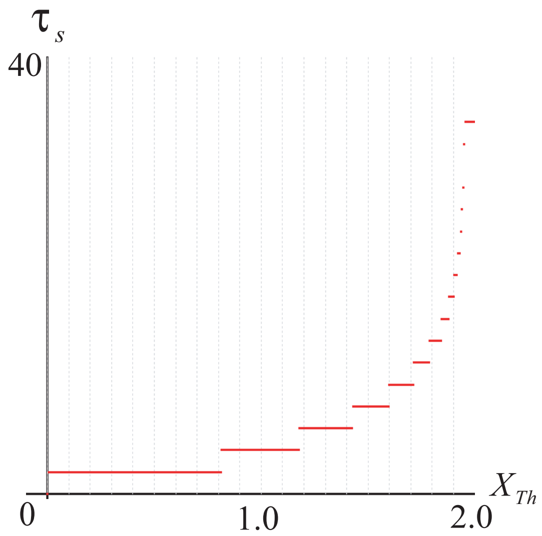

Figure 7: Transient response time

5. Conclusions

The basic CP with TCS is studied in this paper. The TCS is effective to realize stable operation and fast transient. The TCS can realize high-efficiency converter circuit.

Future problems are many, including analysis of generalized CP circuits, design of test circuit for laboratory experiments, and practical applications. The CP circuits devoted various applications such as voltage regulators, inverters and RF antenna switch controllers.

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