Efficiency Analysis of PSM Boost Converter by Energy Balance Model

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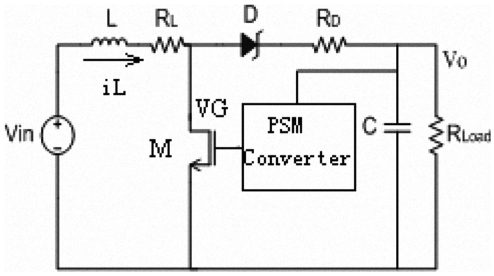
***Abstract*-Pulse Skip Modulation (PSM) is one kind of modulation modes in power converters, which is different from PWM, PFM. Based on the theory of energy conservation, the energy balance (EB) model for PSM Boost converter in DCM (Discontinuous Conduction Mode) is proposed in this paper. Based on the EB model in which all system dissipation is considered, the efficiency of PSM Boost converter operated in DCM is investigated using MATLAB simulation. The comparison with PWM Boost converter under the same circuit parameters with MATLAB and HSPICE simulation proves that PSM converter has higher efficiency at light load.**

I. INTRODUCTION

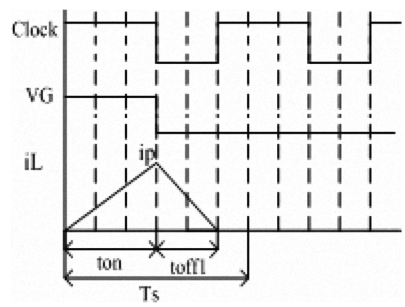
PWM is a common control mode in power converters, but it has lower efficiency at light load[1,2]. To achieve high efficiency in wide load, Pulse Skip Modulation (PSM) is introduced into switching control ICs. PSM mode means control signal will skips some clock periods according to load to regulate the output voltage. PSM mode has high efficiency, especially with light loads, quick response speed and good EMI characteristic and good interference rejection[3,4]. Some products include both PWM and PSM modes[5~7]. When the load is usual, PWM mode is active, and the converter switches to PSM(skip) mode when light load or sleeping status[8]. Although PSM is applied to many products, there are few corresponding research literatures. A research [9] assumes that the regulator operates n cycles as normal "on-off" switching state, while skips m cycles at "off" state, and T_s is one clock cycle. Assume a total large working period is $T=(n+m)T_s$. Because n and m are not known, it is difficult to analyze the efficiency. This paper presents an energy balance (EB) model for PSM Boost converter operated in DCM (Discontinuous Conduction Mode). The efficiency of converter is investigated using MATLAB simulation.

II. ENERGY BALANCE MODEL OF PSM POWER CONVERTER

A Boost converter with PSM controller is shown in Fig.1(a), where V_{in} 、 V_o are the input and output instantaneous voltages respectively. M, D, L, C, R_{Load}, R_L, R_D are the power switch, schottky diode, inductance, capacitance, load resistance, series resistance of inductance and series resistance of schottky diode, V_G is gate voltage of power switch and forward voltage of schottky diode is V_D respectively. Clock signals, control signals of PSM controller and inductance current waveform are shown in Fig.1(b), from which we can get the duty ratio $D_1=t_{on}/T_s$ when switch is *on* and duty ratio $D_2=t_{off1}/T_s$ when switch is *off*. Based PSM modulation principle, PSM converter mainly chooses two kinds of duty ratio signals, one is fixed duty ratio D_1 signal which is maximal duty ratio D_{max} commonly, and the other is zero duty ratio signals. Suppose the setting value of output voltage is V_{ref} and through clock control signal sampling output voltage V_o, when $V_o<V_{ref}$ PSM controller chooses fixed duty ratio signal, otherwise zero duty ratio signal is chosen, namely skipping periods.



(a) Topology of PSM Boost converter



(b) Waveforms of Control signals and i_L

Figure.1 Schematic of PSM boost converter

Considering a general clock period $[nT_s,(n+1)\,T_s]$ and based on law of conservation of energy, it can be written as

$$\Delta E_{in} = \Delta E_c + \Delta E_L + \Delta E_{RLoad} + \Delta E_{loss} \qquad (1)$$

where ΔE_{in} is the amount of energy that has been drawn from the input power source during the considered switching period and can be described as

$$\begin{aligned}\Delta E_{in} &= \int_0^{T_s} V_{in}\cdot I_{in}(t)dt \\ &\approx V_{in}^2 T_s^{\,2} D_1(D_1+D_2)/(2L) \\ &= \frac{V_{in}^2 T_s^2}{2L}\frac{V_{ref}+V_D}{V_{ref}+V_D-V_{in}}D_1^2\end{aligned} \qquad (2)$$

ΔE_L is the difference of the energy stored in the

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inductor and equals to zero because i_L equals to zero at the end of each switching period. ΔE_C is the change of the energy stored in the output capacitor during the same switching period and can be described as

$$\begin{aligned}\Delta E_c &= E_{c,(n+1)T_s} - E_{c,nT_s} \\ &= 0.5C(V^2_{c,(n+1)T_s} - V^2_{c,nT_s})\end{aligned} \tag{3}$$

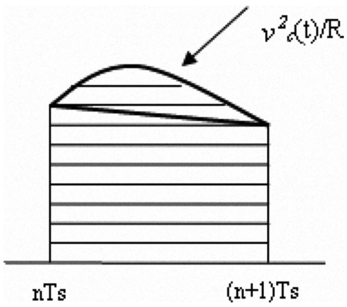

Figure. 2 Trapezoidal approximate method for ΔE_{Rload}

ΔE_{Rload} is the amount of energy delivered to load during the same period and can be described as

$$\Delta E_{RLoad} = \int_{nT_s}^{(n+1)T_s} \frac{v^2_c(t)}{R} dt \tag{4}$$

ΔE_{Rload} can be approximated as trapezoidal area shown in Fig.2. Hence, we can write

$$\Delta E_{RLoad} \approx \frac{T_s}{RC}(E_{C,(n+1)T_s} + E_{C,nT_s}) \tag{5}$$

ΔE_{loss} is the amount of energy delivered to all nonideal components during the same period and can be described as

$$\Delta E_{loss} = \Delta E_{RL} + \Delta E_{MOS} + \Delta E_D + \Delta E_{IC} \tag{6}$$

Based inductance current i_L in Fig.1(b),we can estimate ΔE_{loss}. k_1、k_2 are respectively slope absolute value of inductance current raise and drop, $k_1= V_{in}/L$, $k_2=(V_o+ V_D -V_{in})/L$. ΔE_{RL} is the amount of energy delivered to series resistance of inductance during the same period and can be described as

$$\begin{aligned}\Delta E_{RL} &= \int_0^{t_{on}} R_L\left(\frac{V_{IN}}{L}t\right)^2 dt \\ &+ \int_0^{t_{off1}} R_L\left(\frac{V_O+V_D-V_{IN}}{L}t\right)^2 dt \\ &= \frac{R_L}{3}\times I_P^3 \times\left(\frac{1}{k_1}+\frac{1}{k_2}\right)\end{aligned} \tag{7}$$

ΔE_{MOS} is the amount of energy delivered to power switch during the same period and it includes conduction loss, switch loss and charge loss[10]. The conduction loss is the dissipation of the equivalent resistance of power switch: $\Delta E_{RM} = \int_0^{t_{on}} R_M\left(\frac{V_{IN}}{L}t\right)^2 dt \quad = \frac{R_M}{3k_1}\times I_P^3$; the switch loss: $\Delta E_{switch} = I_{pk}V_{pk}t_r/2$, t_r is the switch time from turn-on to turn-off; the charge loss: $\Delta E_{driver} = Q_g V_g$, Q_g is the charge when gate voltage achieves V_g . Hence, we can write

$$\Delta E_{MOS} = \frac{R_M I_P^3}{3k_1} + I_{pk}V_{pk}t_r/2 + Q_g V_g \tag{8}$$

ΔE_D is the amount of energy delivered to schottky diode which exists series resistance and forward voltage during the same period and can be described as

$$\begin{aligned}\Delta E_D &= \int_0^{t_{off1}} R_D\left(\frac{V_O+V_D-V_{IN}}{L}t\right)^2 dt \\ &+ \int_0^{t_{off1}} V_D\left(\frac{V_O+V_D-V_{IN}}{L}t\right)dt \\ &= R_D\times I_P^3\times\frac{1}{3k_2} + V_D\times I_P^2\times\frac{1}{2k_2}\end{aligned} \tag{9}$$

ΔE_{IC} is the amount of energy delivered to PSM converter chip during the same period and can be described as

$$\Delta E_{IC} = V_{ref} I_o T_s \tag{10}$$

Substituting Eq.(2) to Eq.(10) into Eq.(1) and solving for the energy stored in the output capacitor at the end of the desired switching period, one obtains

$$E_{C,(n+1)T_s} = \frac{1-\theta}{1+\theta}E_{C,nT_s} + \frac{\Delta E_{in}}{1+\theta} - \frac{\Delta E_{loss}}{1+\theta} \tag{11}$$

Where $\theta = \frac{T_s}{RC}$, $K_s = \frac{1-\theta}{1+\theta}$, when $V_0 < V_{ref}$,the period is on, $\Delta E_{in} \neq 0$ and when $V_0 > V_{ref}$,the period is skipped, $\Delta E_{in} = 0$ .So, Eq.(11) can be further expressed as

$$E_{C,(n+1)T_s} = K_s E_{C,nT_s} + \frac{\Delta E_{in}}{1+\theta} - \frac{\Delta E_{loss}}{1+\theta}$$

$$(E_{C,nT_s} < 0.5CV^2_{ref}) \tag{12}$$

$$E_{C,(n+1)T_s} = K_s E_{C,nT_s} - \frac{\Delta E_{IC}}{1+\theta}$$

$$(E_{C,nT_s} > 0.5CV^2_{ref}) \tag{13}$$

Eq.(12) and Eq.(13) are the energy balance model of DCM Boost converter operated in PSM and show the recursive relation of the energy stored in the output capacitor.

III. SIMULATION AND ANALYSIS OF PSM EFFICIENCY

As “on-off” switching state and “off” state are difficult to confirm, so the large working period is hard to get. A MATLAB iterative arithmetic is used to analyze the efficiency in this paper. Take Fig.1(a) as an example, in this circuit, *L=10uH*, *C=33uF*, R_L*=0.161 Ω* , R_D*=0.0378916 Ω*, R_M*=0.198 Ω*, V_D*=0.26V*. The output voltage is 3V stably as the input voltage changes from 1.5V to 2V. The efficiency of the PSM converter will be analyzed as the load resistance changes from 30Ω to 3000Ω.

Suppose the initial energy E_0 is the reference energy, so $E_0 = E_{ref} = \frac{1}{2}CV_{ref}^2$, when $E_n \le E_{ref}$, the period is on, from the energy balance model Eq.(12),we can get

$$E_{n+1} = K_s E_n + \frac{\Delta E_{in}}{1+\theta} - \frac{\Delta E_{loss}}{1+\theta} \qquad (14)$$

So the energy of the next period can be calculated by Eq.(14), the total dissipation of the period is ΔE_{loss}, and the energy transferred to the load is ΔE_{Rload}. When $E_n > E_{ref}$, the period will be skipped, from the energy balance model Eq.(13)we can get

$$E_{n+1} = K_s E_n - \frac{\Delta E_{IC}}{1+\theta} \qquad (15)$$

Similarly, the energy of the next period can be calculated by Eq.(15), the total dissipation of the period is ΔE_{IC}, and the energy transferred to the load is also ΔE_{Rload}.The process above will be calculated by MATLAB iterative arithmetic for 2000 periods, so the total dissipation of all periods E_{loss} and total energy transferred to the load E_{Rload} will be got by addition of every period. Hence the efficiency of PSM power converter is $\eta = \frac{E_{Rload}}{E_{Rload} + E_{loss}}$.

The real line in Fig.3 is the efficiency curve of PSM Boost converter when the input voltage changes from 1.5V to 2V based on MATLAB iterative arithmetic above. Obviously, the efficiency of the PSM converter is high in entire load range and changes little as load changes. To compare with PWM converter with the same circuit topology and parameters, we use the same MATLAB iterative arithmetic to get the efficiency curve of PWM converter when the input voltage changes from 1.5V to 2V as the dashed shown. From Fig.3 we can get that the efficiency of PSM is higher than the efficiency of PWM at light load, and the efficiency of PSM changes much less than PWM in entire load range.

Fig.4 shows the efficiency curve of PSM and PWM converter with MATLAB simulation when the input voltage is 2V and the practice efficiency curve with the same circuit parameters by HSPICE simulation. We can get the efficiency curve by MATLAB accord with the practice efficiency curves by HSPICE. As there are some parasitic resistances and parasitic capacitance in the real circuit which can't be considered in the energy balance model, the practice efficiency curve of PSM will be lower than that by MATLAB. But as the power increase, the influence of the parasitic resistances and capacitance decrease, and the two efficiency curve trend to be compatible. The result of the HSPICE simulation also indicates the efficiency of PSM converter at light load is higher than that of PWM. Fig.5 is the output voltage waveform by HSPICE simulation. The output ripple is below 5％,so the PSM is a good power switching converter.

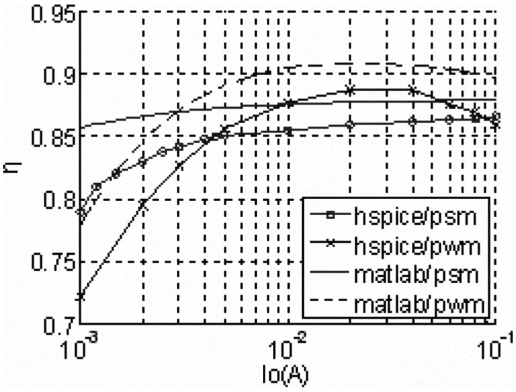

Figure.3 Efficiency waveforms of PSM/PWM Boost converter with MATLAB

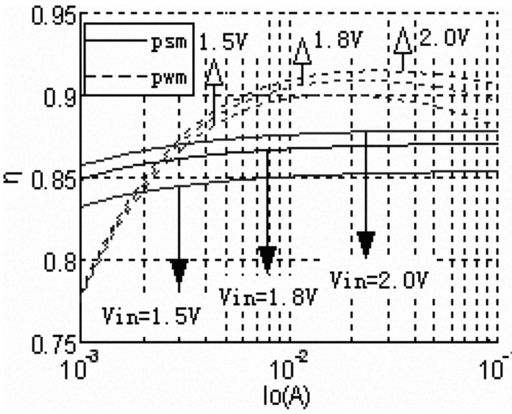

Figure.4 Efficiency waveforms of PSM/PWM Boost converter with MATLAB/HSPICE

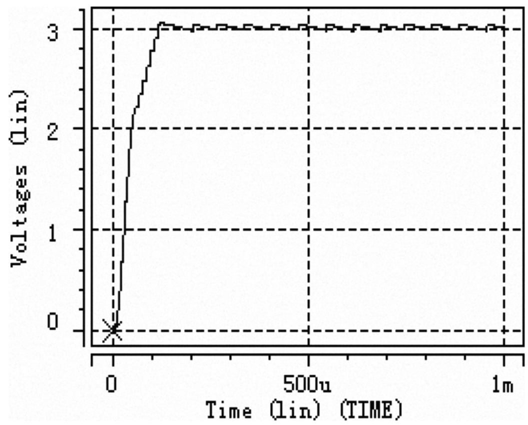

Figure.5 Waveform of output voltage

IV. CONCLUSIONG

Based on the Boost topology structure, an analytic energy model considering all system dissipation in DCM mode is proposed in this paper. Based the energy balance model, the efficiency of the PSM converter is analyzed by MATLAB iterative operation, and the efficiency analysis result tally with the corresponding actual simulation result. Through compared with PWM converter with the same circuit parameters, we get the efficiency of PSM converter at light load in different input voltages is all higher than those of PWM, and changes little as the load changes. As PSM converter has the advantage of high efficiency at light load, skip mode is introduced into PWM control mode to achieve high efficiency in wide load range and low power dissipation.

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