Loss Analysis of a Single Phase Fast Transient VRM Converter

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Abstract*— This paper analyzes the losses of a stepping inductor converter in the presence of load transients. Stepping inductor converter is a buck VRM topology which only employs a single phase. Stepping inductor converter is very effective in dealing with fast transient and at the same time it can give better steady state efficiency. Occurrences of transient load current changes are measured in a PC and data are used for the comparison to evaluate the real world performance of the stepping inductor converter and the multiphase interleaved buck converter.

***Keywords* - Buck converter, fast transient, stepping inductor, VRM**

I. INTRODUCTION

In order to tackle the issues of fast transient several voltage regulator module (VRM) topologies have been proposed. The multiphase interleaved topology [1] is currently the most popular. However, it needs several "phases" with more power devices as well as control channels. A stepping inductor topology has been proposed recently [2] which employs a single phase only which has simpler configuration and has been shown to be very effective. It has been proved that stepping inductor converter is very effective in dealing with fast transient and at the same time it can give better steady state efficiency because a large inductance inductor can be used.

Loss during transient is a concern. This paper attempts to analyze the losses of the stepping inductor converter in presence of load transients. The occurrences of load transients in a personal computer running different kinds of benchmark applications are measured. Then the losses of the VRMs are compared in terms of the occurrence of transients measured.

II. OPERATION OF STEPPING INDUCTOR CONVERTER

The stepping inductor converter is a single phase topology for VRM fast transient application. The detailed operation is discussed in [2]. The stepping inductor converter operates in a fashion that in steady state the output inductor is a large inductor and when in transient the large output inductor is "short circuited" and replaced by a very small inductor. In this way the stepping inductor converter can benefit from a large output inductor so that ripple voltage and current is lower and efficiency is higher, and at the same time it can offer a fast transient response of a very low inductance buck converter. The small inductor can be as low as the leakage inductance between the main and auxiliary windings. The simplified circuit diagram is shown in Fig.1 and the simplified operating waveform is shown in Fig.2. Fig.3 and Fig.4 show the performance improvement by using stepping inductor.

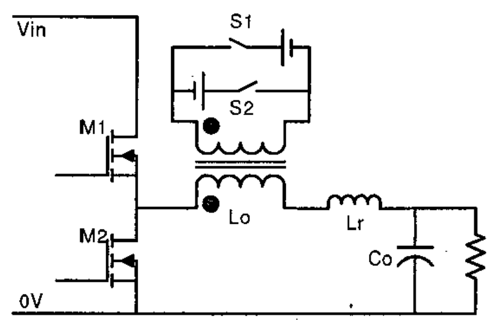


Figure 1. Conceptual circuit of stepping inductor

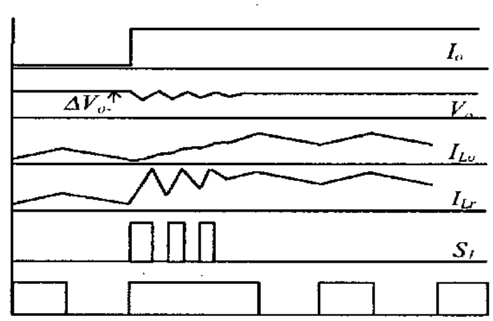


Figure 2. Simplified operating waveform

The additional parts count in stepping inductor converter is low. The control of the stepping inductor converter is also simple. The main loop is the same as that in a buck converter. The auxiliary control loop consists of two comparators only and is separated from the main control loop. It has only one power channel it does not have the problem of current sharing. During transient the current mismatch in Lo and Lr has to be dissipated or reclaimed. This is the reason that stepping inductor is lossy during transient.

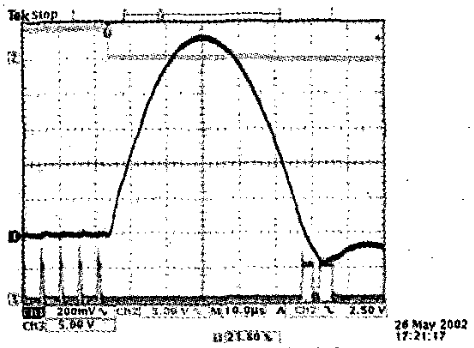


Figure 3. Without stepping inductor

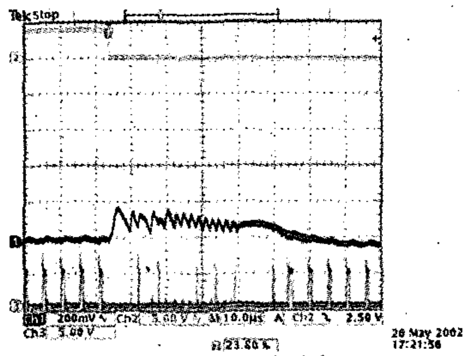


Figure 4. With stepping inductor

III. DETAILED ANALYSIS OF STEPPING INDUCTOR CONVERTER

In the analysis, it is assumed that the main MOSFETs M1 and M2 are kept on and off correctly in the transient, i.e. M1 off and M2 on in step-down transient and M1 on and M2 off in step-up transient. It is also assumed that the leakage inductance Ll is much smaller than the magnetizing inductance Lm. The implementation of the stepping inductor converter is shown in Fig. 5. Fig. 6 and Fig. 7 show the operating waveforms of the stepping inductor converter in response to a load current step-down and step-up respectively.

The equivalent circuits in different stages in a transient are shown in TABLE I. When there is a transient the output voltage will increase or decrease depending on the type of transient. The switches S1 and S2 are controlled by two hysteresis comparators which monitor the output voltage and turns on S1 or S2 according to the transient.

Step-down Transient:

At t=0 in Fig. 6 the load step-down occur and the output voltage begin to rise. At time t1 the output voltage cross the comparator turn on voltage Vth+Vh/2 and the switch S2 is turned on. This is the beginning of stage 1. After S2 is turned on, the magnetizing inductor is shorted by a voltage source Vs and the output voltage falls quickly. Note that at the beginning of stage 1 the current in the inductors Lm and L_l are equal, but as different voltages are applied on Lm and L_l, the currents in Lm and L_l after the beginning of stage 1 will be different. When the output voltage falls to the comparator turn off voltage Vth-Vh/2 the switch S2 is turned off and stage 2 begins. In stage 2 because the currents in the leakage inductance i_L and magnetizing inductance i_M do not match, the mismatch current will flow in to the reset voltage source Vr, which is implemented by a zener diode and the input voltage. After the currents i_L and i_M match it enters stage 3. If the currents i_L and i_M have fallen to the level of the current the output voltage would not rise to the turn on threshold of S2 and the transient ends, otherwise S2 will be turned on again and the converter enters stage 1 again and the process repeats until the currents i_L and i_M equals to the output current. However, it can be shown that the duration of stage 3 is much shorter than stage 1 and stage 2 so that it can be neglected for analysis. The solutions for output voltage and inductor currents are shown below:

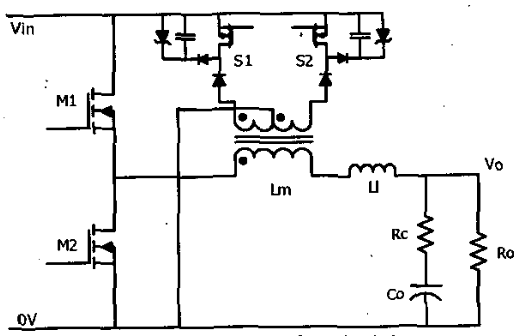


Figure 5. Implementation of stepping inductor

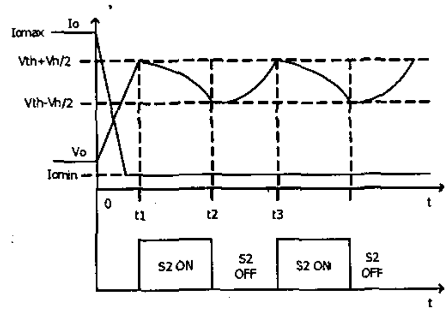


Figure 6. Load step-down transient

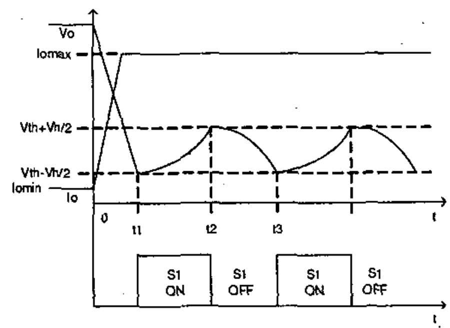
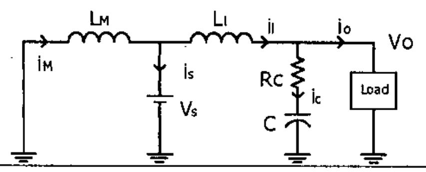
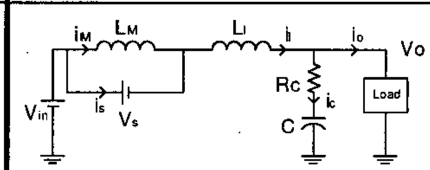
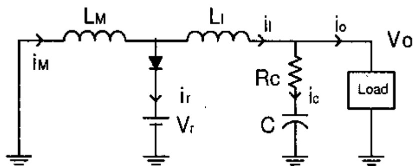
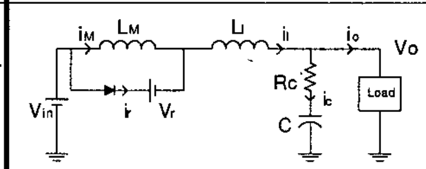
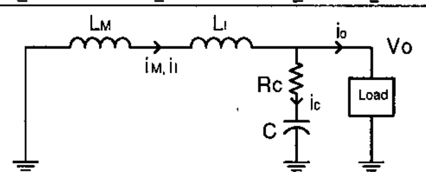
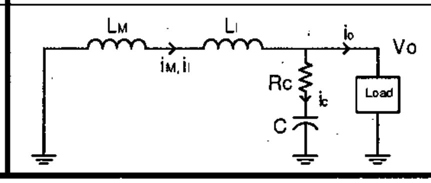


Figure 7. Load step-up transient

TABLE I. EQUIVALENT CIRCUIT DURING LOAD TRANSIENT

	Load Current Step-down		Load Current Step-up	
Stage 1		M2 ON S2 ON		M1 ON S1 ON
Stage 2		M2 ON S2 OFF		M1 ON S1 OFF
Stage 3		M2 ON S2 OFF		M1 ON S1 OFF

	Stage 1	Stage 2
Output voltage and inductor currents	$i_m(t)=I_{omax}-\frac{Vs}{Lm}t$ $i_l(t)=I_{omax}-\frac{V_{th}-Vs}{L_l}t$ $v_o(t)=-\frac{V_{th}-Vs}{2C\cdot L_l}t^2+\frac{L_l(I_{omax}-I_{omin})-C\cdot Rc\cdot(V_{th}-Vs)}{C\cdot L_l}t+V_h+\frac{V_h}{2}\equiv a_1t^2+b_1t+c_1$ $t2=\frac{-b_1-\sqrt{b_1^2-4a_1V_h}}{2a_1}$	$i_m(t)=i_m(t2)-\frac{Vr}{Lm}t$ $i_l(t)=i_l(t2)+\frac{Vr-V_{th}}{L_l}t$ $v_o(t)=\frac{Vr-V_{th}}{2C\cdot L_l}t^2+\frac{L_l(i_l(t2)-I_{omin})-C\cdot Rc\cdot(Vr-V_{th})}{C\cdot L_l}t+V_h-\frac{V_h}{2}\equiv a_2t^2+b_2t+c_2$ $t3=\frac{-b_2+\sqrt{b_2^2+4a_2V_h}}{2a_2}$

The energy that flows into the shorting voltage source Vs is given by:

$$W_1=\int_{t1}^{t2}i_s(t)Vsdt=\frac{(V_{th}-Vs)Vs\cdot t2^2}{2L_l} \qquad (1)$$

This is the energy reclaimed in stage 1 for the implementation shown in Fig. 5.

The energy that flows into the resetting voltage source Vr is given by:

$$W_2=\int_0^{t_{ir0}}i_r(t)\cdot V_r\,dt=V_r\left[\left(i_m(t2)-i_l(t2)\right)\cdot t_{ir0}-\frac{V_r-V_{th}}{2\cdot L_l}\cdot t_{ir0}^2\right] \qquad (2)$$

where t_{ir0} is the time when $i_m(t)=i_l(t)$ *in stage 3.*

Depending on the implementation of the resetting voltage source Vr, a portion of this energy is dissipated and the remaining is fed back to the input. This is the loss introduced by stepping inductor during transient. For the step-up transient the same procedure is followed and the corresponding result can be obtained and it is skipped here.

To calculate the loss of stepping inductor converter in a load step-down transient an iteration of the above procedure has to be carried out. The successive energy losses in stage 2 are added and the sum is the total loss introduced by stepping inductor in response to one load step down transient.

IV. EXPERIMENTAL VERIFICATION

In order to verify the accuracy of (2) for calculating the loss of the stepping inductor converter, a hardware prototype is built and tested using the following circuit and operation parameters: V_{in} = 12V, V_o = 1.5V, I_{omax}= 35A, I_{omin} = 0.5A, V_s = 0.3125V, V_r = 2V, V_{th} = 1.53V, V_h = 50mV, C = 2500μF, L_m = 3.5μH, L_l= 40nH, and R_c = 1mΩ.

A step load change of 0.5A to 35A at the frequency of 167Hz is applied to the converter. Assuming losses due to step up and step down are equal, the loss contributed from stepping inductor at 167Hz step load change from (2) is 0.41W. The measured total loss from the stepping inductor converter (obtained from subtraction of the average input power without the stepping inductor to the average input power with the stepping inductor) is 0.49W, which is close to the mathematical prediction. The extra loss may due to the constant housekeeping power such as fast switching gate drivers, switching and conduction losses of the MOSFETs, and comparators. With the increase of step load frequency or the increase of load step magnitude, the error of (2) to practical measurement data can be reduced.

V. Real World VRM Output Current Transient Measurement

The multiphase interleaved buck converter improves transient response by means of a small equivalent inductance so that output current slew rate can be high. However this brings the problem of large ripple current in each phase although the effective output ripple current is lower due to interleaving. It can be expected that the steady state efficiency of the multiphase interleaved buck converter will be low. On the other hand, the stepping inductor converter allows the use of large inductance while at the same time provides a fast transient response by additional actions. The efficiency of the stepping inductor converter is higher in steady state. However the additional actions in dealing with transient in stepping inductor converter may cause extra loss. In actual VRM application, efficiency will depend on the frequency and amplitude of the load current transient. In order to compare the efficiency of the VRMs fairly, the effect of load transient must be taken into account.

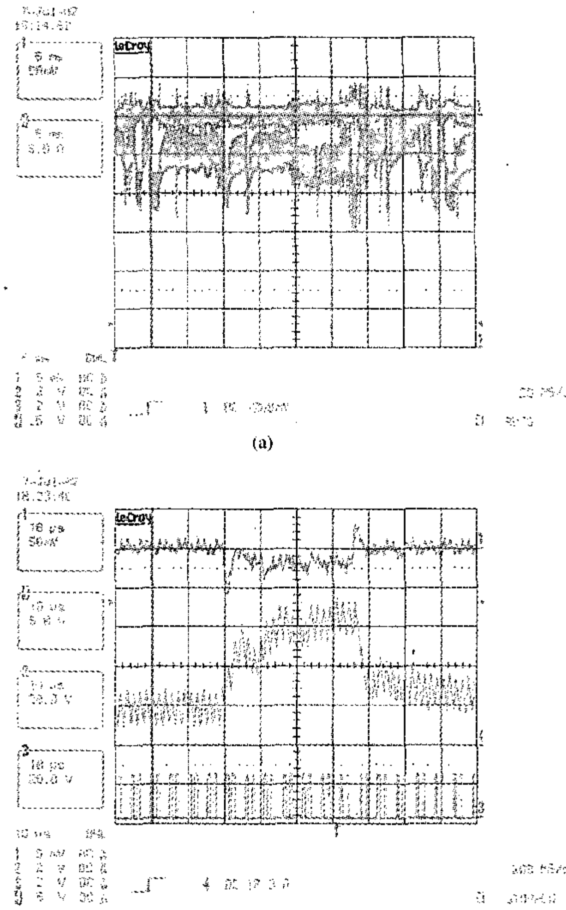
A. Methodology

A Pentium4 PC is set up and different kinds of benchmark program are run on the computer and the output current of the VRM is measured. Afterward the occurrence of VRM output current transient is recorded. Fig. 8 shows a typical waveform of the VRM output voltage and current transient. The specifications of the test PC are listed in TABLE III.

B. Results

As shown in Fig. 9, it can be seen that large step change in current is very rare and most of the transient are of low amplitudes. When the transient step size is small the efficiency of the multiphase interleaved buck converter will approach its steady state value. For the stepping inductor converter, low amplitude transient means a shorter recovery time and lower auxiliary switching cycles; both will lead to a smaller loss caused by the extra actions in stepping inductor converter. It can be expected that the energy loss due to transient in stepping inductor converter will be low. As a result the overall actual efficiency is expected to be higher than that of the multiphase interleaved converter.

To estimate the extra loss of the stepping inductor converter working according to TABLE III, (2) is used to calculate the sum of loss at different load step size (both step up and step down conditions and takes the mean of each load step size) and frequency as given in Fig. 9. The estimated extra loss is 4.93W.



(a)

(b)

Figure 8. VRM output voltage and current
(b) Exaggerated View
Ch1: VRM Output Voltage
Ch4: VRM Output Current
Ch2, Ch3: Gate drive of high side MOSFETs

TABLE III. Test PC Specifications

Processor	Intel Pentium4 2.26GHz Northwood core
Motherboard	Intel i845G Chipset motherboard
RAM	256 MB PC333 DDR-SDRAM, CL2.5
VRM	3 Phase interleaved buck, L=820nH per phase, fs=190k
Measured Maximum Output Current	30A
Idle State Current	5A
Operating System	Microsoft Windows XP Professional
Benchmarks and Settings	PCMark2002 (CPU Benchmark only)
	3DMark2001 SE, Default Settings, 1024x768x16

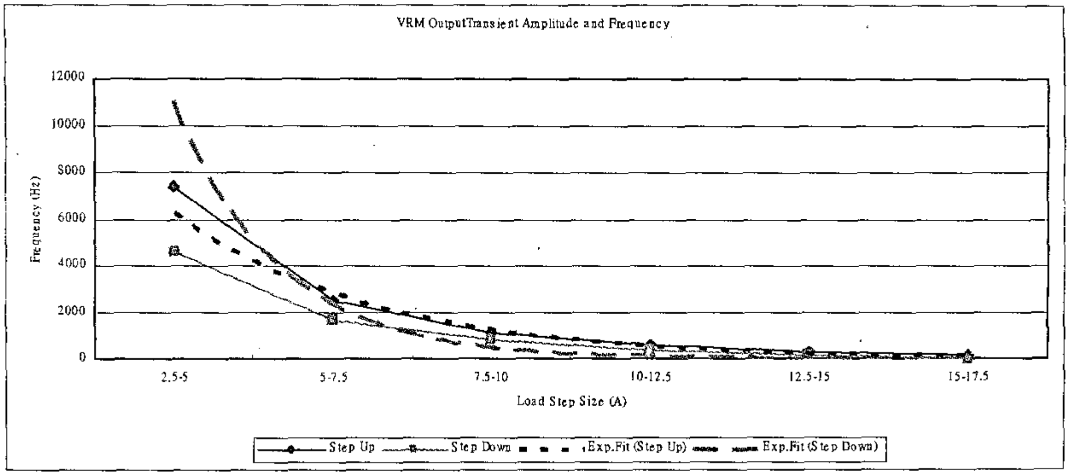


Figure 9. VRM output current transient amplitude and frequency

VI. CONCLUSION

It has been proven that the stepping inductor converter has a higher efficiency than a single channel and multiphase interleaved buck converter in steady state [3]. In this paper a way to calculate the transient loss of a stepping inductor converter is presented so that a complete comparison of the stepping inductor converter to other VRM topologies in real world VRM applications can be obtained.

VII. FURTHER WORKS

Detailed analysis of losses in the stepping inductor converter and other VRM topologies, including multiphase interleaved buck, under a realistic load profile which reflects the characteristics of modern CPU will be carried out, because the frequency and magnitude of the load transients will directly affect the amount of losses produced. Measurements show that the occurrence of high current transient is very rare. However, further work will illustrate this in a quantitative manner.

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