Comparison of Three Topologies for VRM Fast Transient Application

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***Abstract*-This paper compares three topologies for voltage regulator module VRM for fast transient application. The topologies are the most popular multi-phase converter, a synchronous rectifier buck converter topology and a recently introduced new stepping inductor converter. Analysis and simulation show that the stepping inductor topology gives the fastest response with minimal amount of output filter capacitance.**

I. INTRODUCTION

In the past a lot of work had been expended on improving the transient response of the control loop such as load current feedforward [1], feedforward of the capacitor current [2] and V^2 control [3]. Substantial improvement has been reported by these control schemes comparing with conventional control topology, however there is still room for further improvement. Intuitively hysteresis comparator seems to be the fastest because it has the least number of passive components and is able to trigger the power switch on or off with extremely short delay when a step load change occurs.

The simplest method to enhance fast transient of VRM is to reduce the value of the output inductor or increase the output filter capacitance. In the presence of a large capacitance, the voltage regulating loop must be fast enough to produce minimum current ramp-up (or ramp-down time) and if the loop response is sluggish, the peak deviation tends to approach the open loop value of the deviation [4]. Meanwhile large capacitance requires more volume and printed circuit board area. Small inductor produces large current ripple which will result in several problems. The first problem is high switch conduction loss due to high RMS current. Secondly, high ripple current needs more capacitance for ripple suppression. Thirdly, switching loss will increase and larger current ripple will also cause high core loss in the inductor.

Most VRMs today use the conventional buck or synchronous rectifier buck converter. In order to have high efficiency the value of the inductor should be kept large in order to reduce ripple current. But this is a contradiction to the fast transient requirement. The remedy is to use more capacitance because more capacitance produces less overall ESR and ESL producing smaller deviation at the output voltage. Unfortunately, more capacitance with less ESR costs more and has problems as discussed above.

In order to tackle the issue of fast transient, several VRM topologies have been proposed. The simplest topology is the synchronous rectifier buck converter. Another topology is the multiphase interleaved topology [5], it is so far the most popular. However, it needs several "phases" with more power devices as well as control channels. The third one is stepping inductor topology has been proposed recently [6] which employs a single power channel only which has simpler configuration and has been shown to be very effective. This paper compares the three topologies analytically and by simulation.

II. THE THREE TOPOLOGIES

A. Single Channel Buck

The single channel buck converter is the simplest topology for VRM application. When the buck converter is being used in VRM application, in order to offer a fast transient response, the output inductance is made small. However, decreasing the output inductance does cause problems. One problem is that a high ripple current. High ripple current not only decrease converter efficiency but also make the peak semiconductor current high. One method to solve the problem is to parallel several converter modules, with all modules having the same drive signal. When several buck converter modules are paralleled the equivalent output inductance is reduced by a factor of the number of modules being paralleled. This is a quite economic way to increase the transient performance because the gate drive and control is exactly the same as the single channel converter.

B. Multi Phase Interleave Buck

The multi phase interleave buck converter [5] is currently the most common topology for VRM fast transient application. Fig.1 shows a schematic diagram of the topology.

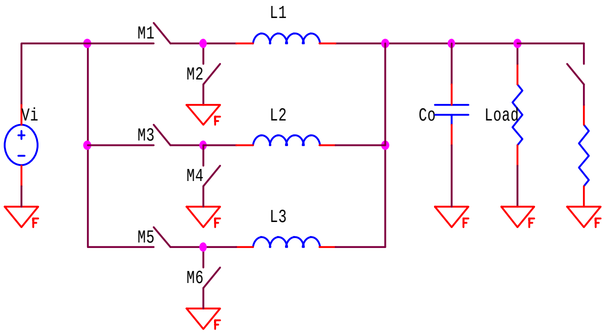


Fig. 1 Interleaved Buck Converter

The connection of this converter is exactly the same as the parallel buck converter but the gate drive signal here are phase shifted by an amount equal to the switching period divided by the number of phase. With this interleaving method the effective current ripple frequency seen by the output capacitor is multiplied by the number of phase. The controller used in this topology is different from that used in single channel buck converter because the controller must be able to produce a phase shifted driving signal for each phase.

C. Stepping Inductor Converter

The stepping inductor converter is a new topology for VRM fast transient application. The detailed operation is discussed in [6]. The simplified circuit diagram is shown in Fig.2 and the simplified operating waveform is shown in Fig.3.

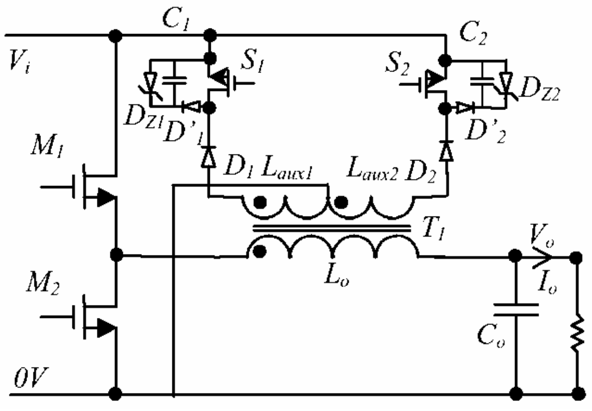


Fig. 2 Simplified Circuit of Stepping Inductor

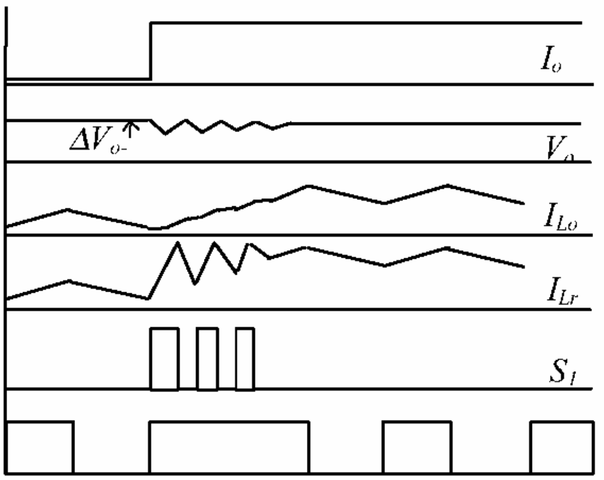


Fig. 3 Simplified Operating Waveform

The stepping inductor converter is a derivative of a single channel buck converter. It operats in a fashion that in steady state the output inductor is a large inductor and when in transient the large output is "short circuited" and replaced with 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, 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. Additional parts count in this converter is low, only two small mosfets and two comparators and a few logic gates. The control of the stepping inductor converter is also very simple. The main control loop is exactly the same as that used in a single channel 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.

III. Comparison Of Steady State Losses

In order to compare the three converters, it is assumed that the control loop, switching frequency and output capacitor are the same but the inductor value of the multi phase converter is n times that of the convention buck converter. It is also assumed that:

1. Multi phase converter has n phases in parallel
2. Switching frequency of the conventional buck converter is the same as the interleaved converter
3. Inductance of the interleaved converter is n times that of the conventional buck converter
4. The MOSFETs used are all the same in all converters
5. Number of MOSFETs is also the same which means that in conventional buck converter there

are n MOSFETs working in parallel both on the high side and on the low side.

The specifications of the two converters are summarized in table I.

TABLE I

SPECIFICATIONS OF CONVERTERS

	Single Channel Buck	Multi Phase Interleave
Phase Number	1	n
Switching Frequency	f	f
Inductance	L	nL
Number of mosfets	2n	2n

A. Semiconductor Conduction Loss

Table II shows the circuit parameters of the two converters.

TABLE II

CIRCUIT PARAMETER

	Single Channel Buck	Multi Phase Interleave (per phase values)
High side $R_{ds(on)1}$	$\frac{R_{ds(on)1}}{n}$	$R_{ds(on)1}$
Low side $R_{ds(on)2}$	$\frac{R_{ds(on)2}}{n}$	$R_{ds(on)2}$
Duty Cycle	D	D
Average output current	I_m	$\frac{I_m}{n}$
Ripple current	$n\Delta I$	ΔI
Maximum current	$I_m + \frac{n}{2}\Delta I$	$\frac{I_m}{n} + \frac{1}{2}\Delta I$
Minimum current	$I_m - \frac{n}{2}\Delta I$	$\frac{I_m}{n} - \frac{1}{2}\Delta I$
RMS current of high side switch	$\sqrt{D(I_m^2 + \frac{n^2\Delta I^2}{12})}$	$\frac{1}{n}\sqrt{D(I_m^2 + \frac{n^2\Delta I^2}{12})}$
RMS current of low side switch	$\sqrt{(1-D)(I_m^2 + \frac{n^2\Delta I^2}{12})}$	$\frac{1}{n}\sqrt{(1-D)(I_m^2 + \frac{n^2\Delta I^2}{12})}$
High side conduction loss	$D(I_m^2 + \frac{n^2\Delta I^2}{12})\frac{R_{ds(on)1}}{n}$	$D(I_m^2 + \frac{n^2\Delta I^2}{12})\frac{R_{ds(on)1}}{n}$ (Total)
Low side conduction loss	$(1-D)(I_m^2 + \frac{n^2\Delta I^2}{12})\frac{R_{ds(on)2}}{n}$	$(1-D)(I_m^2 + \frac{n^2\Delta I^2}{12})\frac{R_{ds(on)2}}{n}$ (Total)

From Table.2 it can be easily seen that under the specified specifications the semiconductor loss are the same for both buck and multi phase interleave converter.

B. Inductor Copper and Magnetic Loss

Because the inductor in the single channel buck converter the inductance is one n^{th} of that in the interleaved converter, direct paralleling of the n inductors used in the interleave converter will give an inductor for the single channel buck converter. In this case the inductor copper will be the same for both converters.

Consider the case of a 4 phase interleave converter, where each inductor consist of 4 turns of wire with inductance 4L as illustrated in Fig.4a. In order to obtain one fourth inductance (L) in a buck converter with equal core count with the interleave converter, it requires only one turn. The inductor for the buck converter can be constructed as shown in Fig.4b.

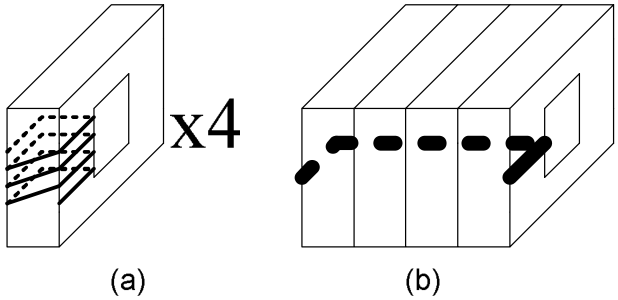


Fig. 4 Inductor construction, a) 4 phase interleave converter, b) Stepping inductor converter

Assume all the magnetic cores are all the same with square cross section of length d, and that the wire in the buck inductor has 4 times the cross section area so that the total wire area are the same for both inducor. The total copper loss for the 4 phase interleave converter is:

$$\frac{15}{4}dik(I_m^2 + \frac{4}{3}\Delta I^2)$$

where k is a constant. The copper loss in stepping inductor is:

$$\frac{3}{2}dik(I_m^2 + \frac{4}{3}\Delta I^2)$$

As a result the stepping inductor offers a 60% reduction in resistance. It should be mentioned that with a load current of 50A, every single milliohm of resistance dissipates 2.5W of power. In addition, a one turn inductor is simpler in construction than a 4 turn inductor.

For magnetic core loss, as each inductor in the interleaved converter consists of 4 turns of wire, the DC bias current and AC current are respectively I_m and $2\Delta I$. In the buck converter, the inductor consists of 1 turn of wire, as a result the DC bias current and the AC current are also I_m and $2\Delta I$ respectively. It can be concluded that in the above case the total inductor loss in the interleave converter is higher than that of a single channel buck converter.

IV. COMPARISON OF TRANSIENT RESPONSE

In order to provide a fair transient response comparison of the three converters, it is desired to have an accurate model of each converter. For steady state analysis, the small signal average model is more than enough. However for large signal transient analysis, there is still no analytical model that can accurately predict the response of the converters. As a result, time domain computer simulation will be performed on the three converters.

A. Methodology

The three converters are simulated using PSpice. The output voltage response to a 50A load step is analyzed. Before the load current step occurs, the converters are operating in the steady state. Simulation is performed with current load step occurring at different position in time relative to the turn-on instant of the high side switch as shown in Fig.5.The switching period is 5us for a 200 kHz converter. The instant at which the high side switch turns on is denoted by t_0. The current load step is configured to occur at $t_0 + t$, with t increases from 0 to 5us.

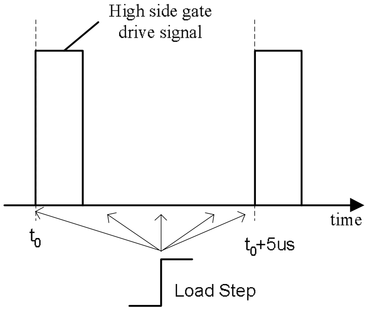


Fig. 5 Load Step Position

After the load step change occurred the maximum voltage overshoot or undershoot is measured and recorded. A typical load step response is shown in Fig.6.

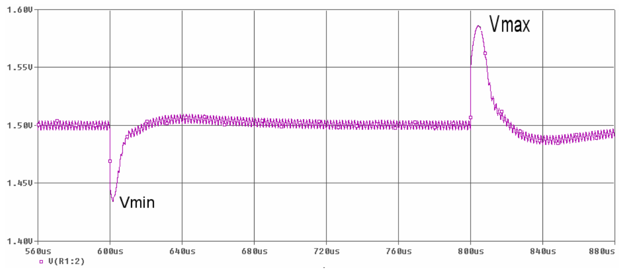


Fig. 6 A typical load step response

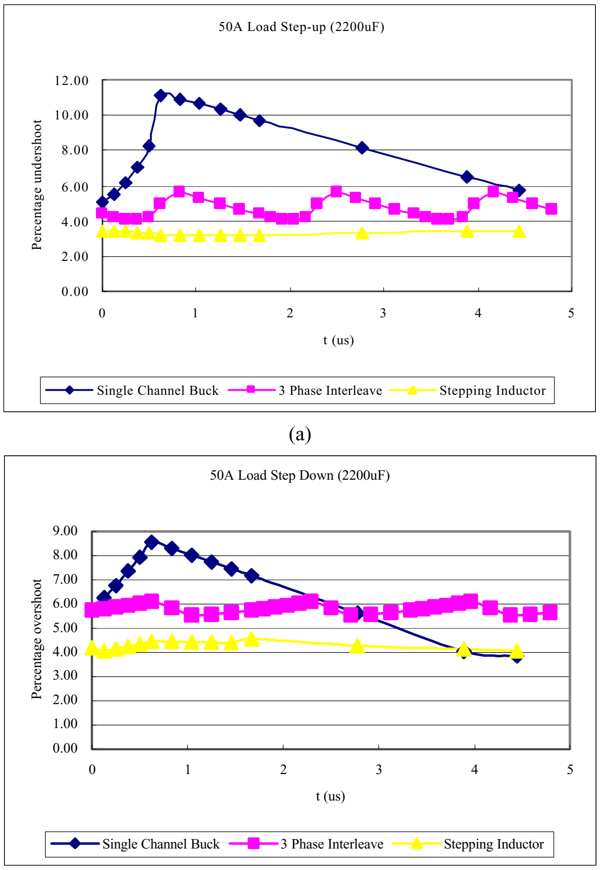
B. Simulation Results

Three converters are simulated using the respective topologies and the main circuit parameters are listed in Table III.

TABLE III
SIMULATION CIRCUITS PARAMETERS

	Buck	3 Phase Interleave	Stepping Inductor
Input Voltage (V)	12	12	12
Output Voltage (V)	1.5	1.5	1.5
Minimum Load (A)	1	1	1
Load Step (A)	50	50	50
Switching Frequency (Hz)	200k	200k	200k
Output Inductance	200nH	600nH (each)	1.8uH+ 100nH
Capacitance	2200µF	2200µF	2200µF
	22000µF	22000µF	22000µF
Close loop gain crossover frequency	80kHz	80kHz	80kHz

Fig. 5 shows the transient performance comparison between the three converters, with step load change occurring in different positions relative to the turn on of the high side switch.



(a)

(b)

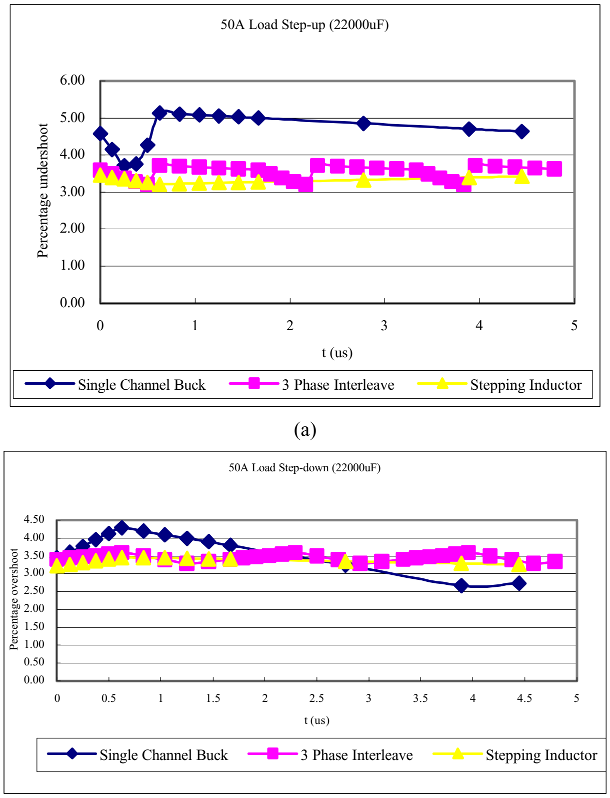
Fig. 5 Transient comparison between converters, C_{out}=2200µF, a) 50A load step-up, b) 50A load step down

From Fig.5, it can be seen that the interleave converter enjoys a more steady transient response over the entire step load position, while the buck converter shows a transient performance very dependent on the position of the transient. It can also be observed that the stepping inductor has a transient response almost independent on the position of the transient, and its overshoot and undershoot is the lowest among the three.

The transient performance of the buck and interleave converters during load step-down is dependent on the position of the load step. At the position where the inductor current is high in the buck converter the load step-down performance shows a higher voltage overshoot and on the position where the inductor current is low in the parallel converter the load step-down performance shows a lower voltage overshoot than the interleaved converter. In the stepping inductor converter, when the voltage overshoot or undershoot is higher that the threshold voltage, the auxiliary circuit takes the control. The large inductor is shorted and leaves only the very small inductor. As a result the transient performance is almost independent on the position of the transient.

Fig.5 concludes that interleaving offers considerable improvement over the conventional buck convert, and the stepping inductor converter can provide even more improvement.

Fig.6 shows the transient performance comparison between the three converters, with output capacitor increased to 22000µF.



(a)

(b)

Fig. 6 Transient comparison between converters, C_{out}=22000µF, a) 50A load step up, b) 50A load step down

From Fig.6, again, it can be observed that the output voltage deviation of the buck converter depends more on the position of the step load change than that of the interleaved and stepping inductor converters, but the dependency is much reduced when compared to the 2200uF case.

Both the buck and the interleave converter gain from increased output capacitance, but still they cannot reach the level of the stepping inductor converter.

In this case, the interleaved converter still offers a improvement over the buck converter, but the amount is less noticeable.

From the above result, it can be concluded that with stepping inductor, the transient response of a conventional buck converter can be much improved without adding a large amount of output capacitors. On the other hand, the interleave converter provides a improved transient response over the buck converter at the expenses of high parts count and complex control.

V. CONCLUSION

A comparison of several VRM topologies is made in this paper. It can be concluded that in steady state the efficiency of the single channel buck and the interleave buck are the same. While the stepping inductor offer the possibility of using a large output inductor to reduce ripple and increase efficiency.

Interleaving can improve transient performance significantly over conventional buck converter only when the output capacitance is low. When the output capacitance is high the improvement of interleave converter over the parallel converter become less noticeable. The interleave converter provides a better transient performance over the buck at the expenses of high parts count and complex dedicated control.

The stepping inductor converter improves transient performance of the buck converter by adding auxiliary circuit. The parts count is low and at the same time it can provide the fastest transient response [6]. Its control is simple and is separated from the main control loop. The capacitance requirement is lowest and has no current sharing problem.

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