Design and Simulation of Synchronous Buck Converter for Microprocessor Applications
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Abstract: The power requirements for the microprocessor have been increasing as per Moore’s law. According to International Technology Roadmap (ITRS), the voltage regulator module (VRM) for microprocessor will be 96W (with 0.8V, 120A output). With VRMs topology of synchronous buck converter, serious technical challenges such as small duty cycle, high switching frequencies, and higher current demands, contribute to decreased power density and increased cost. This paper proposes a multiphase synchronous buck topology to solve the technical challenges of powering future microprocessors. The critical design parameter values are selected using the theoretical design equations and calculations. The design is simulated in Matlab/Simulink to evaluate the performance criteria of the VRM.

Keywords: Voltage regulator module (VRM), MOSFET, multiphase buck converter.

I. INTRODUCTION
"Power electronics is the technology associated with the efficient conversion, control and conditioning of electric power by static means from its available input form into the desired electrical output form”.

It combines power, electronics and control. The control deals with the steady state and dynamic characteristics of closed loop systems. The power deals with the static and rotating power equipment for the generation, transmission and distribution of electric energy. The electronics deal with the solid state devices and circuits for signal processing to meet the desired control objectives. Power electronics refers to control and conversion of electrical power by power semiconductor devices wherein these devices operate as switches.

Advent of silicon-controlled rectifiers, abbreviated as SCRs, led to the development of Power Electronics. Prior to the introduction of SCRs, mercury-arc rectifiers were used for controlling electrical power, but such rectifier circuits were part of industrial electronics and the scope for applications of mercury-arc rectifiers was limited. Once the SCRs were available, the application area spread to many fields such as drives, power supplies, aviation electronics, high frequency inverters, and this originated the new field of power electronics. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors, transistors, IGBTs and GTOs. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. The most typical power electronics devices can be found in many consumer electronic devices, e.g., television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. Power electronics provides power conversion process where goals are to reduce the power loss and increase energy efficiency with reduction in size, weight and the overall cost of the unit.

Types of Power Electronics Circuits
In general, power electronics circuits can be classified into six types:
1. Diode Rectifier
2. AC-DC Converter (Controlled Rectifier)
3. AC-AC Converter (AC Voltage Controller)
4. DC-AC Converter (Inverter)
5. DC-DC Converter (DC Chopper)
6. Static Switch

A. Static Switch
The power devices can be operated as static switches or contactors, the supply to these could be either AC or DC, and the switches are called AC Static Switches or DC Switches consecutively. Electronic switch-mode DC to DC converters convert one DC voltage level to another by storing the input energy temporarily and then releasing that energy to the output at a different voltage. The storage may be in either magnetic components like inductors, transformers or capacitors. This conversion method is more power efficient, often 80% to 98%, than linear voltage regulation, which dissipates unwanted power as heat. This efficiency is beneficial to increasing the running time of battery operated devices. Drawbacks of switching converters include cost, complexity and electronic noise (EMI / RFI). There are two types of DC-DC converters: Non-Isolated and Isolated DCDC converters. Non-Isolated topology is a transformer-less technique in which the input and output share a common ground. Non-Isolated topologies are typically used in board level power distribution and Isolated topologies are used in off-line power supply. Some examples of transformer-less converter topologies include:

- Buck Converter
- Boost Converter
- Buck-Boost Converter
- Cuk Converter
- Single Ended Primary Inductor Converter (SEPIC)

Buck Converter
A buck converter is a step-down DC to DC converter. It is a switched-mode power supply that uses two switches; a transistor and a diode, an inductor and a capacitor. The output voltage function for buck converter is

\[ V_o = D V_{IN} \]

Where \( D \) =Duty cycle

The above equation is valid only when the buck converter operates in Continuous Conduction Mode (CCM). CCM occurs when \( i_L > 0 \).

II. VOLTAGE REGULATOR MODULE
“A voltage regulator module (VRM) is an installable module that senses a computer's microprocessor voltage requirements and ensures that the correct voltage is maintained.”

The number of transistors on a chip has been increasing exponentially and according to Moore’s Law it doubles every two years, shown in Figure 1.2 Based on Intel’s data, transistor’s count in a microprocessor will increase to 1 billion in 2010. In terms of speed, future microprocessors are expected to run at 15 GHz. The increase in both the number of transistors and the speed of future...
It has been known widely that to decrease the power consumption, microprocessor’s supply voltage for that next generation of microprocessor must be as low as possible.

Based on this figure the design of future VRMs will face some serious technical challenges since it will involve low output voltage like 0.8V, high output current, fast transient response, high efficiency, high power density and low cost.

III. SYNCHRONOUS BUCK CONVERTER

The difference between a regular buck converter and a synchronous buck converter is that the freewheeling diode in the regular buck converter is replaced by another switch. This replacement basically enhances the efficiency of the buck converter since diode's forward voltage drop is one of the reasons of poor efficiency of the converter at low voltage and high current output. In addition to the switch, usually another Schottky diode is placed in parallel in order to further reduce the reverse recovery loss and to provide the dead time required to avoid a dead short due to simultaneous conduction of both switches.

In terms of its operation, synchronous buck works the same way as that of the basic buck converter. Referring to Figure 1.3, first switch Q1 turns on and the current flows through it to charge inductor L. After some time Q1, turns off and Q2 gets turned on. Now the inductor will discharge through or free wheel Q2. To prevent the circuit from input current spike, there is always a delay between turning on and off of two switches and that delay is called the dead time. A Schottky or a fast reverse
recovery diode connected in parallel with Q2 serves the purpose of conducting during that dead time with less forward voltage drop before the next cycle starts. The following section discusses the design of a synchronous buck converter.

**Issues with a Single Synchronous Buck for VRM**

The low output voltage and high output current, requirements of the future microprocessors, make the synchronous buck topology a less ideal solution to power the microprocessors. Low output voltage requirement is a setback in terms of duty cycle. In case of 12 V input voltage VRM to 0.8V output voltage, according to equation this topology suffers very small duty cycle and that is below 10%. This increases turn-off loss on the top switch and conduction loss on the bottom switch. Quality of output voltage is of extreme importance for efficiency purposes. Quality is linked with output voltage ripple. To decrease the output voltage ripple in a synchronous buck, switching frequency is increased. This increase in switching frequency results in switching gate drives and body diode losses. These all losses are directly proportional to switching frequency. More efficient, smaller and power dense VRM is need of the time. One of the major drawbacks of conventional or synchronous buck topology is that it operates at lower frequency. Low operating frequency results in higher filter inductance is used, which limits the transient response and it translates to limiting energy transfer speed. In order to meet the microprocessor requirements regarding output voltage ripple, huge output filter capacitors are needed which reduce the voltage ripple as well as help in reducing the voltage spike during the transient. These large sized capacitors would increase the size of the module and thereby make it impractical.

**Synchronous multiphase buck converter:**

![Multiphase synchronous buck VRM](image)

Figure 1.4 Multiphase synchronous buck VRM The above figure shows the 2-phase buck operation will be discussed and how it can be extended to the optimized number of phases. Figure 1.4 shows the basic multiphase buck converter consisting of two buck converters in parallel. Each box with dashed lines in figure represents the individual phase of VRM. When two or more synchronous buck converters are put in parallel, they may form a multiphase converter. To be called a multiphase converter, each buck has a switching control signal with phase difference of 360/N where N is the phase number.

In the multiphase buck converter, duty cycle D is the ratio of the output voltage V_o and input voltage V_IN just like that in a regular buck converter. However, the main benefit of multiphase is the current ripple cancellation effect which enables the use of the small inductance to both improve transient response and minimize the output capacitance. The multiphase buck increases the total output current frequency. The output current frequency is the multiple of the number of phases times the switching frequency of each buck converter, i.e. f_{Total} = f*N. This provides another benefit of
multiphase since the higher the output frequency the less filtering effort needed, further reducing the amount of output capacitance. A multiphase interleaving buck topology greatly reduces the current ripple to the output capacitors. This in turn greatly reduces the steady state output voltage ripple, making it possible to use very small inductance in VRMs to improve the transient response. Interleaving VRMs with small inductances reduce both the steady state voltage ripples and the transient voltage spikes, so that a much smaller output capacitance can be used to meet the steady state and transient voltage requirements. As a result, the power density of the VRMs can be significantly improved. Moreover, interleaving buck converter makes the thermal dissipation more evenly distributed. Studies show that in high current application, the overall cost of the converter can be reduced using this technology.

IV. SYNCHRONOUS BUCK CONVERTER DESIGN

Design of a synchronous buck converter:

Ideal duty cycle is given by

\[ D = \frac{V_o}{V_{IN}} \]

Inductance can be calculated by using volt-second balance during OFF time.

\[ L = \frac{V_o(1-D)f_s}{\Delta I} \] \[ \text{[H]} \] \[ \text{(2)} \]

The output capacitor of the Buck Converter, which is used to reduce the output voltage ripple, is given by

\[ C = \frac{V_o(1-D)}{8Lf_s^2\Delta V_o} \] \[ \text{[F]} \] \[ \text{(3)} \]

The switch used in synchronous buck converter is typically the type that we call MOSFET’s. MOSFET’s are typically associated with switching loss, conduction loss, gate drive loss and body diode loss and can be written as:

\[ \text{PMOSFET} = \text{PSW} + \text{PCOND} + \text{PGD} + \text{PBD} \] \[ \text{(4)} \]

Efficiency of the synchronous buck converter can be calculated as

\[ \eta = \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} \] \[ \text{(5)} \]

V. SIMULATION RESULTS AND DISCUSSION

Using the design calculations the proposed multiphase multi interleave buck converter is simulated in MATLAB/SIMULINK. The MOSFETs and internal diode in parallel with a series RC snubber circuit. The input power supply is modeled by a constant voltage source Vin. The gate signals to the MOSFETs are generated by using Vpulse.

![Figure 1.5 output waveforms of single stage buck converter](image-url)

The above graph shows the output voltage of the circuit and the lower graph depicts the output current. The output voltage and output current reach the steady state at 0.001s with values 0.8 V and 20 A at respectively which meet our specification. The average value of the output voltage is 0.8v which is nearly equal to the specification.
The parallel buck cells are switched at specific phase angles given by $\frac{360^\circ}{N}$ where $N$ is the number of phases. For four-phase buck, the phase angles are evenly distributed by $90^\circ$ but as mentioned before, because of the multi-interleaving, phase 3 will turn on right after the turn off of phase 1. So the distribution angle remains $90^\circ$ but the sequence of turning on is phase 1, phase 3, phase 2 and in the last phase 4.

<table>
<thead>
<tr>
<th>No of stages</th>
<th>Transient Response (in sec)</th>
<th>Output current (in amps)</th>
<th>Efficiency (in %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>30</td>
<td>69.68%</td>
</tr>
<tr>
<td>2</td>
<td>6.5e-5</td>
<td>60</td>
<td>80.52%</td>
</tr>
<tr>
<td>3</td>
<td>5.75e-5</td>
<td>90</td>
<td>82.40%</td>
</tr>
<tr>
<td>4</td>
<td>7e-5</td>
<td>120</td>
<td>82.58%</td>
</tr>
</tbody>
</table>

*Table 1 calculation of efficiency and transient response*
VI. CONCLUSION

The proposed converter design has several features and advantages: High output current, faster switching frequency, reduced ripple in output voltage. The equal amount of current sharing in each phase is achieved and the topology is closed loop. There are several disturbances in the input parameter like resonant inductor current. We can get satisfactory results.

For various switching frequencies the efficiency of four phase synchronous buck converter is listed below.

<table>
<thead>
<tr>
<th>SI.No</th>
<th>Frequency (kHz)</th>
<th>Efficiency in (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>82.90</td>
</tr>
<tr>
<td>2</td>
<td>300</td>
<td>83.01</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>83.06</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>83.18</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>83.31</td>
</tr>
</tbody>
</table>

As frequency and number of stages increase the efficiency increases but the complexity gets increase and cost also more. Among all above frequencies 400kHz is the best one which gives better performance, faster transient response, faster switching frequency and with less ripple.

REFERENCES