Improvement of the Power Conversion Efficiency of a Personal Computer

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Abstract—Most of the research into low-power PC design focuses on the power consumption of devices in the system, in order to reduce the consumption of the peripheral components while the system is in the idle state. In our design, we improve the power conversion efficiency of the multi-phase PWM power regulator by using the auto phase switching control scheme. We use an external load-sensing circuit both to monitor the output current and to change the regulator to a different operation method automatically. We measure the output current and set the optimized operation phase depending on the different loading. The power conversion efficiency can be maintained between 87.73% to 93.27%, when the load current is changed from 2.48A to 110A.

Keywords—Energy Saving; Power Conversion Efficiency; DC-DC Power Regulator

I. INTRODUCTION

According to Moore's Law the number of transistors in an IC doubles every 18 months. This means that the power consumption will increase because of more transistors. This design is an easy way to obtain a better performance from the CPU, which increases the operating frequency of the CPU. However, a faster CPU operating frequency produces more switching loss by the transistors in the CPU. Some other ways to better the CPU’s performance are either by increasing the parallel operational capability of the CPU, by increasing the pipeline, or by performing hyper threading. These performance enhancements increase the number of the transistors in the CPU, thereby increasing the power consumption. At present, the CPU power consumption of a PC can be up to 150W.

The PWM (Pulse Width Modulation) DC-DC buck voltage regulator is often used in the digital home appliances and PCs [1, 2]. The PWM power regulator is the most efficient and applicative regulator. It is used in PCs, home appliances and communication equipment because of the high stability and power conversion efficiency. The PWM power regulators are combined with a PWM controller, a MOSFET driver and MOSFETs. Generally the output current of a single phase PWM power regulator is about 20 to 30A, due to traditional MOSFET structure, semiconductor process, volume, cost and other factors. To provide the large amount of current needed for the CPU, the multi-phase PWM power regulator is commonly used [3, 4].

To improve the power conversion efficiency of the PWM power regulators there has been much research focusing both on the circuit design and on modifying the architecture [5-7]. Two other ways that can be used to improve the efficiency are using either the Zero Voltage Switching (ZVS) or the Zero Current Switching (ZCS) methods. These two methods focus on the effective circuit modification used both to improve the ZCS and ZVS and also to reduce switching loss [8, 9].

To provide more power for the CPU, the number of phases of the PWM power regulator has to be increased [10, 11]. When the system is in the idle state, the new power control technique reduces the power consumption of the CPU. Consequently, in the idle state the CPU both reduces its operating frequency and shuts down its unused cores and circuits [12]. Furthermore, the system is in light operation mode while the user is surfing the Internet, watching movies and processing documents. The disadvantage of the multi-phase PWM power regulator is its poor efficiency in the light operation mode [13].

Fig. 1 shows 6 power conversion efficiency curves for the single-phase to the 6-phase PWM power regulator respectively. The single-phase PWM power regulator shown by the “plus” mark is of higher efficiency at light loads, but this rapidly declines while the load current is increased. In contrast, the 6-
phase PWM power regulator shown by the “X” mark is of higher efficiency at heavy loads, but this efficiency becomes lower than that of the single-phase at light loads. Thus some research is currently being conducted on the light load efficiency improvement of the multi-phase PWM power regulators [14-16].

Table I compares the efficiency of the single-phase and the 6-phase PWM power regulator while the load currents are 12A and 35A. The single-phase PWM power regulator obtains higher conversion efficiency with less load current. However the 6-phase has higher conversion efficiency with more load current.

### Table I. Power Conversion Efficiency of Single-Phase and 6-Phase PWM Power Regulator

<table>
<thead>
<tr>
<th>Power conversion efficiency</th>
<th>Load Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12A</td>
</tr>
<tr>
<td>1-Phase</td>
<td>92.62%</td>
</tr>
<tr>
<td>6-Phase</td>
<td>87.68%</td>
</tr>
</tbody>
</table>

In Section II we design and implement the multi-phase auto control method. Section III shows the measurement result. The final section draws the conclusion and provides a look at future possibilities.

### II. Multi-Phase Auto Control Method

Based on the power conversion efficiency curves shown in Fig. 1 we propose to use the auto-phase control method to control the multi-phase PWM power regulator [17-20]. We change the number of phases for the multi-phase PWM power regulator depending on the output current. We reduce the PWM phase under a light load condition and increase it under a heavy load, thus obtaining the highest power conversion efficiency from a light load to a heavy load. In this paper we improve the power conversion efficiency of the 6-phase PWM power regulator.

There are 3 parts of the multi-phase auto-control design. The first is the output current detection, the second is the setting up of both the comparator and the switching point, and the third is the multi-phase control circuit. The block diagram is shown in Fig. 2.

#### A. Output Current Detection

First, we add a high precision resistor at the load side, thereby obtaining a voltage at both ends of the resistor so that we can calculate the output current ($I_{OUT}$) through the differential voltage by the Operational Amplifier (OP-Amp.), as shown in Fig. 3.

![Fig. 3. Output current detection circuit.](image)

By using the circuit design in Fig. 3 we can detect the output current through the output voltage conversion of the OP-Amp. Equation (1) shows the current-to-voltage conversion. The output current through $R_{SHUNT}$ is $I_{OUT}$, we can calculate the output voltage of OP-Amp. ($V_{IMON}$) as (1).

$$V_{IMON} = I_{OUT} \times R_{SHUNT} \times \left( \frac{R_3}{R_3 + R_1} \right) \times \left( 1 + \frac{R_4}{R_2} \right)$$

$$\Rightarrow I_{OUT} \times 0.001 \times \left( \frac{143k}{143k + 2.32k} \right) \times \left( 1 + \frac{143k}{2.32k} \right) = I_{OUT} \times 0.0616$$

Fig. 4 is a graph of (1). The horizontal axis is the output current $I_{OUT}$ whose output ranges from 0A to 120A. The vertical axis is the output current conversion result of the voltage $V_{IMON}$ whose range is between 0V to 7.392V. By utilizing both this diagram and (1) we can obtain the output current from the $V_{IMON}$.

![Fig. 4. Ideal output voltage conversion of the OP-Amp.](image)

#### B. Setting up Comparator and Switching Points

Second, we have to set up 5 reference voltages ($V_{REF}$) for the switching points as shown in Table II. This method is used
to compare \( V_{\text{REF}} \) with the \( V_{\text{IMON}} \) to switch to different operating phases.

### TABLE II. SWITCH CONDITION OF LOAD CURRENT AND \( V_{\text{IMON}} \)

<table>
<thead>
<tr>
<th>Switch Condition</th>
<th>( V_{\text{IMON}} &gt; V_{\text{REF}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>0.3V 2.3V 3.2V 4.2V 5V</td>
</tr>
<tr>
<td>Current</td>
<td>5A 25.96A 37.31A 51.94A 68.14A</td>
</tr>
<tr>
<td>Phase</td>
<td>2-phase 3-phase 4-phase 5-phase 6-phase</td>
</tr>
</tbody>
</table>

When the \( V_{\text{IMON}} \) is higher than 0.3V \( (V_{\text{REF}}) \), the corresponding output current is 5A, and the multi-phase PWM power regulator is switched to the 2-phase mode. When the \( V_{\text{IMON}} \) reaches 1.6V, the output current is equal to 25.96A, and the regulator is switched to the 3-phase mode. If the \( V_{\text{IMON}} \) is greater than 2.3V, the output current is greater than 37.31A, and the regulator is switched to the 4-phase mode. If the \( V_{\text{IMON}} \) is greater than 3.2V, the output current is greater than 51.94A, and the regulator is switched to the 5-phase mode. If the \( V_{\text{IMON}} \) is greater than 4.2V, the output current is greater than 68.14A, and the regulator is switched to the 6-phase mode.

### C. Multi-phase Control Circuit

We use a linear voltage regulator as the 2.5V basic reference voltage \( (V_{\text{REF}_\text{2.5V}}) \) as shown in Fig. 5.

![Fig. 5. Basic reference voltage generation circuit.](image)

To avoid the switching points being too close, we consider enlarging the reference voltage scale. Therefore the basic reference voltage of 2.5V was transferred by the linear regulator to an amplifier with a magnification of 2.5 times and the \( V_{\text{REF}} \) was increased to 6.25V. As shown in Fig. 6 the ratio of the resistance divider is set at 4.2V, 3.2V, 2.3V, 1.6V and 0.3V for five switching points as close to the 6th phase, the 5th phase, the 4th phase, 3rd and 2nd phase of the reference voltage. Thus we can obtain a good relationship between the \( V_{\text{IMON}} \) and the \( I_{\text{OUT}} \) as shown in Table 2.

![Fig. 6. Transferred reference voltage circuit.](image)

Fig. 7 is the phase switching circuit which connects the \( V_{\text{IMON}} \) to the output current detection circuit to get the corresponding output current. When the \( V_{\text{IMON}} \) is less than the \( V_{\text{REF}} \), the output of the PWMx EN logic becomes 0. The switching circuit disconnects the PWMx to the PWMx DRV and sets the PWMx OFF to logic 1 to disable the PWM of the designated phase. When the \( V_{\text{IMON}} \) is higher than the \( V_{\text{REF}} \), the output of the PWMx EN logic becomes 1, and the output connects the PWMx to the PWMx DRV. The MOSFETs are controlled by the MOSFET driver; and set the PWMx OFF floating in order in the meantime to enable the PWM of the designated phase. The other phase control methods are the same control methods as in Table 2.

![Fig. 7. Multi-phase control circuit.](image)

Fig. 8 shows the \( I_{\text{OUT}} \) conversion from the \( V_{\text{IMON}} \) and the actual switching point of the multi-phase PWM regulator. When the \( I_{\text{OUT}} \) is less than 5A and the \( V_{\text{IMON}} \) is less than 0.3V, the PWM regulator will operate in the single-phase mode. When the \( I_{\text{OUT}} \) is in the range from 5A-25.96A, which means that the \( V_{\text{IMON}} \) is in the range from 0.308V-0.1.6V, the PWM regulator will operate in the 2-phase mode. When the \( I_{\text{OUT}} \) reaches 25.96A and less than 37.31A, this means that the \( V_{\text{IMON}} \) reaches 1.6V, which is less than 2.3V, and the PWM regulator will operate in the 3-phase mode. When the \( I_{\text{OUT}} \) is in the range of 37.31A-51.94A and the \( V_{\text{IMON}} \) is in the range of 2.3V-3.2V, the PWM regulator will operate in the 4-phase mode. When the \( I_{\text{OUT}} \) is in the range of 51.94A-68.14A and the \( V_{\text{IMON}} \) is in the range of 3.2V-4.2V, the PWM regulator will operate in the 5-phase mode. When the \( I_{\text{OUT}} \) reaches 68.14A and the \( V_{\text{IMON}} \) reaches 4.2V, the PWM regulator will operate in the 6-phase mode.

![Fig. 8. Multi-phase switching point.](image)
III. EXPERIMENT AND MEASUREMENT RESULTS

A. Methods for Measurement of Power Conversion Efficiency

Fig. 9 shows the methods for the measurement of power conversion efficiency. The power source of the PWM regulator is CPU_12V from the power supply unit. The CPU_12V first connects to a multi-meter to observe the input voltage ($V_{IN}$) and then to the PWM regulator input connector. We use a clamp meter to measure the input current ($I_{IN}$). On the output side, we use the electronic current load to set the output current ($I_{OUT}$) and use the 2nd multi-meter to observe the output voltage ($V_{OUT}$). We also use an oscilloscope to monitor the output current waveform and the relationship with the control signals, as shown in Fig. 9.

We can get the power conversion efficiency ($\eta$) as (2).

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times I_{IN}}$$

Fig. 10 is the electronic current load we used for measuring the power conversion efficiency. To ensure that the high output current can reach 110A we used a power cord with a higher capacity to drain the output current of the PWM regulator.

According to Fig. 12, by comparing both the measurement and simulation results, we find that if the system has no load, there already is a 0.2984V $V_{IMON}$ present. Thus the $V_{IMON}$ is from 0.2984V when the $I_{OUT}$ is initially zero. The power consumption increases and will react in $V_{IMON}$. When the $I_{OUT}$ increases, the $V_{IMON}$ is actually similar to the linear increase in the proportion.

B. Output Current and Control Signals

We use the test software Prime95 and PiLoop to observe the change between a light and a heavy load. The $V_{IMON}$ is gradually increased by the output current. When the $V_{IMON}$ reaches 0.42V, the PWM2_EN is logic 1, and the PWM
controller enables the 2nd phase of the PWM. When the $V_{IMON}$ reaches 1.66V, the PWM_EN3 is triggered and enables the 3rd phase of the PWM. When the $V_{IMON}$ reaches about 2.49V, the PWM4_EN is triggered and enables the 4th phase of PWM, as shown in Fig. 13.

![Fig. 13. Control signals of output current and PWM_EN 2 to 4.](image)

When the $V_{IMON}$ arrives at 3.27V, the PWM5_EN is triggered and enables the 5th phase of PWM. When $V_{IMON}$ arrives at 4.29V, the PWM6_EN is triggered and enables the 6th phase of the PWM, as shown in Fig. 14.

![Fig. 14. Control signals of output current and PWM_EN 4 to 6.](image)

**C. Power Conversion Efficiency**

We use the multi-phase auto-control method to reduce the power conversion loss. We have also calculated the power conversion efficiency by measuring the input and output power consumption.

![Fig. 15. Switch point and power conversion efficiency.](image)

Fig. 15 is the measurement result of power conversion efficiency. When the load current is 2.48A, the $V_{IMON}$ is 0.42V, the efficiency is 89.33%, and the system automatically switches to the 2-phase operation mode. When the load current is 25.98A, the $V_{IMON}$ is 1.66V, the efficiency is 92.25%, and the system automatically switches to the 3-phase mode. When the load current is 38.99A, the $V_{IMON}$ is 2.49V, the efficiency is 91.87%, and the system automatically switches to the 4-phase mode. When the load current is 52.49A, the $V_{IMON}$ is 3.27V, the efficiency is 91.39%, and the system automatically switches to the 5-phase mode. When the load current is 64.97A, the $V_{IMON}$ is 4.29V, the efficiency is 91.39%, and the system automatically switches to the 6-phase mode.

![Fig. 16. Efficiency comparison of legacy designs.](image)

Fig. 16 compares the efficiency of the legacy 6 phase DC-DC PWM regulator and our auto phase controlled design. The system detects the load current and switches to the different phases, so that we can maintain the efficiency at a high level.
In this paper we use the multi-phase auto-control method to improve the power conversion efficiency. We use simple components to detect the output current and use the OP-Amp as a comparator to control the phases of the multi-phase PWM power regulator. The multi-phase auto-control method improves the efficiency of the regulator. Our design not only determines the optimum number of phases but also switches phases automatically, thus obtaining higher degree of power conversion efficiency. To improve the overall power conversion efficiency, we not only improve the efficiency with a light load but also with a heavy load. In our design the power conversion efficiency can be maintained between 87.73% to 93.27%, when the load current is changed from 2.48A to 110A. Compared with the traditional fixed multi-phase DC-DC buck regulator design, our flexible multi-phase design increases the power conversion efficiency by approximately 2% to 23%.

In the future we will conduct research into the efficiency relationship of the output voltage and the load current adjustment in order to achieve an even better degree of power conversion efficiency.

REFERENCES
