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A novel current-sharing scheme based on magamp*

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Abstract: The magamp (magnetic amplifier) is widely used in power supplies due to its low cost, simplicity and other advantages. This paper discusses a novel application of the magamp in switching power supplies, where the magamp is used to regulate pulse width modulation (PWM) instead of power signal in the main circuit. This method extends the application of the magamp in power supplies, and makes it possible to further regulate control signal when PWMs have been generated. Based on this application, a new current-sharing (CS) scheme using the magamp is proposed, which uses a modified inner loop CS structure. In this scheme PWMs are generated by one main controller, and CS is achieved by regulating PWMs using a magamp in each module. Compared with traditional application of the magamp, the new CS scheme can be used in most topologies and only requires magamps of low power capacity. Then a test circuit of parallel power supply is developed, in which CS is achieved by a PWM regulator with the magamp. The proposed scheme is also used to upgrade an electroplate power to make it capable of paralleling supplies. Experimental results show that the proposed scheme has good CS performance.

Key words: Current-sharing (CS), Magnetic amplifier (magamp), Parallel
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INTRODUCTION

Paralleling of power converter modules offers a number of advantages over a single, high-power, centralized power supply. In order to achieve desirable characteristics when operating converter modules in parallel, a variety of approaches, with different complexity and current-sharing (CS) performance, have been proposed, developed and analyzed in the past (Luo *et al.*, 1999; Huang and Tse, 2007). Generally there are two categories of CS schemes based on their operating mechanisms, i.e., droop method and active CS method (Irving and Jovanovic, 2000; Kim *et al.*, 2002). A CS bus is not necessary in the droop schemes, which have a simple structure but poor CS performance and poor load regulation rate. An active CS scheme is combined with a specific control structure and a current-programming scheme. According to the operation mechanism, an active CS scheme mainly includes four structures: outer loop regulation (OLR) (Jovanovic *et al.*, 1996), inner loop regulation (ILR) (Siri *et al.*, 1992a; 1992b; Mao *et al.*, 2007), double loop regulation (DLR) (Lin and Chen, 2000), and external controller (EC) (Siri and Banda, 1995; Jaber *et al.*, 2007).

The post regulator based on the magamp is widely used in multi-output switching power supplies, such as the forward converter and the flyback converter (Chen *et al.*, 1989; Huber and Jovanovic, 1999; Lin *et al.*, 2005). For accurately regulating the output voltage, a controllable saturable inductor is adopted in the converter to further regulate the effective duty ratio of the voltage on the secondary side. Furthermore the magamp post regulator is also used to realize CS in parallel power supplies (Chen and Liang, 2006). The regulators with the magamp feature simplicity, high reliability, high efficiency and low cost. But in the traditional application, the magamp is connected to the main circuit and withstands the load current, which limits its application to medium and high power converters.

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This paper presents a new application of the magamp, which regulates PWMs of the converter instead of power signal in the main circuit. Based on this application, a new CS scheme with a modified inner loop structure is proposed. To verify this scheme, a 4.8-kW electroplate power based on paralleling of power converter modules is developed. Experimental results show the good performance of the CS scheme.

APPLICATION OF MAGAMP POST REGULATOR

A magamp is an inductor with a magnetic core of a closed magnetic circuit. It is saturable and has high permeability. Fig.1 shows the *B-H* curves of an ideal magamp.

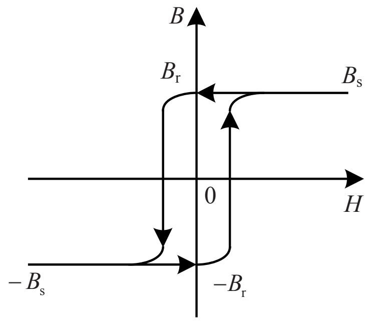

Fig.1 *B-H* curves of an ideal magamp

The magamp can be used as a pulse regulator, as shown in Fig.2a, where u_p is the pulse sequence source, L_m is an ideal magamp, and r is the load. Based on volt-second balance during the blocking time and resetting time, the block duty cycle can be expressed by

$$\Delta d = (1-d)V_{rst}/V_p,$$

where d is the duty cycle of u_p, Δd is the block duty cycle by the magamp, V_{rst} is the reset voltage, and V_p is the amplitude of u_p. Fig.2b shows the waveforms of the pulse regulator using the magamp. The block duty cycle is controlled by V_{rst}.

For many years, the magamp techniques have been mostly applied in the forward converter. As an example, the principle is briefly introduced in Fig.3, and the relative key waveforms are shown in Fig.4. In the forward converter, the regulation of output voltage V_{s1} is achieved by a PWM of the duty cycle of the primary switch S_{w1}, whereas the output voltage V_{s2} is regulated by a local magamp feedback loop, which modulates the duration of the blocking time of the magamp inductor. Besides, the magamp techniques applied in other types of converters, such as flyback converter (Chen *et al.*, 2002; Wen and Chen, 2005), half-bridge converter (Hang *et al.*, 2005), etc., also have been studied recently.

Similarly, the magamp post regulator is also applied in a parallel system to achieve CS. Chen and Liang (2006) proposed a CS scheme in a forward DC/DC converter, as shown in Fig.5. In this scheme several secondary outputs are paralleled to improve the output capability, and magamps are used to achieve CS.

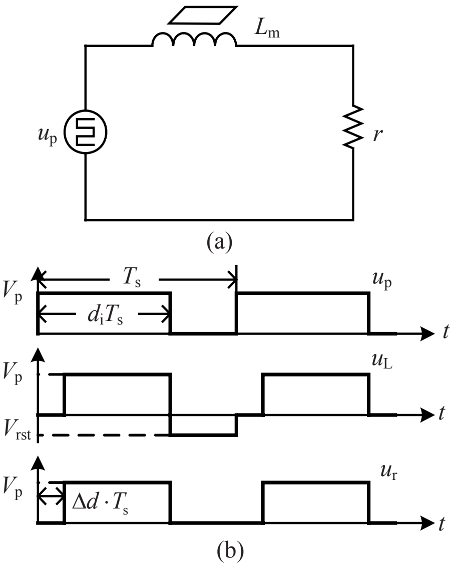

Fig.2 Pulse regulator using a magamp. (a) Principle of a pulse regulator; (b) Waveform of the pulse regulator

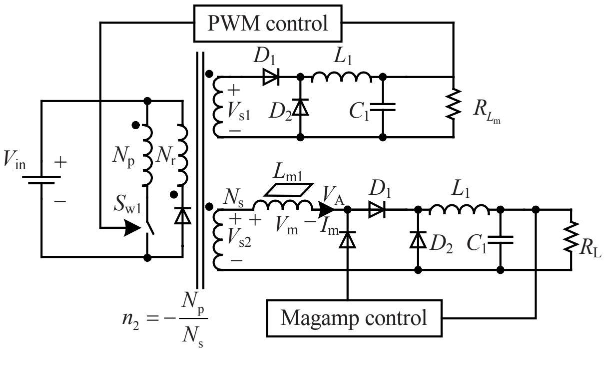

Fig.3 Two output forward converters with the magamp post regulator

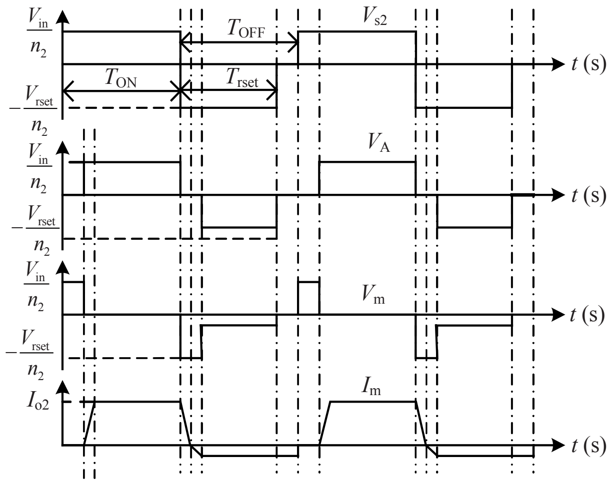

Fig.4 Key waveforms of the magamp in a forward converter

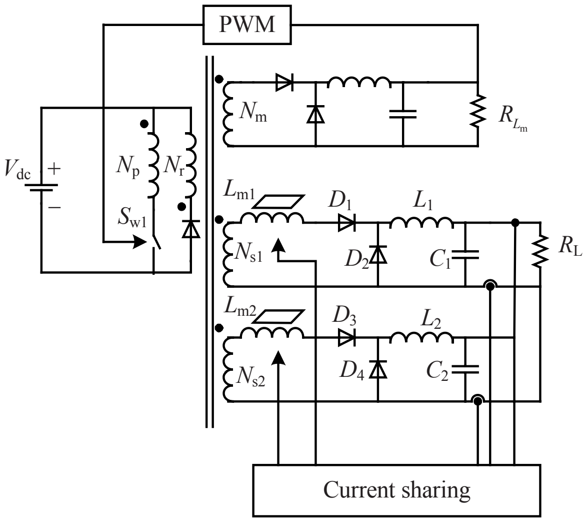

Fig.5 Diagram of paralleling magamp post regulator modules

Applied as the post regulator, the magamp has the advantages of high efficiency, high stability, high power density, simple control and low electromagnetic interference, but several disadvantages listed as follows:

(1) In this scheme, the magamp is connected to the main circuit and withstands all load current of the regulated channel, so it requires a relatively high power capacity. When the output current increases, a magamp with high power capacity is needed, and this will lead to high cost and low efficiency.

(2) It takes time to reset the magamp. If the magamp is connected to a main circuit, the current passing through the magamp should be discontinuous, which limits its application in the majority of topologies. For example, the CS scheme using the magamp cannot be used in a buck converter, because the load current of a buck converter is continuous and the magamp cannot be easily reset.

A NOVEL PWM REGULATOR WITH MAGAMP

To avoid the use of a magamp post regulator, a novel scheme is proposed in this section. According to the principle shown in Fig.1, the pulse width can be adjusted by a magamp, so it is possible to regulate PWMs but not voltage waves of a power circuit by the magamp in power converters. Fig.6 shows how the magamp with a small power capacity, if used as a PWM regulator, can be applied to the converters with medium and high power, where $G_v(s)$ is a voltage regulator.

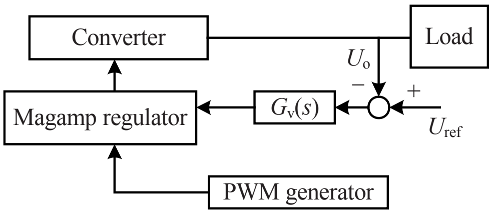

Fig.6 PWM regulator using the magamp

In this scheme, the switching signal is regulated directly by the analog signal using the magamp. A normal analog circuit or a normal digital circuit is not suitable due to the complexity in structure. Compared with the digital scheme, the magamp has the advantages of rapid real-time response and high reliability: since each pulse is regulated by the magamp at the rising edge, there is almost no time delay during the implementation of the proposed control scheme, but at least one cycle delay as for the digital control scheme; the magamp is not sensitive to the rising edge jitter of the pulse, which greatly disturbs the digital control.

Using the proposed PWM regulator, a CS scheme with the magamp can be applied in a parallel supply system with various topologies. As an example, a parallel supply system combining four modules will be developed in the following paragraphs.

Diagram of the parallel converter

A diagram of the parallel system is shown in Fig.7. The main topology of each module is a buck converter. The control system is a double loop system: the outer loop is a uniform voltage regulator which keeps the output voltage stable, and the inner CS loop in each module further regulates the PWMs which are generated by the output voltage regulator.

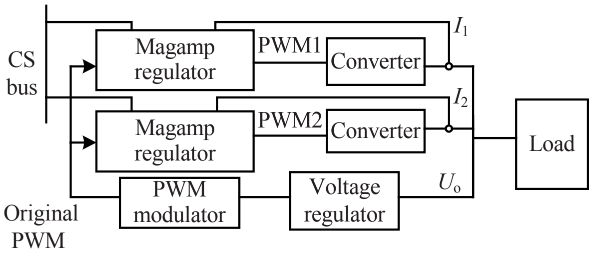

Fig.7 Diagram of a parallel supply system

In this scheme, a modified inner loop CS structure is adopted, as shown in Fig.8. Current of each module is compared with that of the CS bus, and the error signal is regulated by $G_{cs}(s)$. Then the output signal regulates the PWM using the magamp. Here the CS bus is achieved by the average current-programming method, as shown in Fig.9.

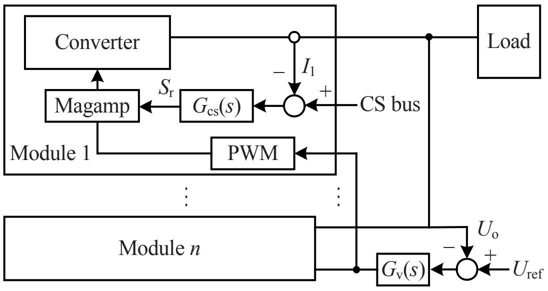

Fig.8 Control diagram of a parallel supply system

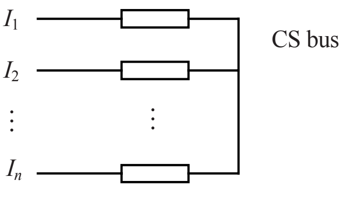

Fig.9 Program method of the current-sharing bus

Design of PWM regulator of magamp

In general, to get enough time to reset the magamp, the maximum duty ratio of PWM should be restricted. In this paper, an auxiliary logic circuit is proposed. The magamp only adjusts the rising edges of the PWM and does not respond to the falling edges of the PWM. The rising edges and falling edges are dealt with separately to avoid the problem caused by a large duty ratio. The diagram of the PWM regulator is designed as shown in Fig.10, which is implemented by the following three steps:

(1) Change the pulse width of the PWM. When the magamp is applied as a PWM regulator, PWM should be modified to a certain duty ratio pulse to ensure that the magamp can be reset to its original magnetic induction status before the next PWM circle starts. It is realized by a monostable flip-flop, as shown in the dashed block ‘Step 1’ of Fig.10, where P_m is the output PWM which has a certain pulse width and the same rising edges as P_i.

(2) Regulate the PWM by the magamp. PWM P_m is regulated by a magamp, and then the rising edges of P_m are delayed, and the delay time is decided by the reset current. The regulator is composed of the magamp, the amplifying circuit and the reset circuit, as shown in the dashed block ‘Step 2’ of Fig.10, where P_{m1} is defined as the output PWM of the regulator.

(3) Recover the pulse width. The falling edges of P_{m1} should be adjusted at the same time with P_i, which is achieved by D-flip-flop, as shown in the dashed block ‘Step 3’ of Fig.10, where P_o is the output signal which has regulated rising edges and the same falling edges as P_i.

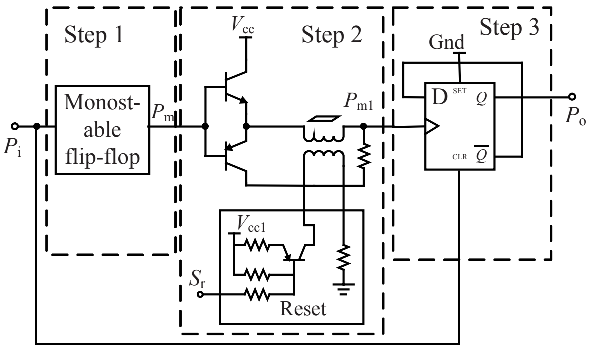

Fig.10 Diagram of a PWM regulator

Fig.11 shows the changing process of the PWM waves during the proposed steps.

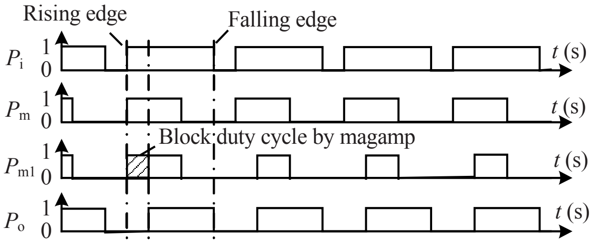

Fig.11 Changing process of PWMs

EXPERIMENTAL VERIFICATION

A test circuit with two modules paralleled is developed to verify the proposed scheme. The main circuit of each module is a buck converter, as shown in Fig.12, where T_1, T_2 are IRF520, D_1, D_2 are MUR820, L_1=L_2=100 μH, C_{o1}=C_{o2}=100 μF. To show the balance effect, different input voltages are selected. Fig.13 shows the experimental results under different conditions, where Fig.13a shows the stable inductor currents of two modules with the CS scheme under the condition U_{i1}=34 V, U_{i2}=40 V, U_o=12 V, R_L=2.5 Ω. Fig.13b shows transient waves of inductor currents when the load steps from 2.5 Ω to 4 Ω. Fig.13c shows the inductor currents of two modules without the CS scheme under the condition U_{i1}=34 V, U_{i2}=36 V, U_o=12 V, R_L=2.5 Ω. The experimental results show that the proposed scheme has good CS performance.

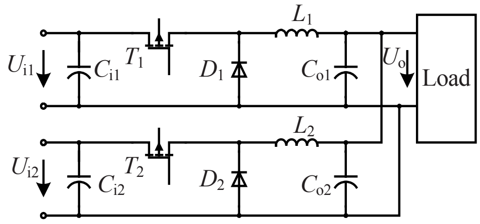

Fig.12 Main circuit of paralleled supply

The most important advantage of the proposed CS scheme is to achieve CS with less modification on the original control scheme. So we use this scheme to upgrade a product of electroplate power and make it capable of paralleling supplies with a low additional cost.

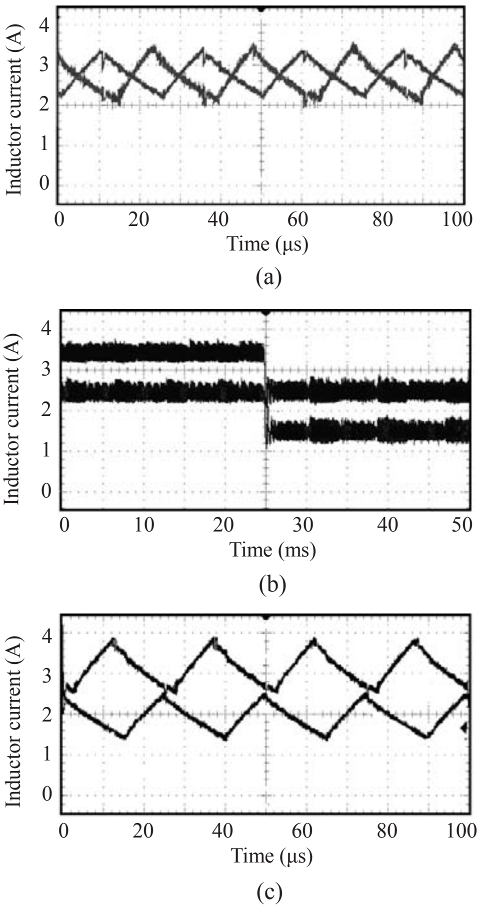

Fig.13 Waves of inductor currents under different conditions. (a) Stable waves of inductor currents; (b) Waves of inductor currents with a step of load; (c) Waves of inductor currents without a current-sharing scheme

The main circuit of the power is an isolated DC/DC converter with half-bridge in primary side and full wave rectifier in secondary side as shown in Fig.14, where the input voltage V_{in} is AC 220 V; output voltage V_o is DC 0~12 V adjustable; the maximum output current I_o of each module is 1000 A; the transfer rate of the transformer T_1 is 6:1. The experiment load is a plating bath which can be considered as resistant and capacitor paralleling. The device parameters are as follows: IGBTs S_1, S_2: 600 V/300 A; Rectifier bridge B_1: 600 V/100 A; Diodes D_3, D_4: 100 V/100 A, 10 modules paralleled; Capacitors C_1, C_2: 3300 μF.

To apply the proposed CS scheme, an additional CS module is inserted between the control circuit and the IGBT drivers. The experimental results are shown in Fig.15, where Fig.15a shows the output current of each module at 25% load, while Fig.15b shows the output current of each module at full load. These results show good CS performance.

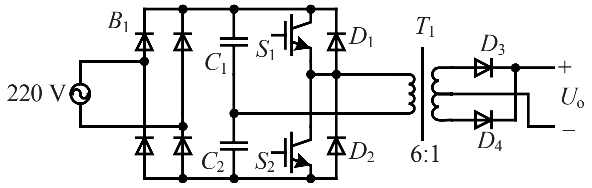

Fig.14 Main circuit of a single module

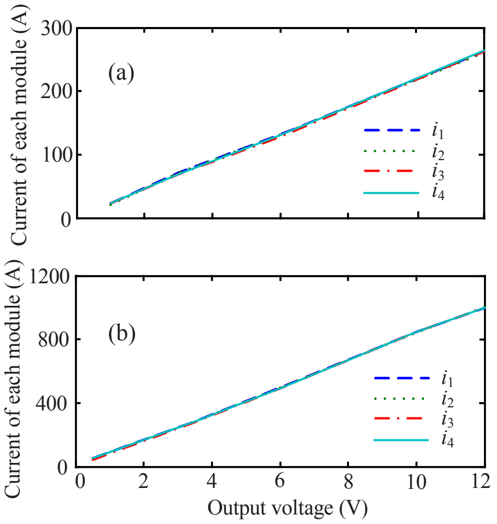

Fig.15 Performance of current sharing with the proposed CS scheme. (a) Load $r\approx12$ mΩ; (b) Load $r\approx3$ mΩ

CONCLUSION

This paper proposes a novel CS scheme using the magamp as the PWM regulator instead of the post regulator in traditional application. Analysis and implementation show that the new scheme has the following characteristics:

(1) It is applicable to medium and high power DC/DC converters. In this scheme, the magamp regulates PWM signals instead of voltage wave of the power circuit, so the magamp only deals with low power even in a high-power converter. In the proposed electroplate power supply, the output current of each module reaches 1000 A, but the power of the regulating magamp is less than 1 W.

(2) It is applicable to the majority of topologies in principle, such as BUCK, BOOST and other PWM based converters. It takes time to reset the magamp, so the traditional post regulator with the magamp cannot be used in the topologies with continuous output current like the BUCK converter. However, the proposed scheme can achieve CS in most topologies.

(3) It is a simple control scheme. In the proposed scheme, the magamp regulates the PWM directly, which is independent of the control circuit. Therefore, several normal modules can be paralleled and CS with only a few additional modifications can be achieved.

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