

Multi-Output PWM Converter using Magnetic Amplifier

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ABSTRACT: The aim of this project is to design and develop multi-output converter for high speed Digital sub-systems. The high speed digital circuits require different low output voltages with high current ratings associated with stringent output ripple and regulation requirements. Push-Pull topology is preferred to other isolated PWM DC-DC converter topologies for this application. For better output voltage regulation on auxiliary outputs, magnetic amplifier post regulators are incorporated as the conventional series pass regulator circuits.

KEYWORDS: Pulse Width Modulation (PWM), Push-Pull converter, Magnetic Amplifier (Magamp).

I. INTRODUCTION

Regulating multiple outputs of a switching power supply has always presented an additional challenge to the designer. With a single pulse-width modulated control system, how can the control loop be conjured to keep all outputs in regulation when each may have varying loads? Although it is sometimes possible to average an error signal from each output -degrading the regulation on some outputs to improve on others -a more common approach, is to close the overall power supply loop to the output with the highest load current and opt for some form of auxiliary -or secondary - regulation for all the other outputs.

Post regulation of the auxiliary outputs can be achieved by linear post-regulators, individual DC-DC converters, magnetic amplifier circuits or switch-mode Secondary Side post Regulators (SSPR). All of these techniques are based on closed loop output voltage regulation of their respective outputs. A popular and effective application of the Square Perm alloy 80 tape wound cores occurs in multiple-output switched-mode power supplies. By using such a square loop core to provide a controllable delay at the leading edge of the pulses at the secondary of the transformer, one or more outputs can be independently and precisely regulated without the losses inherent in linear regulators or the complexity of conventional switching regulators. In cases where the load currents of the subordinate outputs are high (in excess of one or two amps), the advantages of the saturable-core regulators become more and more significant.

In the pulse width modulator (PWM), the primary pulse width is controlled by sensing the 5V output, comparing it to a reference, and using the error signal to adjust the pulse duration. If there were no saturable core (SC) in the circuit, the 5V output would be semi-regulated, since the primary control loop would provide line regulation. But the output would vary with load and temperature.

II. TOPOLOGY OVERVIEW

Any isolated topology with several secondary windings in the transformer can provide multiple output voltages. These circuits employ a single primary side power stage including the input filter, energy storage capacitor, a high frequency power switch, usually a MOSFET transistor and a PWM controller.

On the secondary side, isolated by the transformer, are the output components, rectifiers, energy storage capacitors and output inductors here it is applicable. Among those outputs, one is distinguished as the main output whose output voltage is regulated by a feedback loop. The fundamental element of the feedback loop is the voltage error amplifier. Its output provides the feedback signal which is transmitted to the primary side over the isolation barrier.

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The best known topologies of this category are the fly-back, forward and current or voltage-fed push-pull converters. Comparison of different topologies is given below in table 1:

Table 1 : Comparison of Various Topologies

Characteristics	Fly-back	Forward	Push-Pull
Cost	Economical	High	Economical
Power Output	Low	Medium	Medium to High
Magnetic Components	One	Large	One or Two
Efficiency	Fair	Good	Good
Stress on switching components	Less	More	More
Noise Output	Significant	Low	Low
Cross regulation	Normal	Worse than fly-back	Better
Core Utilization	Poor	Poor	Good

By considering above comparison of topologies, the push-pull converter has been selected for this application. Continuous power flows to the outputs are insured considering the push-pull transistors operate at a nominal 50%-50% duty-ratio all the time. The core utilization of the isolation transformer is optimal because of the first and third quadrant operation, and lack of duty cycle modulation in the push-pull stage. A single winding inductor resides on the primary side which allows simpler inductor design and better optimization.

Consequently, high efficiency and power density can be achieved using the push-pull solution. The following design review focuses on the design procedure of a three-output DC/DC converter. The first step in any successful design is to determine the power supply specification.

Specifications

- ❖ *Input bus:- 70V ± 2V*
- ❖ *Output:-*
 - +5.0V/3.5A
 - -5.0V/2.5A
 - +10V/1.5A

III. POST REGULATORS

In many applications, especially at lower output voltages, adequate output voltage tolerances can not be achieved without some sort of post regulation of the auxiliary (not directly regulated) outputs. These power supplies might employ any topology with multiple output windings. The four most popular post regulation techniques are Linear Post Regulator, DC/DC Switching Post Regulator, Magamp Post Regulator Secondary Side Post Regulators (SSPR). Magnetic amplifiers are preferred over other topologies, as Magamp circuits are very popular in medium to high power application where the limited efficiency of the linear regulators is not acceptable. The saturable reactor in the magamp post regulator functions as a magnetic switch. Before the core of the magamp inductor saturates it represents large impedance in series to the secondary winding of the isolation transformer preventing power transfer to that output. By properly positioning the operating point of the magnetic core on the B-H curve, a variable portion of the secondary pulse can be blocked. Thus the effective duty-ratio for the buck inductor can be further modulated, allowing precise regulation of the auxiliary output voltage.

IV. MAGNETIC AMPLIFIER

Magnetic amplifiers are preferred over other topologies, as Magamp circuits are very popular in medium to high power application where the limited efficiency of the linear regulators is not acceptable. The Magamp regulation principle offers a low cost, efficient and, owing to the simple design, reliable solution to these problems. It meets the increasing demands on modern switched-mode power supplies excellently. An efficiency level of more than 90% can be realized even at higher switching frequencies. The low RF interference level is advantageous to the suppression filter. A magnetic amplifier uses an inductive element as a controlled switch. A magamp is a coil of wire wound on a core with a relatively square B-H characteristic. This gives the coil two operating modes:

- When unsaturated, the core causes the coil to act as a high inductance capable of supporting a large voltage with little or no current flow

- When the core saturates, the impedance of the coil drops to near zero, allowing current to flow with negligible voltage drop.

Thus a magamp comes the closest yet to a true ideal switch with significant benefits to switching regulators [8]. Before discussing the details of mag amp design, there are a few overview statements to be made. First, this type of regulator is a pulse-width modulated down-switcher implemented with a magnetic switch rather than a transistor: It's a member of the buck regulator family and requires an output LC filter to convert its PWM output to DC. Instead of DC for an input, however; a magamp works right off the rectangular waveform from the secondary winding of the power transformer: Its action is to delay the leading edge of this power pulse until the remainder of the pulse width is just that required to maintain the correct output voltage level. Like all buck regulators, it can only subtract from the incoming waveform, or; in other words, it can only lower the output voltage from what it would be with the regulator bypassed. As a leading-edge modulator; a magamp is particularly beneficial in current mode regulated power supplies as it insures that no matter how the individual output loading varies, the maximum peak current, as seen in the primary, always occurs as the pulse is terminated [8].

V. MAG AMP OPERATION

The saturable reactor in the mag-amp post regulator functions as a magnetic switch. Before the core of the mag amp inductor saturates it represents large impedance in series to the secondary winding of the isolation transformer preventing power transfer to that output. By properly positioning the operating point of the magnetic core on the B-H curve, a variable portion of the secondary pulse can be blocked [8]. Thus the effective duty-ratio for the buck inductor can be further modulated, allowing precise regulation of the auxiliary output voltage. Fig.1 (a) shows Mag Amp Push Pull regulator.

Square hysteresis loop magnetic core as a fast acting on off switch with electrically adjustable on off time

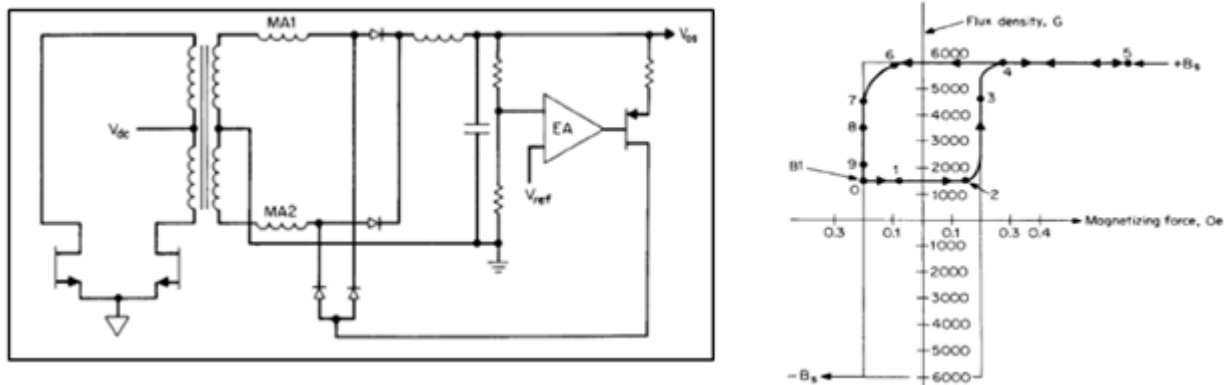


Figure 1 (a) Mag Amp Push Pull regulator (b) Operation of the B-H curve of the magnetic core

Fig. 1(b) shows the BH loop of a typical square hysteresis loop material. The slope of the BH loop ($\mu = dB/dH$) is its permeability. A coil wound around the core will have impedance proportional to the core permeability μ . Thus, so long as the core is on the vertical of its hysteresis loop, its permeability and hence the coil impedance is very high. It is effectively a single-pole switch in the open position. When the core is in saturation on the horizontal axis of its hysteresis loop, the BH loop is so square that the slope μ or permeability is unity. The coil impedance is thus the very low impedance of an air core coil of an equal number of turns. The coil is thus effectively a single-pole switch in the closed position. Such a core with a few turns of wire constitutes the switch SC.

It is shown with the error amplifier and the scheme for controlling the on off time of the switch. Throughout one switching cycle the core moves around a so called minor hysteresis loop—the path 01234567890 shown in Fig. 2. The blocking (tb) and firing (tf) times of the magnetic core switch are controlled as follows. Assume that at the start of a cycle (to), the core had been pushed down to B. When Q1 turns on, a voltage $V_{sp} = (V_{dc} - I)N_s/N_p$ appears across the slave secondary. Just prior to to, D2 had been conducting and its cathode was one diode drop below ground. At to, a voltage $(V_{sp}+1)$ appears across the magnetic amplifier and D1 in series in the direction to drive the core up toward saturation at

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point P4. Until the core gets up to point 4, only a very small coercive current flows through magnetic amplifier and D1 into D2. This coercive current is considerably smaller than the free-wheeling current D2 is carrying. Thus the D2 cathode does not move substantially; it remains at one diode drop below ground and the voltage V_{sp} , is blocked from getting through and raising the voltage at the front end of L. Diode D1 carries the MA coercive current, and although it is much smaller than the D2 current, assume that forward drops in D1 and D2 are equal (and equal to 1 V).

The full V_{sp} , voltage thus appears across magnetic amplifier, whose right-hand end remains at ground. The magnetic amplifier is now in its blocking phase and remains there for a time t_b equal to the time required to move the core up from B, to saturation at B, (point 4). Once the core has reached saturation at point 4, the MA impedance becomes negligible within a few nanoseconds and it cannot support the voltage V. A large current flow from the top end of N_s , into D2 and unclamps it, and its cathode voltage rises to one diode drop (D1) below V_{sp} , and remains there for the duration of the Q1 on time. The time from the onset of saturation to the instant Q1 turns off is the t_{ring} time t_f . The LC output filter is thus presented with a square pulse of amplitude $(V_{sp} - V_{D1})$, duration t_f , and duty cycle t_f/T . It averages this pulse to produce the slave DC output voltage of $(V_{sp} - V_{D1})t_f/T$. Regulation against line and load variation is achieved by controlling the t_{ring} time t_f . This is done indirectly by controlling the blocking time t_b .

VI. DESIGN STEPS

One of the first tasks in a mag amp design is the selection of a core material. Technology enhancements in the field of magnetic materials have given the designer many choices while at the same time have reduced the costs of what might have been ruled out as too expensive in the past. Some considerations affecting the choices could be [8]:

- A lower B_{max} requires more turns -less important at higher frequencies.
- Higher squareness ratios make better switches
- Higher IM requires more power from the control circuit
- Ferrites are still the least expensive
- Less is required of the mag amp if it only has to regulate and not shut down the output completely.

In addition to selecting the core material, there are additional requirements to define, such as:

- Regulator output voltage
- Maximum output current
- Input voltage waveform including limits for both voltage amplitude and pulse width.
- The maximum volt-seconds -called the withstand Area; A -which the mag amp will be expected to support.

Push pull saturable core regulator is shown in Fig. 2. With these basic facts, a design can proceed as follows:

The withstand volt-seconds is first determined to delay the leading edge of the pulse and achieve the required output voltage. Here, the the output must be capable of independent shutdown (for short-circuit protection or turn-off from an external logic signal), or simply regulated at a fixed value.

Withstand = Excluded Pulse Area = $V \cdot t$

Where V = pulse amplitude, t = delay at leading edge.

To allow the pulse width to decrease, the reactor must withstand additional volt-seconds to reduce the pulse width 20% below the nominal value. In the circuit of Fig. 4 for -5V, a regulation only design would require a withstand of

$$A = 8.4V \times 1\mu s + 20\%; \text{ or } 10.08V \mu s: (4.1)$$

And for 10V output with stand voltage is 17.28V

Here, for slave output of 5V, 8.4V is the voltage on the secondary side of transformer given by equation-1 for push pull converter.

$$V_1 = \frac{N_s}{N_p} \times V_p$$

Where, $N_s=7$, $N_p=60$, $V_p=72V$

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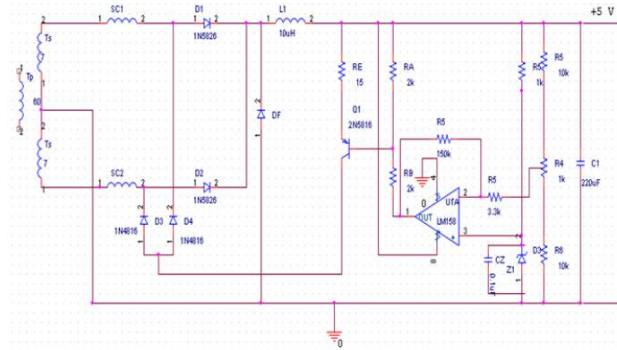


Figure 2: Push pull saturable core regulator

Choosing the core:

Following steps are there for proper core selection:

- The wire size is picked, based on the current. An appropriate wire size is 24 gauge. A reasonable value is 750 circular mils per amp of current (rms) for a temperature rise of 30 to 40 degrees C. This yields A_w , the cross-sectional area of one conductor.
- The core material is chosen, to determine the saturation flux density, B_m . In this application, Ferrite core is selected; Its B_m is approximately 4000 gauss.
- The fill factor K is taken, using .3 to .5, with the lower values for power applications.
- $WaAc$ is calculated for proper core selection is as follows:

$$WaAc = \frac{Ax \times A \times 10^8}{\Delta B \times Ae \times K}$$

$$WaAc = Aw \times A \times 10^8 = .00012 \times 10^6 \text{ c.m.cm}^2$$

similarly, for 10V $WaAc$ is $.00019 \times 10^6 \text{ c.m.cm}^2$

where

Wa = Window area, cm^2 ,

Ac = Effective core area, cm^2 ,

Ax = Wire area, (one conductor) cm^2 ,

A = required withstand area, V-sec

B = Flux excursion, gauss,

k = Fill factor = 0.1 to 0.3

For the purpose of this example the ferrite core is chosen. Its effective core cross sectional area, Ac , is $.050 \text{ cm}^2$; its mean length of magnetic path, MI , is 5.98 cm.

The number of turns is determined by the withstand A , to produce the desired output of the regulator.

Using the control circuit and the chosen core, the required number of turns is:

$$N = \frac{A \times 10^8}{\Delta B \times Ae}$$

No of turns calculated are 2 turns for 5V and 4 turns for 10V output. Ferrite core mounted on the pcb is shown by Fig. 3.



Figure 3: Ferrite Mag-Amp core mounted on the PCB

Designing of Control Circuit

It is helpful to estimate the current required to reset the core and thus calculating the average control current based on the duty ratio of the resetting (negative portion) of the input pulse [3]. The current related to the magnetizing force is :

$$I_c = \frac{H \times l_e}{0.4 \times \pi \times N} = 70 \text{ mA}$$

Where: H = Magnetizing force in Oersted

H is taken from manufacturer's curves, it increases with frequency. l_e = Magnetic path length in cm. the value calculated for slave output1 -5V is 70mA and for slave output2 10V is 30m.

VII. MAGNETIC AMPLIFIER POST REGULATOR EXPERIMENTAL RESULTS

Schematic of Multi output Push Pull Converter

The schematic of Push-pull pulse width-modulated converter is shown in Fig 4. It is a three output converter having +5V master output, -5V and +10V are the slave outputs. Isolation in the converter is provided by transformer, whose left side is considered to be as primary side comprised of switches Q1 and Q2, a current mode controlled IC UC3846 is used in the circuit for closed loop control, for regulating the master output of the converter. Auxiliary supply +12V is used here for giving continuous supply to the IC UC3846. Right side of transformer consist of three outputs, consist of rectifier and filter circuit with magnetic amplifiers which are used for regulation of slave outputs, consist of saturable core, transistors and op-amp circuit.

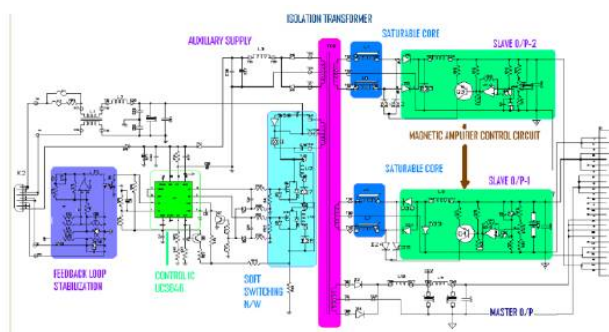


Figure 4: Push-pull Pulse Width Modulated (PWM) Converter Schematic

Pragmatic Waveforms

Secondary output voltage without post regulation is shown in Fig 5 shows the waveforms by applying post regulation at the output voltage. The waveform obtained for setting and resetting of the core is shown in the Fig 6(a) Transformer output, (b) Saturable Core Output, channel 1 shows waveform at transformer end and end of the saturable core.

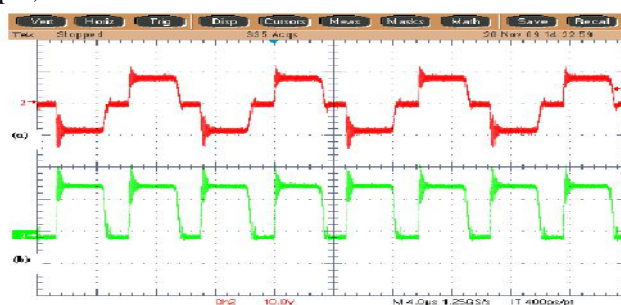


Figure 5: Waveforms obtained at slave output-2 10V/1.5A without post regulator (a) Transformer secondary output, (b) Rectifier output

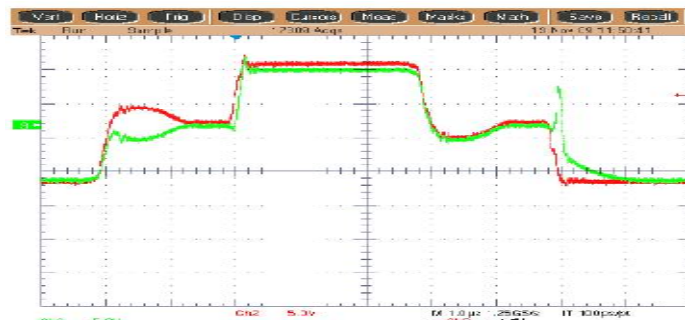


Figure 6: (a) Transformer output, (b) Saturable Core Output

VIII. EXPERIMENTAL RESULTS

The line regulation of the multi output push pull regulator is within the limit specified in the objective and for load regulation magnetic amplifier is incorporated as post regulator for slave outputs for better load regulation. Here magnetic amplifier circuit is tested for different load conditions and results are compared with the linear regulators. Measurement results of multi output push pull converter with magnetic amplifier post regulator for different outputs and with different input are shown below.

a. Master Output:

Line regulation = 0.2%

Load regulation = 0.58%

b. Slave-1 Output:

Line regulation = 0.42%

Load regulation = 0.47%

c. Slave-2 Output:

Line regulation = 0.3%

Load regulation = 0.7%

Hence the line and load regulation is within the limit specified in the objective.

Why Mag-Amp Post Regulators are used other than linear post regulators?

Linear regulators, equivalently called series-pass regulators, or simply series regulators, also produce a regulated dc output rail from an input rail and are preferable only for low outputs. They produce this by placing a transistor in series between the input and output. Further, this series-pass transistor is operated in the linear region of its voltage-current characteristics, thus acting like a variable resistance of sorts. This transistor is made to literally drop (abandon) the unwanted or excess voltage across itself. The excess voltage is clearly just the difference ($V_{IN} - V_O$) and this term is commonly called the headroom of the linear regulator. We can see that the headroom needs to be a positive number always, thus implying ($V_O < V_{IN}$). Therefore, linear regulators are, in principle, always step-down in nature that being their most obvious limitation.

Another limitation of linear regulators is poor efficiency: Here for linear regulators the secondary turns should be chosen such that the rectified secondary voltage is $V_O + 2.5$ V (assume for the moment that the filter capacitor is large enough to yield insignificant ripple) when the input AC is at its low tolerance limit. But when the input AC voltage is at its high tolerance limit, the headroom will be much greater, series-pass element dissipation will be greater, and the power supply efficiency will be significantly lower. This effect of very poor efficiency at high tolerance limit input voltage when the raw DC input has been chosen for a minimum 2.5 V headroom at lowest DC input is much more pronounced at lower output voltages. Graph between Magnetic amplifier and Linear regulator is shown in Fig. 7. It can be seen that at the efficiency is significantly higher for magnetic amplifier other than linear regulator.

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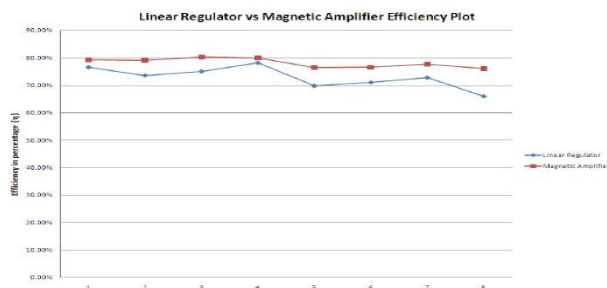


Figure 7: Efficiency plot between Mag Amp and Linear regulator

Thus magnetic amplifiers are preferred over other topologies, as magnetic amplifier circuits are very popular in medium to high power application where the limited efficiency of the linear regulators is not acceptable. The magnetic amplifier regulation principle offers a low cost, efficient and, owing to the simple design, reliable solution to these problems. It meets the increasing demands on modern switched-mode power supplies excellently. As auxiliary outputs is well regulated for different load and line regulation and efficiency achieved after post regulation is about 79%.

IX. CONCLUSION

This paper has presented the most frequently used topologies for multi-output power supply design. Pros and cons of each implementation have been listed in addition to the most popular application areas. The detailed design review of a three output current-fed push-pull converter culminated in the description of a step-by-step design procedure to insure meeting certain power supply specifications. The completed prototype circuit and the measurement results proved the effectiveness of the presented approached the benefits of the selected topology.

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