

11

WAYS TO GENERATE MULTIPLE OUTPUTS

by Dr. Ray Ridley

After reading our last magazine on high-density power supplies, it may seem that all power systems will be assembled with purchased high-density building blocks. Those new to the field may feel that the future of custom power supply design is limited. This is far from the truth. Industries requiring power often go through cycles of building in-house, purchasing modules, then returning to in-house building again.

Why is this? There are three reasons. The first reason is cost. Purchased high-density power does not come cheap. When companies look at the parts on a high-density converter, they can see how much is cost, and how much is profit for the power supply company. It's tempting to think that they would benefit by designing their own power.

The second reason is form factor. Space for power supplies is always limited. High-density power can stuff more into a small space, but sometimes the available space for a power supply just doesn't work with the available form factors.

The third reason is the need for multiple outputs. It is rare that we run into a custom design situation that only needs one power supply output voltage. When using

purchased modules, you must frequently buy many modules to cover all the voltages that are needed, and this, of course, impacts both the overall system cost, and the final power density.

When looking at a power supply design specification, a crucial part of the design cycle is in selecting the architecture. This is the combination of power supply topologies used to generate the outputs needed in a cost-effective way. The right decisions made early in the design cycle will influence the final system performance and cost.

As previously mentioned in *SPM*, there are a handful of power circuit topologies which are practical and useful for modern design, and choosing between them is fairly straightforward for given input and output requirements. However, choosing how to generate multiple outputs with these topologies complicates the process, as there are many options.

In this article, we present 11 different ways to generate multiple outputs, together with their strengths, and weaknesses. It is by no means a comprehensive list of "how to" instructions. But armed with these architectures, you can design systems for most of the custom power requirements that you will encounter.

11

MULTIPLE SINGLE-OUTPUT CONVERTERS

Figure 1 shows the simplest way to deal with multiple outputs—build (or buy) a complete converter for every output voltage that is needed by the power system. If power supplies were like logic gates (infinitely small), close to 100% efficient, and very low cost, this would be an ideal solution. It would also be the end of custom power supply design, as the design process would be automated and power supplies would be true commodities.

Fortunately (for power supply designers) we are nowhere near reaching these goals, and the design trade-offs of cost, size and efficiency still require a myriad of different approaches to be able to optimize every power system requirement. However, the multiple converter approach is certainly the best solution in some cases.

For example, you may need a 1500 W supply with three outputs that are all tightly regulated, and at approximately the same power range. This

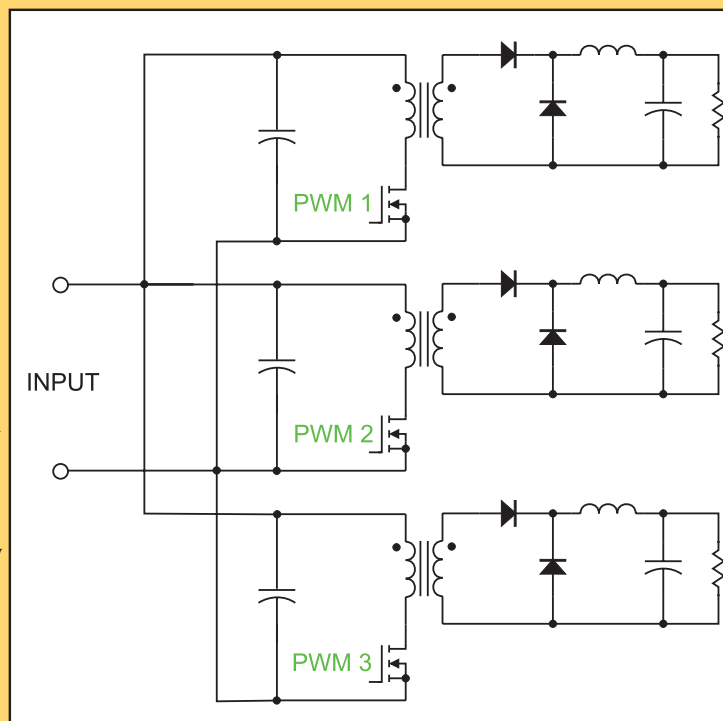


Figure 1: Using a complete forward converter for each output. Switching can be synchronized and phase-shifted for improved performance. (Note: for these forward converters, and all other forwards in this article, the transformer reset scheme is omitted for clarity.)

1. MULTIPLE SINGLE-OUTPUT CONVERTERS

Advantages

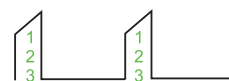
- All outputs can be tightly regulated
- All outputs are independent of loading on other outputs
- Straightforward design of single-output converters
- Standardized design process for all power systems
- Units can be synchronized and phase-shifted for lower input noise
- Failure of one unit has no impact on other outputs
- Fully predictable operation including small-signal
- Shortest development time

Disadvantages

- All power must be processed across isolation boundary
- Noise between multiple converters complicates development
- Highest parts count of all solutions
- Not a cost-effective approach for low-power outputs

System Input Current

Synchronized



Synchronized and Phase Shifted



Figure 2: Input currents with phase-shifted modules at equal power ratings

would use a single topology such as a two-switch forward converter at its optimum power range (about 500 W), and would provide a good solution. Personally, I would not stop at just three independent converters. Consider synchronizing the converters with 120 degrees phase delay between each to greatly reduce the input ripple voltage on the system. Realize, of course, that making this choice of synchronization and phase shifting brings additional control complications that may make it undesirable.

Only Need One Topology?

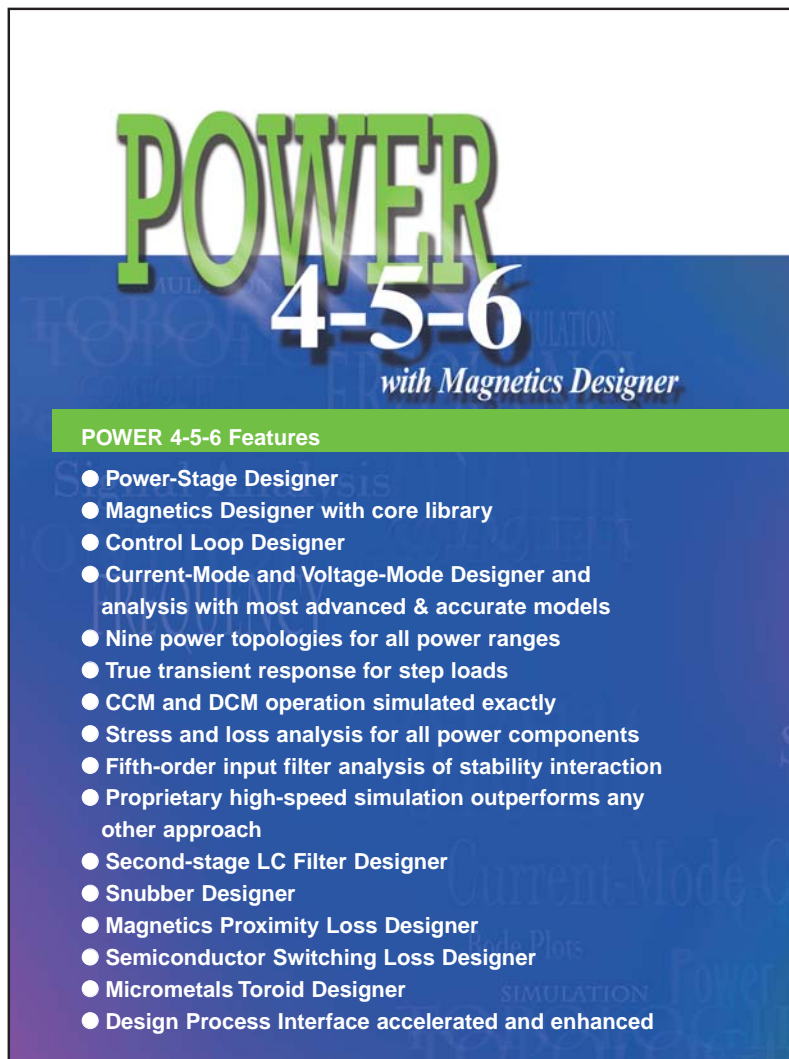
Buy a module at a time . . .

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SINGLE ISOLATION STAGE, MULTIPLE LOAD CONVERTERS

In many cases, the solution with complete multiple converters is not ideal. In looking at the finished design of this approach, the largest and most expensive components are usually the magnetics. The isolation transformer is often the most expensive since it is custom designed in relatively low quantities. For more advanced planar transformers with PCB windings, the transformer is still expensive in terms of the amount of costly multilayer PCB real estate consumed.

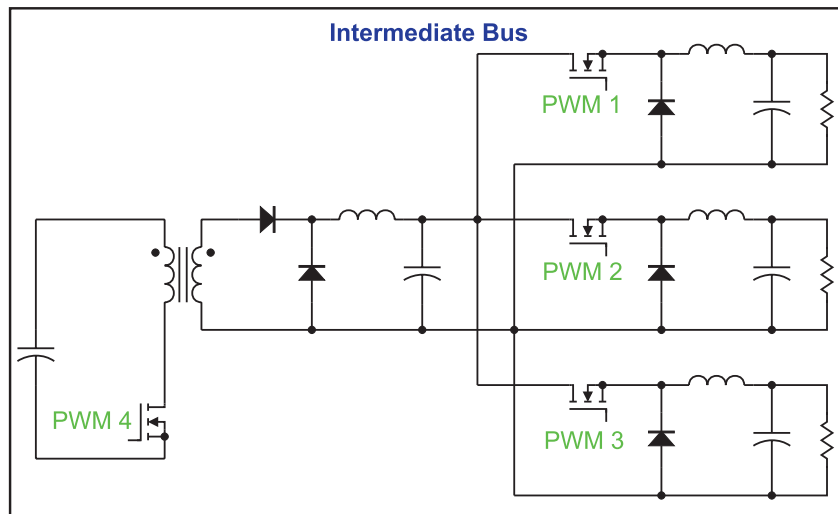


Figure 3: Single isolation stage to isolated bus and multiple load converters

As semiconductor packages continue to shrink in size and cost, while increasing performance, the magnetics tend to stick out even more as the largest components. Architectures that minimize the magnetics components, especially the transformer, are attractive.

The second solution shown in Fig. 3 reduces the isolation stage to just one power topology that produces an intermediate bus to supply the remaining outputs with single-output dc-dc converters. These point-of-load converters can be purchased dc-dc modules, power supplies built with the latest integrated semiconductor

parts, or fully custom power supplies. And, of course, each of the point-of-load converters could have multiple outputs using approaches discussed in this article.

Whether or not the loads require isolation from each other will drive the choice of the point-of-load converters. Choosing buck converters may be ideal in terms of cost these days due to the flurry of new components available for this topology.

While this architecture reduces the isolation stage components, the total parts count is still high. It also requires double processing of the power that will

affect the efficiency of the system (usually downwards). But if you need to get power designed in a hurry with predictable performance, this is a viable solution.

2. SINGLE ISOLATION STAGE, MULTIPLE LOAD CONVERTERS

Advantages

- All outputs can be tightly regulated
- All outputs are independent of loading on other outputs
- Straightforward design of single-output converters
- Single isolation transformer
- Standardized design process for all power systems
- Units can be synchronized for lower bus noise
- Failure of one load unit has no impact on other outputs
- Predictable small-signal model for system stability

Disadvantages

- All power processed twice
- Noise between multiple converters complicates development
- High parts count
- Less flexibility in isolation of outputs from each other



MULTIPLE OUTPUT FLYBACK

Options 1 and 2 provide the highest parts-count and highest performance systems. They may be the optimal solution for some high-power applications, but will often be too expensive for low-power applications.

For many low power applications, the preferred solution is the simplest. One example would be the multi-output flyback converter, shown in Fig. 4. The main strength of this converter is its very low parts count. Each additional output requires just an extra winding on the transformer, a rectifier diode, and an output capacitor.

Whenever we do a design for a customer, the first question is whether we can use a flyback. This is the cheapest solution with multiple outputs, keeping in mind that the flyback converter is limited in power. The output current on the transformer is pulsating, and the secondary current that flows is higher than the load current. This limits the application of the flyback to a few amps before a forward-type converter becomes more effective in terms of efficiency and noise on the output.

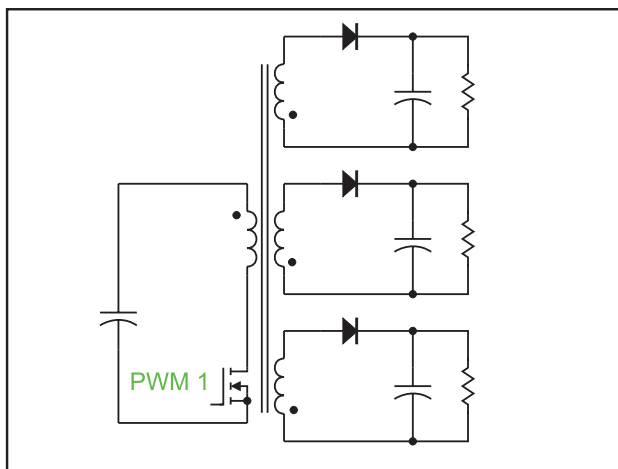


Figure 4: Multi-output flyback converter

3. MULTIPLE OUTPUT FLYBACK CONVERTERS

Advantages

- Lowest parts count
- Lowest cost
- Simple circuit design
- Single transformer/inductor for many outputs
- One output tightly regulated
- Suitable for wide range input due to flyback conversion ratio
- All outputs isolated and either polarity

Disadvantages

- Auxiliary outputs cross-regulation only, expect 2-30% regulation depending on line and load conditions
- Cross regulation is strong function of transformer design, try several variations of transformer winding layouts
- Pulsating output currents not suitable for high current ($> 10\text{ A}$)
- "Worst-case" regulation analysis depends on empirical data
- Small-signal model difficult to match with measurements at higher frequencies

In terms of power rating, the flyback is typically limited to about 25 W, although we have seen applications above 100 W for high-output voltages where the pulsating current is less critical. If you have an application where the flyback converter can handle the power requirements, the next important area to look at is the regulation that you need on each output, and the load range for each. If you have more than one output that needs better than 5% regulation, this can be difficult, although not impossible, with the flyback converter. The worst-case regulation will be with the extremes of load—ranging from maximum load on the main output with minimum load on the auxiliary, to minimum load on the main output with maximum load on the auxiliary.

Transformer design is crucial to the flyback converter. Only one magnetic element serves the function of a transformer and inductor, and is responsible for energy storage, voltage step down (or up), isolation, and cross-regulation. Proper design of the windings of the transformer, their relative positions on the bobbin, and the right size of wire all affect how well the transformer will regulate. Detailed magnetic design is beyond the scope of this article, but bear in mind that a change in winding position can easily have a 10:1 effect on the final regulation. We have seen real-world examples where a 20% regulation winding is improved to 2% with a change in the magnetics design only.

A word of warning with the multi-output flyback—there is nothing you can do to reliably predict the final cross-regulation that will be observed when you build the hardware. You must build a breadboard early in the design cycle to know what kind of regulation can be achieved for your particular application. This may be disconcerting to designers of high-reliability power, or aerospace applications, but it is just a fact in designing cross-coupled output converters.

It is also important to note that this converter is more complex than it initially seems. Even when there is light load on one output, it does not enter discontinuous mode until all of the outputs enter DCM at the same time. This is not immediately obvious, but it is a very important phenomena that preserves good cross regulation. What you will observe on the current waveform outputs is that the ripple current changes with load in each respective output to be able to preserve the CCM mode. We will talk about this "ripple steering" effect in some detail in a later issue of SPM.

4

Multiple Output Forward: Coupled Inductor and Transformer

The simplicity of the flyback converter is desirable, but at high-output current levels it becomes an impractical converter. Fortunately, we can use similar techniques on a forward converter that are more suited to high-output currents.

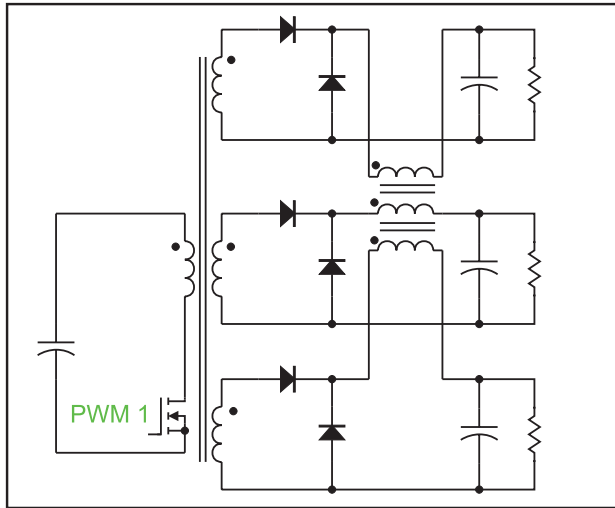


Figure 5: Forward converter with coupled transformer and inductor

Figure 5 shows a three-output forward converter with multiple windings on both the inductor and transformer. It is critical in this scheme that both the turns ratios on the transformer and the inductor are exactly the same. This can be difficult with low turns counts on low-output windings, and we often must increase the number of turns on the inductor core just to be able to meet this objective. Once this is accomplished, the outputs should theoretically track each other according to the turns ratios.

In reality, of course, the tracking of voltages is less than ideal. At the extremes of load and line ranges, it is not uncommon to see a substantial rise in an output that is lightly loaded. Generally speaking, the cross-regulation will be worse than the equivalent flyback converter.

The technique of coupling the inductor and transformer outputs can be applied to any of the other converters in the buck family of which the forward converter is just one example. This also works for the

two-switch forward, half-bridge, full-bridge, and push-pull topologies.

As with the flyback converter, coupling the inductors together has the advantage of keeping all of the outputs in continuous conduction mode at the same time. This preserves good cross-regulation for a wider range of load and line conditions.

Improved coupling can be achieved if the outputs share a common ground, and the transformer can be wound as an autotransformer. This also applies to the flyback converter with coupled outputs.

4. FORWARD CONVERTER WITH COUPLED INDUCTOR AND TRANSFORMER

Advantages

- Low parts count
- Low cost
- Simple circuit design
- Single transformer/inductor for many outputs
- One output tightly regulated
- Suitable for high power
- All outputs isolated and either polarity
- All power only processed once

Disadvantages

- Auxiliary outputs cross-regulation only, expect regulation a little worse than the coupled-inductor flyback converter
- Cross regulation is strong function of magnetics design, try several variations of transformer and inductor winding layouts
- Board layout can be difficult with multiple outputs on inductor and transformer
- Small-signal model complex and difficult to match with modeling

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5

MULTIPLE OUTPUT FORWARD
WITH INDEPENDENT INDUCTORS

While coupling the outputs of the transformer and inductor is theoretically the best way to do multiple outputs with the forward converter, it is often inconvenient for board layout, especially with several high current outputs. It is not uncommon to see power supply manufacturers generating second outputs coupling only the transformer of the converter, with separate inductors for each of the outputs. This is shown in Fig. 6.

This approach provides more freedom of inductor design and board layout. It also improves noise performance. The dc value of each output voltage will still track according to the transformer winding turns ratios, as long as there is enough load on each output to keep the current continuous in each inductor.

However, during dynamic conditions, we lose control of the extra windings, and step loads will ring at the resonant frequency of the respective outputs. Well-damped output filters, with large capacitances and small inductors can keep this effect at a reasonable level.

At very light load on an output, the inductor current in that output becomes discontinuous, and the dc gain of the output climbs. Operation in this range should be avoided if good regulation is to be preserved—except in one special case.

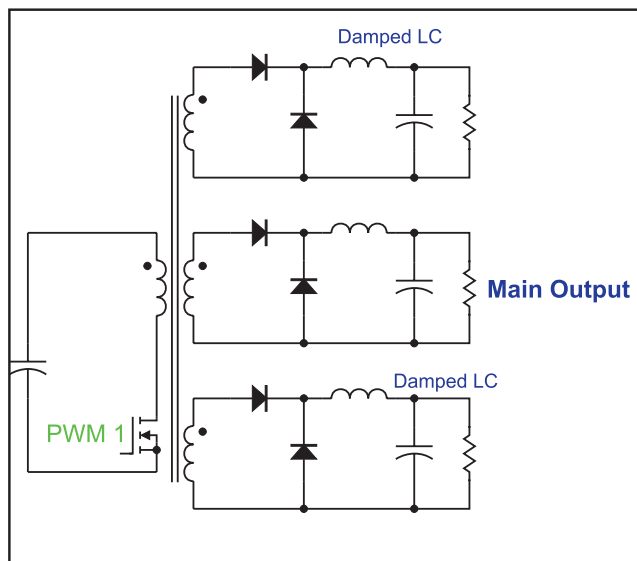


Figure 6: Multiple output forward converter with independent inductors

PWM-FM Control Scheme

It is possible to utilize the two modes of operation of this circuit's outputs. In doing so, you can achieve precise regulation of two outputs at the same time. The continuous conduction-mode output is regulated by altering the power switch duty cycle. It is independent of the switching frequency of the converter, as long as the frequency does not drop so low the output enters DCM.

The discontinuous-mode output is affected by both the duty cycle of operation of the converter and the switching frequency. DCM is the mode in which an inductor is charged and discharged completely in a switching cycle. If the frequency of operation is lowered, the DCM inductor will charge to a higher current during the longer on-time (duty cycle is kept constant) and more energy will be delivered to the output.

Note: this is the opposite of the DCM flyback converter with which you may be familiar. We often run this in current-mode control, fixing the peak current, not the duty cycle, and increased frequency in this case results in higher output.

In this scheme, the drive of a single primary power switch can be adjusted to precisely regulate both outputs. Seems like a great idea. So why don't we always

5. MULTI-OUTPUT FORWARD CONVERTER
WITH INDEPENDENT INDUCTORS

Advantages

- Low parts count
- Low cost
- Simple circuit design
- Single transformer/inductor for many outputs
- One output tightly regulated
- All outputs isolated and either polarity
- Predictable small-signal performance

Disadvantages

- Wide range of regulation with light loads on any outputs causing DCM
- "Worst-case" regulation analysis depends on empirical data
- Auxiliary output LC filters must be damped to prevent ringing during transients
- Post regulation will be needed to meet tight specs on auxiliary outputs

do this? Firstly, the requirement to keep the secondary output in DCM adds stress to the semiconductors. This limits the power level at which this technique can be applied. Secondly, the required frequency range can be quite wide with varying load and line. These disadvantages, coupled with the lack of an integrated controller for such a scheme, make this more of an interesting intellectual curiosity than a practical circuit.

Two-Output Feedback

This separate inductor technology is sometimes combined with a feedback control that takes information from more than one output voltage, as shown in Fig. 7. This technique can be useful when the main converter output regulation can be relaxed. For example, single loop feedback can regulate the main output to within 1%, and the secondary output may be within 10% by cross-regulation.

Two-output feedback can allow the main output to vary by 5% and tighten the secondary output to 5%, which may be a more desirable combination for the power user. Great care must be taken in designing feedback networks such as this. As a first design approach, it is tempting to optimize each compensation network alone, giving it good phase margin and crossover frequency. The second loop can then be designed to give the same response when the first one is open. However this is precisely the wrong way to design the two-output feedback. If you do it this way, the system will be unstable, with the two outputs oscillating out of phase with each other, but maintaining a constant sum.

The proper way to design is to decide which output is most critical, and optimize that loop alone. The second loop is then used with much lower crossover frequency to provide dc and low-frequency feedback information from that output.

It must be emphasized that the two-output feedback scheme does not improve the power stage regulation performance. It merely tightens up the regulation of one output at the expense of another. In some cases, this may be the cheapest way to meet specifications, requiring just the addition of a few small-signal parts.

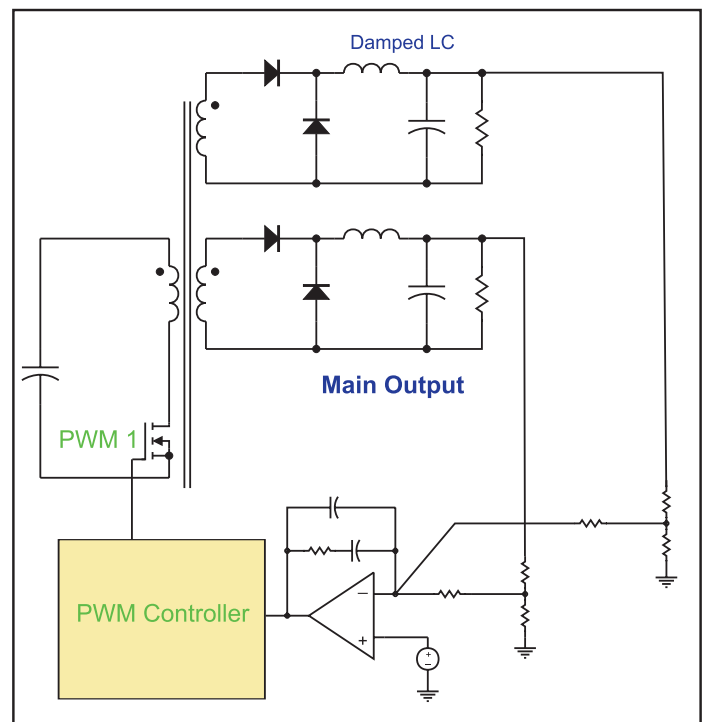


Figure 7: Two-output feedback scheme for modified regulation

TWO-OUTPUT FORWARD CONVERTER WITH SEPARATE OUTPUT INDUCTORS AND PWM-FM CONTROL

Advantages

- Precise regulation two outputs
- Simple circuit design
- Both outputs isolated and either polarity

Disadvantages

- One output must always be kept in DCM, limited power output
- More complex controller
- Variable frequency operation with wide frequency variation for large load changes



Current-Driven Converters

Another way to avoid problems involved in coupled secondary inductors is to use a topology that puts the power inductor for all outputs in a single primary element, with the transformer next to the load. Then, as with the flyback converter, the output voltages are set with just the turns ratios of the transformer.

There are numerous power stage topologies that can achieve this. Fig. 8 shows a buck circuit followed by a push-pull transformer. The transformer operating at a 50% duty cycle on each side of the push-pull, provides an almost continuous current output. It will, however, create more noise than a conventional forward.

Note: this is actually the basis for Synqor's technology, as described in the last issue of SPM, although they do not use it for multiple outputs.

6. CURRENT-DRIVEN TOPOLOGIES

Advantages

- Good cross regulation with multiple transformer windings (typically <10%)
- Single inductor
- Simple to add additional windings and standardize design

Disadvantages

- Higher voltage stress on primary side
- Higher noise on the outputs vs filter inductor on secondary side
- More complex topologies with more switches
- Small-signal model difficult to match with measurements at higher frequencies

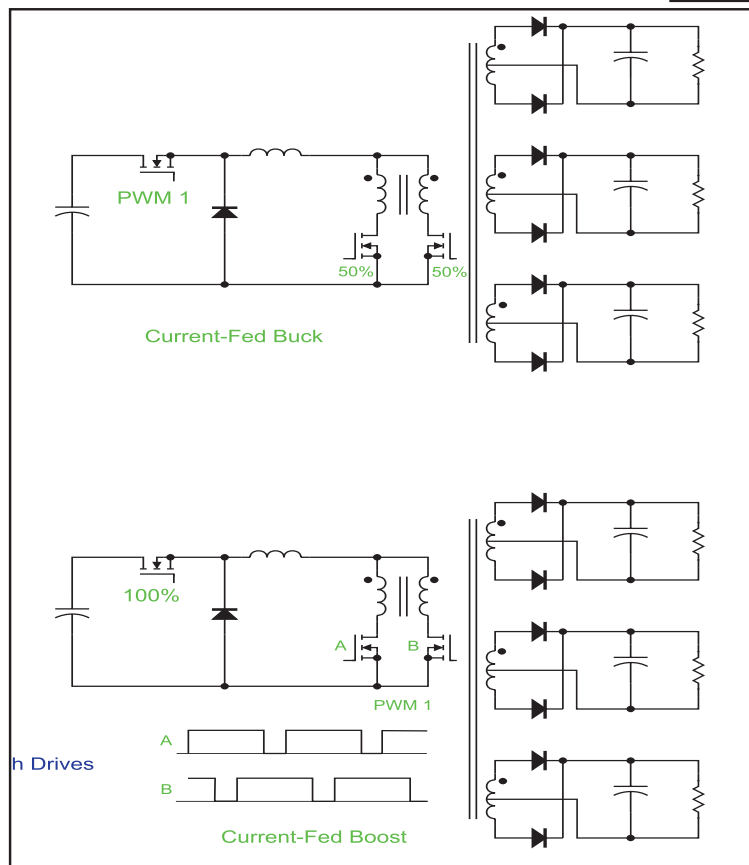


Figure 8: Current-driven topologies

Figure 8 also shows the boost current-driven topology. Notice the schematic is the same, although some texts will show the circuit without the input switch and diode. Under normal operating conditions, the buck switch at the front end is always kept on, and the diode never conducts. This input switch is used for start-up and overcurrent protection.

7

Multiple Output Forward: All Switched Output

The problem of standardized design

plagues all power supply manufacturers. They are expected by their customers to produce custom designs rapidly and at low cost of both production and NRE. This is difficult to do when you use multiple schemes to achieve the required output voltages.

One straightforward way of standardizing without the high cost of multiple dc-dc power stages is to use a forward converter with the primary always switched at 50% duty cycle, as shown in Fig. 9.

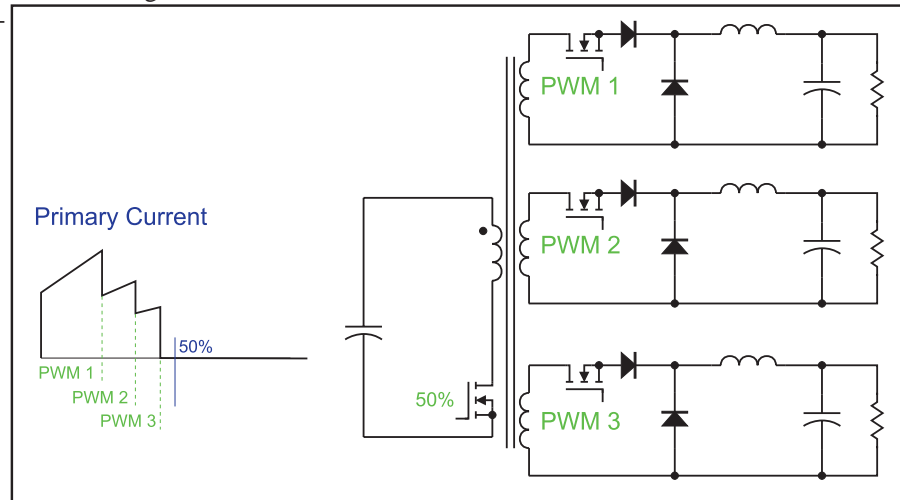


Figure 9: Forward converter with primary switched at 50% duty cycle, and independently regulated outputs

Notice that on each output we use a power FET in series with a rectifier diode. It is not possible to eliminate the series diode since the switch needs to be able to block in both directions. This is NOT the same as a synchronous rectifier application where the FET is ori-

ented the other way round. As the name synchronous rectifier implies, its operation is synchronized with the waveforms applied to it, and it is only turned on when the equivalent forward diode is on.

For the switched forward in this multiple output scheme, it must be able to block forward voltage to regulate the output, and block reverse voltage when the primary switch is off.

7. FORWARD CONVERTER WITH CONTROLLED RECTIFIERS ON ALL OUTPUTS

Advantages

- Tight Regulation on every output regardless of line and load
- All outputs independent
- Standardized design procedure for all requirements
- Standardized primary circuit
- Predictable small-signal model for system stability

Disadvantages

- Separate PWM controller needed for every output
- All power outputs have additional switch in series - lower efficiency
- Primary-side current mode control cannot be used

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- Design and Build Forward Transformer
- Design and Build Forward Inductor
- Magnetics Characterization
- Snubber Design
- Flyback and Forward Circuit Testing

Day 2

Morning Theory

- Small Signal Analysis of Power Stages
- CCM and DCM Operation
- Converter Characteristics
- Voltage-Mode Control
- Closed-Loop Design with Power 4-5-6

Afternoon Lab

- Measuring Power Stage Transfer Functions
- Compensation Design
- Loop Gain Measurement
- Closed Loop Performance

Day 3

Morning Theory

- Current-Mode Control
- Circuit Implementation
- Modeling of Current Mode
- Problems with Current Mode
- Closed-Loop Design for Current Mode w/Power 4-5-6

Afternoon Lab

- Closing the Current Loop
- New Power Stage Transfer Functions
- Closing the Voltage Compensation Loop
- Loop Gain Design and Measurement

Day 4

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- Magnetics Proximity Loss
- Magnetics Winding Layout
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MULTIPLE OUTPUT FORWARD: ALL AUXILIARIES SWITCHED

If your power supply has one main output, it usually does not make sense to add a switch in series with that output, and it can be regulated directly with the primary side duty cycle control. This is shown in Fig. 10.

The main advantage with this scheme is that we use the primary duty cycle controller to regulate the main output directly, and eliminate the power switch in series with the main output rectifier.

As with the previous example, this is NOT a synchronous rectifier application on each of the auxiliary outputs. A diode must be placed in series with each of the controlled switches.

8. FORWARD CONVERTER WITH CONTROLLED RECTIFIERS ON AUXILIARY OUTPUTS

Advantages

- Tight Regulation on every output
- Highest efficiency on main output

Disadvantages

- Separate PWM controller needed for every output
- Auxiliary outputs must run at shorter duty cycle than main output - increased stress, transient regulation issues
- Primary-side current mode control cannot be used

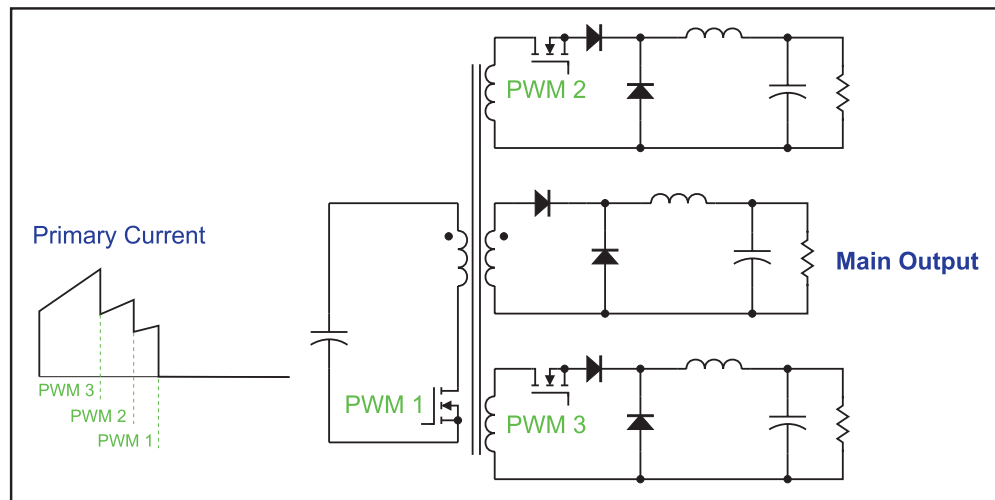


Figure 10: Forward converter with regulated main output and independent switches on all auxiliary outputs

A disadvantage can be seen in the current waveform in Fig. 10. The total primary current steps down as each of the outputs turns off, and the current waveform is unusable for conventional current-mode control. If current-mode is needed, you can use a winding on the main output inductor to generate clean waveforms.

In this example, the current is shown for the case where all of the output switches turn on at the same time, and are turned off with the individual controllers. It could be done in a different way, where the switch is used to control the turn-on time, and the waveforms for this case will be the same as for the mag amp scheme described next.

9

Multiple Output Forward: Mag Amp Auxiliary Outputs

Driving a controlled switch in series with a high current output as in the previous system is not necessarily a straightforward task. The power device requires a substantial gate drive, and a power source to operate it. Even with the new low-cost power FETs that you can buy today with very low on-resistance, this scheme can become expensive.

As an alternative to silicon in the days when silicon was very expensive, mag amps (or magnetic amplifier) found a place in the power supply world with outputs ranging from about 10 A to 50 A. Below this range, it is often simpler to use silicon switches. Above this range, the mag amp design becomes unwieldy.

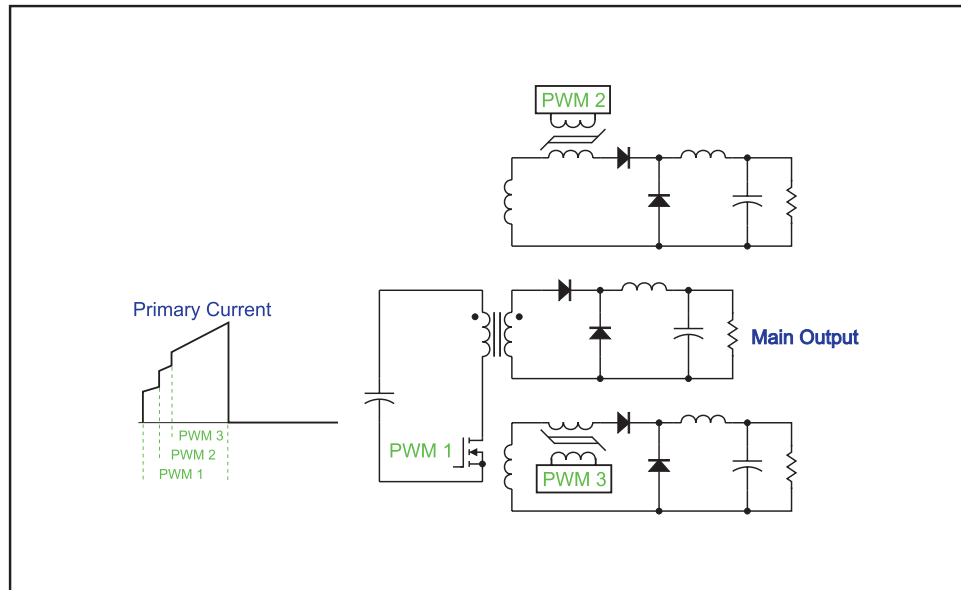


Figure 11: Forward converter with magnetic amplifiers (mag amps) on the auxiliary outputs.

A mag amp in this application is a saturable inductor used to delay the turn-on of the diode on the auxiliary output. When the primary power switch is off, a voltage is applied across the control winding (may also be just the power winding) of the mag amp to bias the core magnetization to a controlled level. When the power switch is turned on, the core magnetization is driven in the other direction until it saturates due to the square-loop material characteristic, and allows the diode to turn on.

This technique delays the turn-on of the current into the auxiliary outputs. Each auxiliary must operate at a lower duty cycle than the main output. The corresponding primary current waveform is shown in Fig. 11. As with the previous scheme, the waveforms cannot be used for conventional current-mode control.

Applying mag amps to a circuit is definitely an art form that is lost with modern design. It can work extremely well, but you need to know what you are doing. Also beware: there have been a few obscure papers suggesting that the mag amp circuit can work without the diode in series with the saturable core. These papers belong in the file with perpetual motion machines.

9. FORWARD CONVERTER WITH MAG AMPS ON AUXILIARY OUTPUTS

Advantages

- Tight Regulation on every output
- Highest efficiency on main output
- Lower cost for some applications

Disadvantages

- Extra magnetic components needed
- Magnetics core loss in mag amps
- Controller needed for each mag amp - complex to design, and complex small-signal performance
- Auxiliary outputs must run at shorter duty cycle than main output - increased stress, transient regulation issues
- Primary-side current mode control cannot be used

110 DUAL OUTPUT WITH AUXILIARY BUS

Many power supplies actually use a combination of many of the above techniques to get multiple outputs in the most efficient and cost effective way. They may even add linear regulators, or switched-capacitor converters for very low power outputs.

One good combination of technologies that provides a balance of good efficiency and flexibility of outputs is the dual output converter where one output is used as an auxiliary bus. The main output power is processed only once for maximum efficiency and regulated with the primary PWM control.

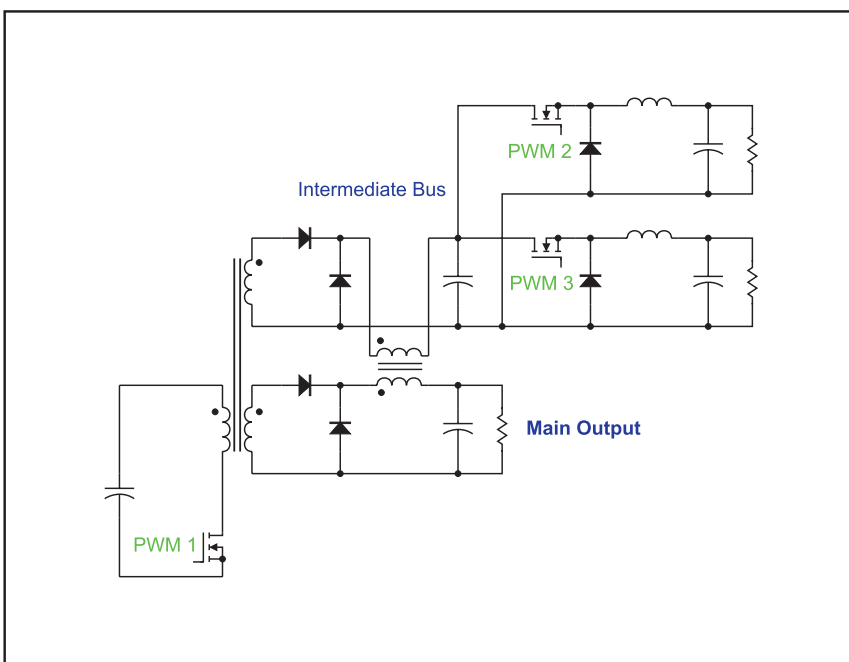


Figure 12: Dual output power stage with auxiliary bus for multiple outputs

The auxiliary output bus is cross-regulated with a coupled inductor and transformer to provide a pre-regulated bus for all of the other outputs. There will be variations in this auxiliary bus with load conditions. The remaining outputs are all tightly regulated by their own converters.

111 REGULATED BUS AND DC TRANSFORMERS

In section 2 of this article, a pre-regulated bus is followed by multiple buck converters. Another variation of this is to start with a converter that generates a non-isolated and tightly regulated bus, and follow this with multiple isolation transformers.

we've included this technique because it is exactly what Vicor proposes with their latest products— a pre-regulated dc bus, followed by as many transformers as needed for the outputs. We don't know yet the impact of this approach— it's too early to predict how the industry will react to the new Vicor components. More information on this is located in the Components Section of this issue.

This article has covered many of the techniques used for multiple output converters. It is by no means exhaustive. You can add other more obscure techniques, or use different

topology converters if you wish. You can also mix and match all of the above techniques to provide the optimum power architecture for your system needs.

There is no single answer for a "right" technology for every single application. This is one of the reasons that the power supply industry defies standardization. As different components are developed by the semiconductor and capacitor vendors, we can expect the increased application of multiple power stages, rather than more complex magnetics solutions.

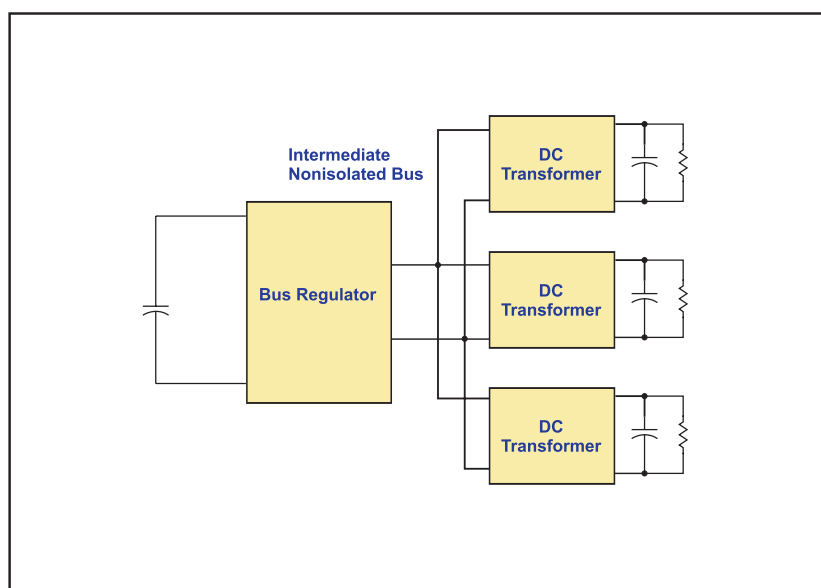


Figure 13: Regulated, non-isolated bus followed by dc-dc transformers