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APPLICATION NOTE 5569

Integrating Power Passives and Tactical Trade-Offs for Power Efficiency: Part 1, Harmony - Design like a Symphony Conductor

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Abstract: In the quest for smaller, thinner, and more powerful devices, designers need to decrease the size of power passives, inductors, and capacitors. This application note explores paradoxical engineering trade-offs, focusing on power management and switching supplies. After a discussion of switching and filtering losses, switching glitches, dead time, and shoot-through, discussion turns to tricks of the trade in using integrated ICs to solve power efficiency issues.

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Introduction

Power passives, inductors, and capacitors are big in today's consumer products. That's big as in physical size compared with the tiny thin phones and tablets appearing everywhere today. What's an engineer to do? We have to be smart and apply scientific methods. It seems like I hear this every week. "Let's reduce the switching power-supply size and increase efficiency", which usually means adding more battery operational time. Sure, good idea, but we still need to reduce the physical space. A promising approach to the dilemma is to attack the power passives because of their relatively large size.

We start this two-part series by exploring many contradictory, incongruous, and paradoxical engineering trade-offs. Part 1 focuses on the wide range of knowledge, much like a symphony conductor, that a good designer must have to ensure a well-integrated, power-efficient solution. The symphony conductor must know the sound and the capability of each instrument and each musician to direct a harmonious production. His clever intertwining of the music adds to the audience's delight and creates return customers. Yes, it's a good role model for us.

Why Concentrate on Switching Supplies?

The trend in appliances is toward small, lightweight, thin, and power savings with lots of "cool" features. This is true for portable consumer devices, ultra-thin big-screen TVs, and even for white goods like dish and clothes washers and clothes dryers. Consumers are demanding longer lasting batteries for operation and faster charging. The issues really crystallize into power management and batteries. Battery technology has promised breakthrough advances but these have been slow to materialize because problems in chemistry are hard to solve quickly. As a result, we must focus on addressing the management issue. Linear analog regulator power supplies must turn excess voltage into heat where switching supplies can transform the voltage with minimum loss.

The initial thought is to save power. First, we must aim for nanoamperes so we do not need as much power. While there are many techniques for saving power in discrete components, there are many more that can be used inside integrated circuits (ICs). Second, we must place the passives inside a hybrid IC package. We might get away with placing one or two discrete components inside, but surely not 10. Let's try. Third, we must ask how small can we get, which is logically the same as asking how high can we go in frequency without sacrificing efficiency. Can we get high enough in frequency so we could actually use a bond wire or an on-chip capacitor?

There are many types of switching supplies, but in this application note, we concentrate on the buck supply. This takes a higher voltage and reduces it to a lower voltage. Our focus is on small supplies, less than a few amps, and with voltages under 10V. Small, light, efficient power supplies are the hallmark of those found in consumer and portable battery devices.[1, 2]

Start by Understanding Power Switching Losses

The power losses (mainly heat) occur in two areas: switching and filtering losses. Switching losses are in conduction and in the actual switch time; filter losses happen when reducing ripple to an acceptable level.

Conduction loss is the power lost in transistors because they have a small resistance in the on-condition. Remember, having a short circuit with no resistance is not possible, because even a mechanical switch has some resistance. Bipolar junction (BJT) and metal-oxide semiconductor (MOS) transistors could be used in different applications. In this application note, we concentrate on complementary MOS (CMOS) transistors, as they are the most commonly integrated components. One trade-off is that a CMOS with a low drain source on-resistance (R_{DSON}) tends to be physically larger and switch slowly. Small-pattern CMOS transistors are fast but have higher R_{DSON}. Inside an IC we can parallel many small CMOS transistors to lower R_{DSON} but, of course, we never get something for nothing. Soon the capacitance, resistance, and inductance of the parallel devices start slowing the switching speed.

Switching losses are associated with the time that it takes to switch the transistors on and off, and the losses can be considerable. Obviously, we must switch faster, but how? There are limits because it is necessary to charge and discharge inductance and capacitance. Eventually as the switching speed reaches its shortest time and the frequency rises, we reach a point where we have all switch, rise and fall times, and no "on time." By that time, efficiency is pretty well gone.

Let's compound the problem by introducing dead time and shoot-through prevention.[3, 4] In **Figure 1**, the top and bottom transistors cannot be on simultaneously without shorting the power supply to ground. Great care is taken to ensure that the gate-drive signals are well timed to prevent this. Because of process variations, designers force a short dead time in the waveform when both transistors are off. This time is subtracted from the available time period, further reducing the highest possible switching frequency. Dead time is not always enough to prevent all shoot-through. Alternatively, the needed dead time is so long that, in the worst case, switching efficiency suffers. Shoot-through events occur when both output devices are on (e.g., with circuit faults or transients such as sudden load changes). Shoot-through is most common near crossover (dead time) when the transistors are almost completely on or off. A transient at this time can drive both transistors partially or completely on.

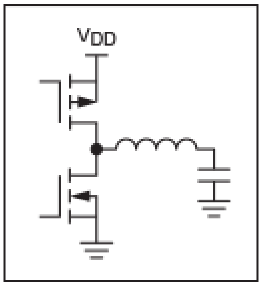

Figure 1. A CMOS switching supply output stage.

Now let's pile on yet another conflicting requirement, where the "cure" wastes energy and actually makes heat. Switching glitches primarily form impedance mismatches at the output. With general-purpose supplies where the load is highly variable, it is sometimes difficult to remove switching glitches. Thus, transient snubbers are added. A transient snubber usually comprises a combination of resistors, inductors, capacitors, and sometimes a diode. The snubber is used to reduce switch transients that might damage the output transistors and other components. Snubbers are, however, not good at returning the extra energy back into the circuit to increase efficiency. Instead, they convert the energy into heat.

Filtering losses are usually defined by the amount of ripple that the load can tolerate. Digital circuits can withstand more ripple because of their digital thresholds.[5] Analog circuits cannot withstand even a small amount of ripple.

Inductor and capacitor size is related to frequency. As the frequency increases, the inductor and capacitor shrink. Think of the analogy of drinking a large soda in big gulps—that might be the "manly" thing to do, but a child could do the same job in many smaller sips. The total power transferred is the same, but the small inductor and capacitor can do it at a higher frequency and, with proper design, less ripple and less power lost to needed lowpass filtering.

Starting Power-Supply Design

Now some good news. The switching losses outlined above are very challenging for large supplies with multiple discrete components intended for general use. Those supplies must accommodate a wide range of conditions. However, well-defined, highly integrated supplies inside ICs let the designer control, simulate, and custom fit some special circuit topologies. It's not that difficult to design, if you know some tricks of the trade.

Know the Application

First, we must gather information about the design and thoroughly define the issues. Included in the exercise are details about each voltage and current required. What are the tolerances, accuracy, load, and line regulation? Most important, what voltage is really required? If the voltage does not require tight tolerances, would a resistor-divider and an impedance converter, such as a transistor or operational amplifier (op amp), do the job?

Heat is a major concern for several reasons. Heat must be dissipated to prevent a device from overheating. This can be a very difficult challenge when, for example, a cell phone is left in the sun and sealed in a closed automobile. Moreover, any heat from overheating wastes battery life and requires the battery to be charged more often. Nobody wants that. Time between charges is the paramount consumer concern. Thus, efficiency counts.

Switched or Linear?

Now we need to decide how to partition the supplies into switched and linear configurations. The best way to make a switched supply efficient is to understand both the supply voltage (usually the battery and battery under charge voltages) and the load variations. The most efficient switcher is one that has little change in load current. One easy way to shrink the physical size of the inductor and capacitor is to increase the switching frequency.[6]

Let's take an example, a specialized computer that has large differences in power required in different operating modes. We can think of two applications with similar requirements: a satellite receiver and a computer monitoring a physical process, perhaps inside a factory. Both situations intermittently utilize a hard disc for low-cost storage. To save energy and increase the disc life, the disk can despin. We specify that the disc must be able to spin up and be ready to read or write within 20 seconds. This means that the satellite receiver must provide a minimum of 20 seconds of semiconductor memory so that any command from the operator appears as a seamless part of the operation. The process-monitoring device has to have enough memory so that data can be intermittently recorded on the hard disc, while minimizing the necessity of spinning the disc up to speed. Another operating mode might be deep sleep, which needs minimum power. Here, the satellite receiver or factory process is not in use during the night. In either case, each operating mode must be accommodated to maintain top efficiency.

Integrated Tricks of the Trade—Think "Inside the IC"

Generic switching and linear three-terminal voltage regulators need to operate over wide extremes of current draw because the designers cannot predict how or where they will be used. When we know the exact application, we can tailor a circuit and optimize the efficiency. For example, the easy way to make a generic regulator is to confine it to low bandwidth to prevent oscillation. Then we depend on the decoupling capacitors to supply the fast high-frequency transient currents; the regulator supplies the slower average current. This is usually a good design trade-off because the small local capacitors near the ICs mitigate the resistance and inductance losses in the connections between the ICs and the regulator.

A different tactic is employed for known loads in audio amplifiers: use wider bandwidth power regulation. The simplest example is fanning out a reference voltage to many stages of amplification. In this approach, one could use op amps to isolate small circuit portions and prevent interactions.

Another way to minimize the decoupling capacitor size is to place a relatively small capacitor on the input of an amplifier and use the gain to increase the effective size of the capacitor (i.e., the Miller effect[7]).

Think transistors. ICs have the advantage that all of their transistors are made at the same time through a photographic process. This ensures a close matching of parameters, much closer than with discrete transistors made at different times. The output stage in Figure 1 can add two transistors if they match well. The top transistor and the bottom one each become two transistors in a cascode configuration. Because the transistors have half the voltage applied to them, they can be controlled more easily to improve switching speed and efficiency. Well-matched transistor circuits on a single die can more easily control parasitic capacitance and, thus, time delays to reduce dead time and to control the phase and timing of multiple supplies.

Another "inside the IC" option at first sounds silly—until we do the math and a simulation. For example, we have a 5V supply and want to make 2.5V and 1.2V supplies. Conventional thinking says that we build two parallel supplies, 5V to 2.5V and 5V to 1.2V. At high frequencies (i.e., 30MHz to 100MHz), the filter or ripple losses diminish compared to the switching losses. One must do the math to see if cascaded supplies would have less loss. Cascading the supplies actually means that the 5V becomes 2.5V and then the 2.5V supply becomes 1.2V. In essence, there is a double conversion and double efficiency loss to two-step the 1.2V power. Restated simply, the 5V-to-2.5V supply must pass all the current used at 2.5V *plus* all the current used at 1.2V. Something surprising can happen now because the 1.2V supply transistors have half the voltage across them compared to the parallel condition: their switching loss drops, especially with loads light enough to make the cascaded pair more efficient.

It is very common to make a clean power supply in an IC and then provide power to multiple circuits with current mirrors. Many designers use identical npn transistors because they are made at the same time, with the same process, and have identical V_{BE} voltage drops. By tying the bases together, each emitter can distribute identical voltages to many different circuit stages. Since we are replicating a clean power supply, the number of decoupling capacitors is greatly reduced.

Conclusion

A symphony conductor coordinates the instruments to produce a harmonious, clean sounding, and enjoyable musical presentation. The project engineer controls the power parameters that result in a harmonious, efficient system that pleases the end user. For both the conductor and the engineer, the devil is in the details. Our conductor must be able to recognize a perfect instrumental rendition as well as a poor one. Our design engineer must be able to identify even small deficiencies in the power structure that may negatively impact the entire device.

There is much more to say on this topic. In application note 5570, "Integrating Power Passives and Tactical Trade-Offs for Power Efficiency: Part 2, Balance - Work Through All the Choices," we discuss controversial and seemingly impossible engineering trade-offs in power system designs.

References

1. For more ideas about battery systems, see tutorial 671, "Energy Management for Small Portable Systems."
2. See tutorial 5290, "Higher Integration Drives the Newest Generations of Smartphones."
3. For more information on shoot-through, see application note 1135, "Small Capacitor Improves Efficiency in High-Power CPU Supply."
4. For more information and an example of dead time and shoot-though protection, see Figure 6 in

application note 5424, “Thermoelectric Cooler Control Using the DS4830 Optical Microcontroller.”

5. For more information on digital thresholds, see application note 4345, “Well Grounded, Digital Is Analog.”
6. For more information on a 4MHz switcher, see application note 3603, “Buck Converters Proliferate in Handhelds as Features and Processing Power Increase.”
7. See “Origin of the Miller Effect” (PDF), scanned by Kent H. Lundberg; John M. Miller, “Dependence of the input impedance of a three-electrode vacuum tube upon the load in the plate circuit,” Scientific Papers of the Bureau of Standards 15, 351 (1920): 367-385. This paper was written in June of 1919 and published in 1920 by the Government Printing Office in Washington, D.C. The copyright on this paper has expired. It is now in the public domain.

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