CHAPTER 8

Home-Grown Strategies in Troubleshooting

Peeling the Onion

As you can imagine, there is no way I can write about every conceivable problem that may arise. And for sure, I haven’t seen all the possible problems either. That’s what makes power so much fun. But maybe I can share a tip or two with you. Because even though we all learn a little more every day, all we are really destined to see eventually is a tip—the tip of the iceberg. Luckily, we do eventually develop a certain type of logic that can help us get through the next problem a little more easily. And that’s what I am going to talk more about here.

Troubleshooting, to me, is akin to peeling an onion. And often thereafter, reverse-peeling it, reassembling it back from its peels, almost like playing a movie backwards. In simpler systems, like DC-DC converters, looking for clues during the peeling phase is practicable, but in more complex systems like AC-DC supplies, reverse-peeling is my personal preference. For that, I first take out everything superfluous very carefully, until I reach the very core of the circuit—the switching engine of the converter. I make sure that that is ticking away just fine. I might even need to peel a few steps deeper into that engine, by disconnecting secondary outputs, for example. Then I start systematically putting back everything else around it until the problem reappears. But be warned—there is some carefully considered trace-cutting and also some ill-considered cussing involved in this process. Also do not forget to retain the basic functionality in the process. For example, if you “lift” the diode going to the 12V output, you may need to hook up a bench power supply to provide this rail externally, so you continue to provide the necessary current for the 5V regulation opto-coupler to do its job. Remember: you shouldn’t try to use the primary regulated rail to provide the current to the opto-coupler as well. That can lead to a weird loop response. You should have a separately regulated rail if possible, for the opto.

What do I mean by taking out everything superfluous? That could mean any external circuitry not directly linked to the core functionality (such as current limits, OVPs, crowbars, OTPs, etc.). But it can mean much more. For example, a few days ago I walked into the lab to talk to a junior colleague of mine. He happened to be looking at some minor issue on a small DC-DC converter board in front of him. It was meant for a Li-ion cell input, and set for 1V output. Suddenly, he started looking really puzzled. “Why is the input
supply showing 2mA at no load? It should be only a few μA in this condition. Is the part suddenly leaky?” So to be doubly sure I physically disconnected the leads going to the electronic load, knowing by now that electronic loads can malfunction and that even at a setting of 0A they can draw up to a couple of mA (especially the high-power rated ones, and more so after a year or two in the field, or a month on my bench). But the input supply reading stayed rock steady at 2mA. Clearly, the electronic load was good, but we weren’t. In my experience, at such moments we need to pull back and start thinking, rather than just plunging headlong on. We need to start applying some very basic logic. Asking questions. One of the first things we should always ask is, what can I possibly do to make the problem get better or worse? That usually gives a clue to the cause of the problem. For example, we can ask, how does the problem respond if we change the input voltage? Or what if we change the bench power supply altogether? Does the problem change with temperature? (For the latter, it is often convenient to use a hot air gun, or hairdryer, along with a HFC-134a (“Freon”) canister; though you should be forewarned: that might unmask another problem that you haven’t seen so far!). What if I change the diode, does the problem go away, and so on. We need to think of everything, however unlikely it seems to be. The clue we got in our above case was that the 2mA reading stayed very steady as we varied the input. If it were simply a quiescent current issue caused by some leaky structure between the VIN pin and Ground, this reading was likely to go up as we increased the output. But it didn’t! And what was getting more suspicious to me was the fact that it was almost exactly 2.00mA. How come? At the corner of my mind I realized that there is only one thing in the converter that also stays rock solid as the input increases. You guessed it! It’s the output. So in some mysterious way, could this be related to the output voltage or output rail? But we had already disconnected the load. I checked again. Nothing seemed unusual with the setup. We had a few innocuous-looking scope probes hooked on to the board, but that was all! Or was it? At that moment I started peeling the onion. I started blindly removing anything extraneous. So off came the scope probes one by one. And suddenly the problem went away! I had in the last step just removed the probe hooked to the output rail. The problem was in fact quite simple—the scope channel had been set up for a 50Ω input termination. And since the signal was being DC-coupled to it, we were getting 1V/50Ω = 2mA. The entire process above actually took less than a minute or two to diagnose and fix. You may ask, why had the engineer been using a 50Ω termination setting anyway? Because he had been trying to characterize the noise on the output rail, and for that, a 50Ω termination (AC coupled) is in fact recommended to avoid scope cable reflections from distorting the observed signal.

Asking the Right Questions

At every stage, we must learn to ask plenty of questions. Because if we don’t have answers to all of them, or haven’t even bothered to asked, how would we ever know they were the right ones anyway? Here is a likely list (see Figure 8-1).
Question 1: Is what I think I am seeing truly abnormal? Is it really a problem, or isn’t it?

For example, if you are seeing an overshoot of 50mV on startup, there is no reason to worry about that usually, because that amount of overshoot is considered quite normal. In fact for a 12V output setting, that may even be considered remarkable. In other words, look at it in percentages, such as 50mV on top of 12V is an overshoot of 0.4%. On a 1.8V output it would be about 3%, getting to the point where you might get slightly worried, depending on the application of course. Same for the DC regulation level of the output. However, if the system board connected to the output of the converter is failing, you can be quite sure your output did overvoltage for some reason, however temporary that event may have been.
that case, the problem is actually worse than you think. Now you have to try and capture
the event first, before you try to understand its cause.

Yes, sometimes you may find the customer expecting what my colleague used to call
“unobtanium.” The customer may simply post a line in the product specification without
fully realizing what it entails, or what it might cost. Negotiating politely with the customer
is usually recommended if you are in doubt about the validity of a spec (unless of course
the customer “hates wasting time with stupid questions,” and all questions are, by definition,
stupid). So if the customer is expecting 20 years life on his output aluminum electrolytics at
a room ambient of 45°C, tell him that that will cost him. A good capacitor will usually have
a life of around 2000 hours (83 days, operating 24 hours a day). This life number applies
when the capacitor is passing its rated ripple current at an ambient of 105°C. So with the
doubling rule every 10°C fall in temperature, at best we will get to $2000 \times 2^6$ which is 128
thousand hours. Five years is about 44 thousand hours, so even if we pass no current
through the capacitor at all, we can’t get up to 20 years of life, not under these ambient
conditions. We might go looking for “5000 hour capacitors,” and then apply enough
derating on the ripple current (more capacitors in parallel) to get there. But the question
is—is it really necessary?

Many years ago, when designing AC-DC Flybacks for a well-known company making
computers with alternative operating systems, we were pleasantly surprised that all they
wanted in their spec was an estimated life of 15 thousand hours (about 2 years) for their
output aluminum electrolytics, versus 5 years for almost every other customer out there. But
their engineer explained it to us quite succinctly. “Why should we ask for 5 years life? The
customer is not likely to operate the computer for more than 8 hours a day. So our “2
years” would amount to 6 calendar years for him. In any case, we think that is more than
enough considering that customers will typically change their computers once every couple
of years.”

But you could find customers at the other extreme of the spectrum too. In that case you may
need to tell them honestly they do need to pay more attention to a certain problem you have
spotted, and may in fact need to pay more to have it resolved. You can also find other
vendors out there, knowingly playing down known problems to their customers, for
whatever reason. In other words, you always have to be careful, whichever side of the table
you are on.

Once, while working as an Apps engineer at this maker of high-voltage Flyback monolithic
switcher ICs, I happened to express concern about the way they were selecting the input
bulk capacitors for their evaluation boards. To this day, in my opinion, they are making
several misleading/erroneous recommendations to their customers via their eval boards.

a) They recommend an input capacitor selection based on the magic figure of 3μF/W.
Though that does, in principle, give the converter a holdup time of 20ms as is
usually required, it should be clear that what you really need is 3\(\mu\)F per input Watt, not output Watts. The front end (where this capacitor really is) cares only about the power it sees, which is the input power. The relationship between input power and output power is through efficiency, which could be all over the place. So you should not simply pick 180\(\mu\)F for a 60W universal-input Flyback. At 70% efficiency, the input power is about 85W. So you need to pick 255\(\mu\)F.

b) The second mistake, in my opinion, was that a typical electrolytic may have an initial tolerance of \(\pm 20\%\). And in addition, a fall of 20% capacitance occurs by its end of life. Assuming you still want the equipment to meet 20ms holdup time (and a respectable life), you really need to start with a capacitor of nominal value about 40% higher than what your 3\(\mu\)F/W rule tells you. In other words, for the 60W Flyback, you may need to pick a capacitor of nominal value \(255 \times 1.4 = 357\mu\)F. You may get by with 330\(\mu\)F, but certainly not with 180\(\mu\)F! And I don’t think that amounts to overdesign. Just good engineering. In fact we were explicitly asked to do so by one of our major customers, a well-known computer manufacturer headquartered in Cupertino, California, when I was working in Singapore.

c) This high-voltage IC company also did no calculations whatsoever to verify that the ripple current passing through the capacitors was indeed within their respective ratings. Chemicon, for example, warns you that the usual life prediction formula applies only if you don’t exceed the rated ripple current.

d) Further, in their apparent hurry to present cute, nifty eval boards to customers (to propel the sales of their ICs), the company would also instruct its CAD person to put the components in “as close as possible . . . period.” They also ended up rewarding him or her with small bonuses for that effort. But I clearly remembered in Singapore, when we looked at a very nicely performing commercial power supply made by world leaders “Delta,” the first thing that caught our attention was how carefully they had tried to keep heatsinks and hot components physically apart from the electrolytic bulk capacitors (to avoid diminishing their life severely). They were right after all. We had learned a lot from them. So I went back to the inventor-VP (now CEO) and stated my opinion on the capacitor issue. His answer simply was “if it fails they just throw it away, who cares?” An early end to something you may have paid good money for? I felt a wee bit behind the times.

**Question 2: Is my equipment somehow responsible?** That is sadly often the case. For example, some electronic loads can show weird glitches in the load profile they present to the converter under dynamic conditions. For example, if we are doing step load testing from 10mA to 200mA, all may be fine. But if we go from 0mA to 200mA, and see an output overshoot/undershoot, it could also be because of the electronic load. We may need to do
that test either with another electronic load, or even a resistive load (an actual resistor). We could also put in a current probe in the leads going to the electronic load and ensure that the electronic load is indeed going smoothly between the two set load levels. Never assume anything.

Once we were doing repetitive output short circuit tests on our small DC-DC board, and sure enough, we managed to destroy the switcher IC. But the IC had pretty good current limiting (we had already ascertained that). It turned out that the DC power supply had caused the blow up because its output had started careening around all over the place whenever we shorted (and un-shorted) the outputs of our converter board. It got worse when we did that at a certain rate. We then really realized that even a bench power supply has an internal feedback loop and can go into oscillations. We had thought only switchers were suspect! It seems that whenever we shorted the output, we dragged down the input rail (the output of the bench power supply). So the bench power supply kicked in aggressively (rather too aggressively), trying to correct the situation. It ended up overshooting and then undershooting repeatedly, until finally it exceeded the voltage rating of the switcher IC. We actually did have some clues that led us on the trail of this hitherto unsuspected culprit. First, the likelihood of damage decreased if we reduced the input voltage. Therefore, it seemed to be not a current overstress, but a voltage overstress. Second, we noticed the wobble on the input rail and tried to pass on that information better to the bench power supply, hoping it would correct it. This we did by connecting remote sense leads from the bench power supply to the input prongs of our converter. But that only made matters worse, as the bench power supply now saw even bigger swings at its output, and became even more aggressive (and lousier too). Its loop was apparently poorly designed (we couldn’t get our switchers to behave that badly). That’s when we realized that this was not normal behavior for a bench power supply—up until then we were still under the impression that we were somehow instigating this behavior. We quickly replaced the lab supply with an HP/Agilent one, and that showed no further problems at all.

Incidentally, whenever you undertake corrective action and things get worse, you are actually still very close to identifying the cause. Also, we should remember that certain problems depend on timing. So in our case above, the rate at which we applied the load transients was important.

In another case involving timing, my colleague was sitting and toggling the enable pin of our latest HV (high-voltage) switcher IC and discovered that if the disable command comes within a certain 100ns window of the switching cycle, not only does the switcher ignore that command completely, but loses regulation, too, for a few cycles. So the output would overshoot every now and then. The only way to catch this type of occurrence is to set the scope to trigger on the rising edge of the output voltage, at a level about 10 to 25% higher than its steady value (past its normal noise and ripple platform), and in single acquisition mode. Then keep doing everything possible to get it to trigger.
Similarly if you toggle the enable pin at a certain rate in many ICs you can get to see current overshoots too. This often depends on allowing the input capacitor to discharge below the UVLO threshold, but not to the point where it hits the internal POR (power on reset) threshold. Because in that case, if you suddenly enable the IC, it has no soft-start anymore, and you will hit max duty cycle, and possibly staircase if the current limit circuitry is not well designed.

**Question 3: Is the reading real?** Artifacts of measurement are indeed common. Sometimes my colleagues have asked me about a high-frequency noise spike on the output they were particularly concerned with. All I did was to remove the tip of the probe from the output and touch it exactly where its own ground lead clip was attached. If they had expected to see a nice quiet straight line at 0V, they were wrong. Because the same concerning spike was still visible, which simply meant it was just noise picked up by the probe itself. It wasn’t real. So either we do a proper measurement of noise, or at least we need to mentally subtract this pickup from whatever we are seeing on the screen. This is not unlike a conducted emissions test where we first take a scan without the converter being powered up, just so we can be sure which spike is real and which is actually just a cocky shock-jock on some nearby FM station.

In another case, my colleague discovered this for himself—if you have several probes connected to a board, you should try as hard as possible to have all their ground clips at exactly the same ground prong of the PCB. Because if you don’t, imbalances in the PCB ground can create sizeable circulating currents in the grounds of the probes themselves (ground loops), leading to truly amazing artifacts on the output noise and ripple, and sometimes even chaotic behavior on the part of the controller.

All these stories inspired an old colleague of mine to present a seminar to the company’s FAEs (Field Applications Engineers) tentatively titled “Be Sure What You Are Seeing Is Really True?” (Admittedly, I was then asked by my supervisor to “get some of the Chinese out of it!”). We have to realize that the measuring instruments become part of our larger system whenever we hook them up to take some data. Therefore, it is wise to question not just the quality of the instruments themselves, but their natural interaction with the device under test. For example, the few picoFarads of probe tip capacitance may be enough to either quench oscillations or create a new one altogether, especially if we touch it to the high-impedance feedback pin (not the type of feedback pin in fixed voltage option switchers). In fact I have never managed to put a probe tip on this node for too long. Things just seem to happen when you do! Though, by putting a DMM across it, we can have more success, but only in getting to know the DC voltage on this pin. Portable instruments, incidentally, fare better in some cases, since they aren’t connected into the ground wiring of the building (which eventually loops around and comes straight back into the ground clip of your scope or your bench multimeter).
Chapter 8

Question 4: Is the supply rail to the IC well-decoupled? We have dedicated an entire chapter to this (Chapter 2). You must read that carefully. In brief, we must always ensure that the supply rail is clean enough before we give any credence to malfunction.

Question 5: Is the controller/switcher IC at fault (by design)? This is actually a fairly common occurrence. No semiconductor product is released without its fair share of shortcomings. These are usually known to the company at the time of release, with the internal understanding that there were some lessons learned, and these will be resolved when the time comes for the next Rev, or the next product. Fair enough! But there are several variations to this theme, some that you may need to be aware of as you seek answers to a particularly stubborn problem. The three main variations are that the company knows about the problem; the company knows about the problem but does not want to admit it; or the company does not know about the problem.

   a) The company knows about the problem.

      1. The company knows about the problem and mentions it in the electrical characteristics (EC) tables of the datasheet (though remember that a TYP, or typical value, is not guaranteed; only the MIN/MAX values are). This then becomes a guaranteed spec since experts have opined that only the electrical characteristics (EC) tables are truly part of the contract with the customer. The rest, it is argued, is just general guidance (especially the first page of any datasheet which is best described as hyperbole). This company seems very upfront and will likely give you all the guidance you may ever need.

      2. The company knows about it and mentions it in the first few pages of the datasheet. This is an instance where the company is quite forthright about the problem, but perhaps not definite enough about its spread or its impact, to guarantee it in the EC table (or unable to test it). Fair enough. You can work with them if you suspect a widening problem.

      3. The company knows about it and mentions it in some remote part of the datasheet. You should know that every company has by now keenly realized that most customers barely go past the first couple of pages of a datasheet anyway (it is mentioned in internal meetings all the time). That’s when you should be wondering if the company is just trying to create some sort of liability alibi, and no more. You are not likely to get any more detailed information from them about the problem either, since that portion of the datasheet probably wasn’t directed at you in the first place (it was meant for the courts). At this point you should consider if you are better off looking decisively in another direction altogether. Learn to recognize the signs.
b) The company knows about the problem but doesn't admit it.

1. Why should they? There is no guarantee that a part must switch without excessive jitter, for example. These are only implied expectations you may have when you buy an IC. Further, what exactly constitutes “excessive?” Every switcher has some jitter!

There are also implied expectations such as if you short the output and release it, the part must remain undamaged. But check whether the datasheet even mentions short-circuit protection. If not, it may be implied (to you) but not guaranteed (by them). In fact I recently learned that a giant semiconductor company had regularly been supplying giant PMICs (monolithic and complex power management ICs) to a very well-respected Japanese manufacturer for their state-of-the-art digital cameras, but none of the outputs of the integrated DC-DC converters had any active current limiting whatsoever! They said the loads on such custom ICs are so well-known that they don’t think they need short-circuit protection. They were apparently depending on some divine intervention in the form of parasitics and duty cycle combinations to save the show. But what about normal startup stresses, component failures, and the like? It was even more galling that the semiconductor company, in an unbridled effort to generate more revenue, simply rechristened the part, and released it as a standard product for anyone out there to buy. No particular changes were made in the datasheet, and not the slightest mention that current limiting was not present on this PMIC. It was your risk if you had assumed anything that wasn’t stated.

Similarly, you may think a switcher is not supposed to have any output glitches or overshoots during startup. But to some extent all switchers do. And so, what you consider unacceptable may no longer bear any relationship to what the company says is acceptable, considering they have now realized they may be looking at a potential recall of a few million units!

Many years ago my company asked me to fix a problem with a whole bunch of 3844 ICs purchased from a specific vendor that weren’t working properly. The “same” part from another vendor worked flawlessly. I have described the entire episode in the Appendix of *Switching Power Supplies A to Z* if you are interested. I did learn several lessons from this. First, seemingly similar parts from different vendors can behave very differently. The primary reason for this is not just different levels of design expertise existing in different companies, but different fabrication processes. Every process has its own quirks, strange behaviors, nuances, leakages, noise pickup and sensitivities, feedthrough and crosstalk, and on and on. So the part may carry the same number “3844” but it
Chapter 8

could be an entirely different animal. Second, I truly learned about implied expectations. The end result was that the 3844 part had excessive jitter, which manifested itself as an unacceptable increase in the output voltage ripple. But where in the datasheet did they ever promise: “Jitter < 10%?” It was an inferred expectation, but only our inference. Obviously the vendor disagreed when confronted. Third, I learned that with some creative bench/design skills you can manage to put a poorly performing part (a cheaper one!) to good use. I would try to do that to save some money, assuming the part otherwise performs quite well, and the vendor is not consistently dishonest.

c) The company really doesn’t know about the problem.

1. Maybe because this is a newly released part. But the vendor and the customer are now obviously handcuffed tightly together as they go up a steep learning curve. For all you know, looking back, this may have been the very part that ultimately caused the company’s soaring stock to nosedive on the Nasdaq. Hopefully, you weren’t on board at that time. In particular, you should stop dead in your tracks if the company tells you this is a new process. Because all their previous experience, device models, and so on, were based on their previous process. Now you should expect the unexpected. You might see ESD structures fail mysteriously, outputs go suddenly out of regulation after a few months of operation (e.g., the zener drift/mismatch issue that plagued the third-gen 267x Buck family in its early Revs), and so on. I personally would always prefer a mature part, even if its performance is not considered state-of-the-art or “best in class.” Call me a little distrustful of all the marketing hype if you wish. But I learned that, for example, many of the ultra-new, high-tech (and expensive) creations of my previous analog semiconductor company were happily lapped up by, hold your breath, manufacturers of very high-end cars. The auto manufacturers used them knowingly to create some glittering/exciting electronics and control systems to attract buyers to their blazing new $250k MSRP convertibles. Pretty soon, the unsuspecting wannabe celebrities would drive off with the wind in their hair, without the slightest clue of all the possible things around them that were tantalizingly poised on the verge of complete failure.

2. They just haven’t found out about the problem—maybe because they have a very small, underpaid, and overworked Apps/validation group. In effect they are secretly hoping the customer helps them overcome their internal human resource limitations, and helps them evaluate their creations! So if you have the desire to work for them, at least make sure you don’t have a PO (purchase order) all lined up and ready to go. Take your time. Be in no big hurry to buy their product (you obviously aren’t or you wouldn’t be there to start with).
**Question 6: Is a particular part or component defective?** Here we are considering the possibility that the specific IC mounted on the board is behaving oddly for some reason. Or a specific component on the board. Of course we can just unsolder all the IC/components and send them en masse for vendor analysis. But that can take a very long time, and the reply is likely to be inconclusive. We need to be a little surer than that, before we go through all that trouble. So how do we identify which specific component is at fault? One of the most standard tricks in troubleshooting is to take one “good board” and one “bad board,” and meticulously start swapping components from the good board to the bad one, testing after each step. We have to take extra care these days not to rip the delicate traces off, or create small inadvertent solder bridges that come back to haunt us. We should examine the board carefully after each step to ensure that it still looks good before powering up. We need to keep going doggedly in this manner till the problem goes away on the bad board. Then, the component we have just removed from the board is the culprit. That part we can test ourselves, or confidently send to the vendor for further analysis.

You can ask, does the swapping method always work? In other words, what if we go through all the components and still find that the bad board stays bad? Or the problem did go away, but the component just removed tested “good!” Puzzling! At this point we should zoom in on the PCB itself or some bench setup issue we may have overlooked. Better late than never. But once, in the process of swapping components, I believe I unknowingly cleared a very fine solder bridge, and the problem was gone. But that was deduced only from circumstantial evidence. There was no other explanation.

So is that all? Actually, there is another possibility, one that I have seen at least twice in my experience. And both are related to the magnetics.

In the first case, my colleague in Germany had observed that roughly half his AC-DC power supplies were passing the preproduction CISPR22 conducted emissions test with aplomb, whereas half were failing badly because of an inexplicable spike in the EMI spectrum. Actually that statistic itself was a vital clue, one that we all missed initially. Some other clues—all had been made in the same production batch, and the same tape-and-reels had been used throughout. None of them had any differing “histories” of any sort—none of them had, say, gone through any special testing. The engineer tried swapping some suspect components, and also the controller IC, but the problem was stubbornly stuck to the bad boards. I saw him struggle on for at least two to three weeks until he finally discovered the most unlikely cause. The EMI problem was related to the orientation of one of his common-mode EMI chokes. In other words, if he inserted the EMI choke with its four legs into the PCB in one way, the EMI problem showed up, but if he rotated the choke a full 180 degrees and then inserted it, the problem went away. Most EMI chokes have no silk-screened dots on them to indicate the polarity of the windings, so the chances of the production staff mounting them in one way or the other were 50:50. That is why half the
boards had problems, and half didn’t. We had to request the vendor of the chokes to start
indicating winding polarity on future parts for us.

In the other case, the Portable Power group had just released the hysteretic switcher, the
3485. This IC ultimately sold huge quantities (via the early iPods). I happened to belong to
the “evil empire”—that is, their Power Management group (though everything is relative—
we thought they were the evil ones!). Anyway, since we all shared the same lab (and the
same company in case you’ve forgotten), I happened to get accosted one fine day by their
Apps engineer. He was very concerned why some of the boards worked just fine and some
had horrible pulsing and a different switching frequency altogether. I remembered my
experience in Germany immediately once he used the magic word “half.” I got two hot
irons, removed his inductor and flipped it around and the problem was gone. I had also
noticed the feedback trace was passing just a millimeter away alongside the inductor, and
on the same side. In some mysterious way, it was interacting sufficiently with the magnetic
fields to throw the hysteretic controller into hysterics—but only when the orientation of the
inductor was “incorrect.” In this case, I recommended simply moving the feedback trace a
little further away, and on to the other side of the board through the ground plane if
possible. Which they did finally, and with great success. The feedback trace always seems
to benefit from being surrounded by a sea of tranquility (i.e., the ground plane). We just
have to ensure the cut in the ground plane is done judiciously, so as not to affect the natural
distribution of power-related return currents (see Chapter 5).

**Question 7: Is a particular part or component wrong?** There are a surprising number of
variations of this theme too.

1. Many years ago I remember, I had gone and bought a whole bunch of some
specific CD40xx family ICs from the open marketplace for my private garage
project (no, I didn’t end up making anything close to the venerable “Mac,” or even
the Big Mac). Though these parts had perfectly silk-screened markings indicating a
well-known Japanese brand, they were certainly not the D-type flip-flops I was
expecting. I had a curve tracer built into my 20MHz low-cost Hameg scope, and it
confirmed the parts were something else entirely. I don’t know how that happened,
but you should be aware of this possibility too. Try returning such parts to the
vendor, though.

2. There was another moment of truth in the ballast project I described in Chapter 1,
when we had ordered several new boards with its innovative 2N2222–2N2907
nnp-pnp latch. But the protection latch on all these boards was not working at all.
Design issue? We looked hard at the transistors and thought they were OK. After a
couple of days we took the transistors out, finally suspecting they were faulty
(maybe inadequate “hfe,” etc.), and then made a discovery—we learned that
so-called 2222 transistors do not even have the same pinouts! Each manufacturer
has its own favored pinout, even though they are all sold as equivalents, and that’s how we bought them. Check that out closely, too.

3. With component sizes decreasing steadily, vendors first reached the threshold where most of us can no longer read the markings without a magnifying glass (or a Lasik procedure in my case). Thereafter, they have become so small, I just have to presume there are no markings at all. We just have to learn to be able to keep them apart, otherwise we will never be able to tell. But visualize an average lab bin, with small open boxes for all the components. Or even one of those small plastic shelves in a component rack, with several vertical partitions. An apparently desperate power conversion engineer grabs a few chip resistors or capacitors and accidentally/unknowingly spills/drops some of them into nearby boxes. There is now no way to tell them apart. Along comes the next engineer and picks what he or she thinks is a 10nF capacitor, but which in reality is a 0.1μF capacitor. He or she struggles with the board for weeks (even sending out data on the strange waveforms all the way from Taiwan to New Mexico), until finally suspecting a rat. The engineer then gets resigned to the arduous procedure of swapping components, and only then does he or she arrive at the doorstep of the culprit. If the engineer is very lucky, the LCR meter has not gone for calibration on that day, and he or she can finally get closure. It was the wrong part from the right bin all along! My preference is to keep all SMD components on their original tape-and-reels at all times, not in bins, however convenient bins may seem at first sight.

4. Inductors—be aware that many vendors put cryptic markings such as 102 or 103 on them. For capacitors, there are industry standard markings. For example, 221 is \(22 \times 10^1\) pf, 222 is \(22 \times 10^2\) pf, and so on. All are referred to the base unit, “pF.” But in inductors, “102” may be \(10 \times 10^2\) in \(nH\) or \(μH\). In other words they could be a factor of 1000 apart, with the same marking. If necessary, find an LCR meter and double-check.

5. There are at least a dozen semiconductor manufacturers making the popular 384x series controllers. All of them behave slightly differently. The same applies to any other semiconductor device made by several vendors. Be cautious of so-called equivalents. So if your company’s smart-alecky purchase officer has just cooked up a new deal to procure your 1N5408 diodes at half price (from some hitherto unknown manufacturer on the Mainland, for example), replace it and confirm that it is not causing the problem.

6. In one case, I remember that a standard Non-Synchronous Buck switcher IC was not working right. Everything seemed OK, the PCB, the decoupling, and so on. We tried swapping the switcher IC at first, but the problem stayed with that board. Eventually we traced it to the Schottky catch diode. We then discovered that cheap
Schottky diodes can have almost 10x the leakage current of a good Schottky. In this case, that was what was ultimately confusing the switcher IC to break into chaos every now and then. We replaced it with a quality diode and everything was fine thereafter.

**Question 8: Is there some interaction with the load?** This is a tricky one. It may involve getting to know both your prospective load and switcher IC well enough. Loads present varying profiles to the converter. Their interaction could spell trouble. A load profile is basically the $V$-$I$ curve of the load. For example, if we have a simple resistor as the load, we know its $V$-$I$ curve is a straight line with positive slope (compare its equation $V = IR$ with the generic equation $y = mx + b$). We can emulate this type of load by using the constant resistance (CR mode) setting on our electronic load. It is the most benign type of profile. Very few converters have any trouble starting up into a resistive load within its rated maximum. If they do, they shouldn’t even be on the market!

But consider what happens if, for example, we use our DC-DC converter to power another downstream DC-DC converter. Then the downstream converter becomes our load. What is its $V$-$I$ profile? In any switching converter, if we increase the input voltage, the input current decreases, because $V_{IN} \times I_{IN} \equiv V_{O} \times I_{O} = P_{OUT}$. So this is a constant power load (down to the UVLO level). Its $V$-$I$ profile is, geometrically speaking, a rectangular hyperbola. Alternatively expressed, if $V$ increases, $I$ decreases; therefore we have, in effect, a **negative** input impedance. This profile has been known to instigate severe oscillations. So at the minimum, we need to try and decouple the two DC-DC stages by placing LC filters between them. We can supposedly emulate this situation by using the constant power (CP mode) setting on our electronic load. But that really doesn’t tell us the whole story. Because a real downstream switching converter can also send a good amount of high-frequency noise back into the upstream switching converter, causing it to delve into the exciting world of chaos. That is where the intervening $LC$ filter can help. But ensure the “$L$” has very low parasitic capacitance, or it will have no blocking capability for noise frequencies.

In general, most converters are tested on the bench with the electronic load set to constant current (CC mode). True, that’s not benign, nor as malignant as it gets. But the implied expectation is that converters should at least work in CC mode. They should, in particular, have no startup issues with this type of load profile. But even that may not be the end of the story! Some loads can also vary with time. For example, an incandescent bulb has a resistive profile, but its cold resistance is much lower than its hot resistance. That’s why most bulbs fail towards the end of their natural lifetime just when you throw the wall switch to its ON position. And if the converter is powering a system board characterized by sudden variations in its instantaneous supply current demand, that can cause severe problems to the converter, too. The best known example of this is an AC-DC power supply inside a computer. The 12V rail goes to the hard disk, which can suddenly demand very high currents as it spins up, and then lapse back equally suddenly into a lower current mode.
These cause dynamic issues to the switching power supply, and usually the only solution to that is to have enough bulk capacitance present on the 12V output rail. Luckily, since the main feedback loop is derived from the primary 5V/3.3V rails of the power supply, there is no minimum ESR requirement for the 12V rail output capacitance, and we can freely add several electrolytic capacitors in parallel. However, modern core processors can place very fast transient load demands on the primary regulated rail, too, and for that we need a whole bunch of ceramic capacitors sitting right at the point of load. In that case we must ensure the converter is designed to accept ceramic loads. Otherwise it will break up into oscillations.

Remember in general, most switching converters need to be designed with no foldback of any sort. Look at the datasheet very closely for this. Otherwise they almost certainly will have startup problems, or recovery-from-a-fault issues, even with the CC mode setting on our electronic load. “No foldback” could mean that the overload protection present on the output rail is a simple constant current type. So, for example, a 5V/20A rail must deliver a regulated 5V until it hits 20A. Its overcurrent protection may be set at, say, 25A (to allow margin for drifts, tolerances, inaccuracies, etc.). So as soon as we hit 25A, the output voltage will start to fall, but the converter will continue to provide 25A into CC mode without any problem. Now, if we back off just a little, to say 24.5A, the output should immediately recover to 5V. Very few converters are that precise, however. There is some natural hysteresis involved in all current limiting circuits (and for good reason), but we are still within spec if the output comes back to 5V by the time we reduce the load to, say, 21A. But we truly have serious foldback issues if, for example, we need to reduce the load to much less than the rated maximum. We will likely see startup issues on this converter.

Another odd type of foldback is implemented in some current mode control ICs from Linear Technology. The original purpose was good—to provide good, effective current limiting under short circuits. They had realized that because of blanking time requirements, there was a minimum on-time pulse-width limitation. In other words, if there was an output short circuit, the current would hit the internal current limit of the IC and it would respond as usual, by lowering its duty cycle. But if there were a certain minimum on-time ($t_{\text{onmin}}$), corresponding to the blanking time, the controller would be unable to reduce the duty cycle beyond a certain minimum value (equal to $D_{\text{min}} = t_{\text{onmin}}/f$). In other words, the current limit is in effect not even present now! And this could cause the current to staircase above the set current limit with almost no control. In fact I was testing a similar part and found the current could go as high as 40A momentarily, for a 1.5A switcher! (I have described this current overshoot in more detail in Chapter 12). One answer to this situation is to use frequency foldback. So under fault conditions, if we lower the frequency, the minimum duty cycle becomes much smaller for a given minimum on-time. And that helps significantly in reducing the fault currents, by allowing more time for the freewheeling current to decay to zero before the next ON-pulse. But the way it was implemented in the Linear Technology
Chapter 8

chips was that the frequency of the switcher was made roughly proportional to the voltage on the feedback pin. So under a short circuit, since the voltage on the feedback pin would start collapsing, so would the frequency. It seemed simple and effective enough. But consider what happens if you are starting up naturally into the presumed maximum-rated load of the IC, and the switching frequency is too low to start with. You can then enter foldback, and you may never be able to deliver the rated maximum load of the IC at startup. But at least the relevant Linear Technology datasheets boldly carry front-page warnings that you will be able to achieve full load in CR mode, but not in CC mode.

My suggestion is to open the pdf datasheet of any prospective switcher IC and carry out a text search (Ctrl + F) for the world foldback. If you find it, question the vendor about its full impact before you select the part for your application. Foldback is, in general, a good idea in terms of protecting the converter under abnormal conditions, but it should be used very judiciously so as not to impact normal behavior. For example, the Simple Switcher family has a hidden second-level current limit protection at which frequency foldback (or skipped pulses) occurs. But that trip level can only be encountered under very severe conditions—namely, a sudden overload with a completely incorrectly sized inductor that hard-saturates in the process. At other times it is not encountered and doesn’t therefore interfere. It is considered transparent to all but the most novice engineers. And that is what I consider the right type of foldback.

An exception is the foldback behavior discovered in the third-gen 267x family whenever the duty cycle exceeds 50%. That has really nothing to do with the protection of the IC, though it can be successfully argued that this belatedly discovered “feature” does eventually help in that respect—by almost turning off the IC altogether (yes, that would work!). Read the following clarification apparently issued by them on their public discussion forum. Keep a few bags of salt readily available.

March 1, 2006: The condition described is the result of what amounts to a foldback current limit design that’s intended to prevent damage to either the regulator or the load under unusual fault conditions. Anyone familiar with foldback current limit will realize that there are always conditions that can be realized that force the foldback to get “stuck” in a stable, low output voltage operating mode. The solution in general is to reduce the load until the output is allowed to recover. The datasheet clearly advises the user what to look for and how to deal with potential problems that may arise from this. Any implication that the information is deliberately obscured is clearly misleading. . . .


Page 12 is clearly “non-obscure” from now on. Also, what this doesn’t explain is why the protection activates only above 50% duty cycle, and why all previous and subsequent switchers from the same company (and all others) did not and do not have this type of
intrusive foldback. They also all have a second-level foldback current limit anyway, so why
does this particular device family need two foldback circuits? It also does not tell you that
it is not about just “reducing the load and allowing the output to recover” but that this IC
fails to even start up at half the rated current, if you have innocently set, say, 12V output
from an 18V input. But surprisingly, if you have set 12V input and 5V output, for some
mysterious reason the company now thinks you don’t need any further foldback protection,
and hey presto, your startup is perfect. I couldn’t put up an engineering rejoinder on their
discussion forum, because by then they had thoughtfully deleted my login privileges! In
other words, they decided I was the problem (with their chip) all along. And that I finally
needed to remain equally obscure from now on.

**Question 9:** Is there some interaction with nearby circuitry? Yes, you could be picking
up fields from nearby circuits, but that shouldn’t affect a typical switcher, simply because
it produces enough noise and fields of its own. However, it is a good idea to do the
reverse-peel here. If I find the converter is on a larger system board, I immediately and
carefully first cut off all the traces leading from its output and divert them to my predictable
electronic load. I also cut the input traces and divert them to my bench power supply. If the
problem is gone, it is an interaction problem.

One of the most obvious mistakes customers make is to try and parallel several DC-DC
converters off the same input. They make the situation worse by allocating one full layer
of their board to the supply Vcc. I always like to see a nice ground plane, but in such
cases I would consider creating two big ground islands, one under each converter, and
then connect them together at a single point so as to avoid interactions. But the worst thing
you can do is to have the two converters share a complete ground plane and a full input
supply plane too. Basically, the two converters are no longer independent because there
are no intervening trace impedances between them. Take a look at the upper section of
Figure 8-2 and tell me why converter A won’t draw its input current from the input
capacitor supposedly assigned to converter B. The schematic is, incidentally, again lying,
though in the opposite sense now. It may be making you think each converter is separate
from the other, whereas in reality they are not. They will therefore interact, and it is
impossible to predict how this will affect their performance. My preferred layout is to create
long thin traces going to their respective Vcc (i.e., $V_{IN}$) pins as shown in the lower section
of Figure 8-2. That way the converters do not interact much, though a more formal solution
is to insert small LC input filters. We have to be very careful, however, of not introducing
any significant “L” to the input side of any DC-DC converter, because this affects the
ability of its input voltage source to refresh its decoupling capacitors quickly enough, and
so the wobble on its input pin can increase sufficiently and trigger oscillations or chaotic
behavior on its own. Also, even little beads on the input of a Buck or a Buck-Boost have
been known to generate nasty inductive spikes of their own, which can kill the IC
eventually.
Chapter 8

Question 10: Am I trying to achieve something that is really possible? The number of young engineers who try to parallel converters for higher power and then fall flat on their faces is legendary. Well, you can’t just take two switchers and tie their outputs together for higher power. The problem is that they have very high gain error amplifier stages and their reference voltages are not exactly the same. For example, if one of them has a reference voltage of 2.5V and the other is at 2.51V, and suppose they have perfect 10kΩ resistors on their respective voltage dividers, we expect 5.00V output on one converter and 5.02V on the other. If you think they will settle down nicely at either an average of 5.01V, you are wrong. Because if that were so, one converter’s feedback pin would still be 5mV below its reference level, whereas the other would be 5mV above its reference. And that will cause one converter to go to almost max duty cycle in an effort to bring the output voltage up, whereas the other will go to near-minimum duty cycle to bring it down. But for sure, there is no synchronized teamwork in the works here! They will end up fighting with each other and if you are lucky, the output will stabilize at some intermediate/average level. But if you measure the currents through each of the two inductors, you will find the net load current is far from being shared equally. So two 2A switchers won’t give you anything close
home-grown strategies in troubleshooting

Figure 8-3 Paralleling Converters for Higher Power

to 4A, because the current limit of one or the other will activate (and then they will start motorboating). You may be able to get say 3A, but it could end up being distributed as 2A and 1A, certainly not 1.5A each. It is often also said rather blithely that “current-mode switcher ICs can be easily paralleled.” But try it and you will discover that too is not possible, at least in such a simple manner. Don’t ever attempt the impossible. Ignore the marketers. To succeed here, you will either need fairly large ballasting resistors on each of the outputs or a dedicated load-share IC (as from Unitrode/TI). If you try the ballasting technique shown in Figure 8-3, you need to carefully calculate what value of resistance you need. Note that the feedback to each converter needs to be taken from the left side of these resistors. Also, if you use too large a resistance, the current sharing will tend to get better and better, but obviously the output will droop dramatically. At best you can search for a good compromise.

Another milder example of this is a standard Non-Synchronous Buck switcher IC. Every single “typical applications” diagram on the datasheet shows a Schottky diode, without perhaps explicitly stating as much. This is an example of an “implied expectation” on the part of the vendor—that you, the customer, won’t miss the truly obvious. Yet there are many who think they have achieved some slender advantage in substituting an ultra-fast diode in its place. First read the Abs Max section of the EC tables carefully. Most vendors specify that the SW node should never be taken more than 0.4V below IC ground. That is because...
Chapter 8

they expect substrate currents flowing back into the chip, affecting its performance and possibly damaging it. So if you use an ultra-fast diode, you are almost certainly forcing the SW node roughly 1 to 1.5V below ground when the switch turns OFF (equal to the forward voltage across the diode). You are on your own now. Incidentally, while doing a survey on this topic, I learned that Maxim Integrated Products typically specifies a maximum of only 0.3V below ground (hardly achievable with even the best Schottky diode in the universe), whereas Linear Technology doesn’t seem to even want to specify this Abs Max parameter in most of their datasheets.

Incidentally, there are customers who come and ask, “I know you have stated in your Abs Max table that I shouldn’t apply more than 24V to the device. But what if I apply 28V for just 1ms?” The principled answer to that is, you can’t apply even 24.01V, for even $10^{-12}$ seconds! The company officially doesn’t stand by it. Yes, internally they do test at higher stress levels than published, and have also got various guard-bands present (for their protection and reputation). But remember you don’t know what these are. Also, keep in mind that voltage overstress leads to almost instantaneous death, whereas current ratings are related more to internal heat buildup, so you can always exceed them somewhat for a short time.

**Question 11:** Am I trying to achieve something that is generally known to be risky? Yes, if you are trying to use an SCR crowbar on the output for overvoltage protection, for example. There is enough industry experience by now that these can trigger spuriously and should be avoided. Rather than troubleshoot this, replace it quickly. You may get a few prototypes working satisfactorily on the bench, but do a mass production on this, and your Boss will certainly overvoltage and lock you out.

Similarly, if you are trying to use current-mode control for your *Half-Bridge*, you should know that that control method is well-suited for a Push-Pull topology, for example, but it actually aggravates the chances of flux staircasing and core saturation in a Half-Bridge. Oh yes, you should also know that voltage mode control will not protect the Push-Pull. There you need current mode control. By the way, who makes a Push-Pull with voltage mode control nowadays? Try the 5033!

I also remember years ago, my colleague was struggling with the Push-Pull topology for his high-power inverter project (yes we had three engineers working simultaneously on inverters at that time, and we all learned *what not to do!*). We were all using the popular voltage-mode 3524 controller IC at that time. My colleague was achieving great success (everything is relative). He could actually run it at 500W for about 10 minutes, and then it would explode with a huge bang, opening up all the high-current circuit breakers he had thoughtfully put in series with it. One evening he was getting extremely puzzled and called me to show me something. He had just noticed that in the few minutes preceding the blow up, the waveform of the Push-Pull would develop a mysterious edge as shown in Figure 8-4. But only for one transistor! I never fully figured this out for years. Now I realize
that the core had staircased to one side of the BH curve (core imbalance), and was saturating at the point where the edge was. So, essentially, the core had lost its ability to hold any voltage across it at that moment. We didn’t have a current probe those days and probably hadn’t put in a sense resistor either. If we had monitored the currents, we would have seen the cause. We had tried larger cores too, but I am now convinced that almost no core can ultimately prevent this slow creeping death (staircasing) in a Push-Pull with voltage-mode control. You could depend on good current limiting to save the switches (but not necessarily to save the performance of the converter), because the truth is the core is running completely imbalanced, and so are the two “halves” of the Push-Pull converter (the two switches, the two winding halves, the output diodes, etc.). The only reasonable way out is to move to peak current mode control for this topology. A contributory factor to our early disasters perhaps was the fact that current limiting on these early devices was not really effective. Today it is common to design any IC such that if the current limit is ever reached, the switch is turned OFF firmly for the entire duration of that switching cycle (latched). But these ICs would turn the switch OFF when the current limit was reached, but as soon as the current dipped below the current limit threshold, the switch would turn ON again. So it would sort off buzz away around the current limit region, eventually causing enough noise to break through completely and damage the switch. I believe they fixed it later. I also checked that, as of today, Texas Instruments still sells the 3524 (accompanied by its vintage 1977 datasheet, last revised in 2003), and also includes a typical schematic for Push-Pull applications. Think about it—Unitrode (now part of TI) were the original pioneers of current mode control and heavily publicized all the above-mentioned weaknesses of 3524-based, TL494-based (voltage-mode control) Push-Pull topologies.
As mentioned briefly, a recent contender to the hall of fame is the 5033, officially labeled a “100V Push-Pull Voltage-Mode PWM controller,” and released in 2003. Luckily, this analog vendor’s datasheet only shows a Half-Bridge at work, and that we are aware is a good match for voltage-mode control. So I personally tend to think that marketing (alone) was responsible for this misleading push (or pull).

Another inverter my colleague was making years ago looked a lot like Figure 8-5. He had been having some success, and was feeling optimistic, until I asked him where the output choke was! You don’t make a Forward converter without an output choke! He had apparently been lured astray by similar looking schematics of traditional AC inverters made from iron laminations. But this was a high-frequency switcher, man!

Any Buck-derived topology (e.g., the Forward converter, the Half-Bridge, the Push-Pull, the Full-Bridge, etc.) needs an output choke. Otherwise it is akin to running a Buck without its inductor—you can thereby create a dead short across the input supply rails.

Another common mistake we used to make in those days, and one that a very large number of engineers still make, is that if we ever thought the transformer might be getting too close to saturation, we would quickly wind another bobbin with additional turns on it. We thought we should increase the inductance and thereby reduce the peak currents, and that would help. Actually, this intuition is probably again a leftover of the days of winding big AC line transformers with CRGO laminations. Those were almost impossible to saturate, which is why in their design manuals, vendors would often give you an equation to calculate $N$, which was the minimum number of turns of the Primary. In switchers, the picture changes entirely, because if your transformer (or inductor) is saturating, you actually need to reduce the number of turns (and reduce the inductance). You are puzzled, because you are mentally thinking that the peak currents would then be even higher, and so the chances of saturating your transformer would be greater. Wrong! The reason for saturation is not $I_{PK}$ alone, but $1/2 \times L \times I_{PD}^2$. That determines the energy-handling capability of any core. So suppose your
An inductor is designed for a 1A with ±20% current ripple, and you double the number of turns. Yes, your peak current will decrease. By how much? Remember that inductance is inversely proportional to the ΔI, which in this case was 0.4A to start with. So by doubling the number of turns, you have increased the inductance four times (L being proportional to N²), and the ΔI therefore goes from 0.4A to 0.1A. So now your peak current is 1A + (0.1/2) = 1.05A. Which is about 1A. But now calculate the product 1/2 × L × Iₚk². This has gone up almost four times because of the increase in inductance (with very little corresponding reduction in the peak current). That simply means you need a transformer/inductor about four times bigger now. So how do you ever expect to solve the problem of core saturation by increasing the number of turns? You must always keep in mind that in switchers, smaller inductance leads to smaller inductors. Converters that use DCM or BCM (boundary conduction mode) will always feature much smaller magnetic components than those operated in CCM. Their inductance is much smaller! The problem with them is that other components may need to be unnecessarily larger, such as the switch and input/output capacitors. See Chapter 12, too!

Another IC designer’s dream that can sour quickly is a Flyback with 100% duty cycle. We all know that a Flyback delivers power to the output only when the switch turns OFF. But if you have 100% duty cycle to start with, there will be no energy going to the output, so the feedback pin would remain at zero, and the controller would never know it now needs to start pulling back on the duty cycle. The switch could stay on forever in an effort to get the output to rise. You can easily get into a self-destructive Catch-22 situation here, if the current limit and/or soft-start do not step in quickly enough to save the show. Maybe that is why I could not find a single Flyback IC out there with 100% maximum duty cycle. You will find plenty of Buck ICs with 100% max duty cycle, but not Buck-Boost (i.e., Boost) ICs, though an exception that proves the rule is the 3478/3488. Judging by the datasheets’ front pages, these devices are somehow intended to work beautifully for all Flyback, Boost, and Sepic applications. I doubt that. But they do have “proof” in the form of an online seminar called “Designing DC-DC Power Supplies using High Performance Switching Controllers.” In that 2001 product release collateral, we see a young, motivated engineer enthusiastically delivering a message of excellence vis-à-vis these specific products, with the legend of Analog (the self-proclaimed “Czar of the Bandgap”) sitting right beside him in full regalia. I would really like to personally believe that the king wasn’t there vouching for these products. Because he does end up giving an aura of credence to these ICs, very undeserved in my opinion.

I would recommend you try nothing overtly risky in power, especially not by ignoring well-known industry experiences. There could be a high price to pay, and troubleshooting the boards could be the very least of your burgeoning problems. “Power” hates to be taken for granted, as we all discover sooner or later. Also carefully go through discussion forums to see what problems others may be facing with the proposed part. Don’t fall for the
possibly glib/evasive company responses, though. Just count the queries and that should tell you. Also don’t forget to read Chapter 12.

**Question 12:** Am I the one somehow managing to inflict damage on the IC? If you ever suspect the IC is damaged, just pack it in an ESD bag and send it off for failure analysis. But then suppose the next part looks good to start with and eventually develops similar symptoms. You should then realize you are somehow managing to damage the part, without realizing it. Here are some interesting (and common) examples of this.

a) You have a regular Synchronous low-voltage Buck switcher working on your bench. You unplug the load, power down, then decide to immediately power up again for some reason. The IC gets destroyed almost immediately. You send it for failure analysis and a few days later they tell you the part was damaged by a high voltage on the input pin. Why?

When you decreased the load to zero, the IC probably entered energy saving mode (PFM), in which the lower transistor turns OFF permanently. So the output capacitor stayed almost fully charged up when you powered down and powered up again. But when your converter tried to start up again, it did so with its usual “soft-start.” Therefore the duty cycle was very low to start with, and the lower Fet stayed ON for most of the time each cycle (normal Synchronous/complementary drive). But because the output capacitor was almost fully charged, it drove a huge current in reverse direction through the inductor (see path 1 in Figure 8-6). At some point the lower Fet turned OFF—and all this reverse inductor current cycled into the input capacitor (see path 2 in Figure 8-6). If the high-side Fet were ON, the current went through its channel, but if the Fet were OFF, the current went through its body diode. Either way, all the output energy starts getting dumped into the input capacitor, raising the voltage on the input pin. Basically, what has happened is that the Buck switcher has momentarily become a Boost switcher in the opposite direction! To avoid this situation, you may need to pick an IC that is designed specifically to handle such pre-biased load conditions and/or to increase the input bulk capacitor significantly. One of the ways to do this is shown in the lowermost part of Figure 8-6—basically, we need to implement complementary soft-start for the lower Fet, too.

b) You have an older generation part with an external voltage divider. Since you want to use it with a ceramic capacitor on the output, you have thoughtfully put in a feedforward capacitor across the upper resistor of the divider. But then you short the output a few times and the part gets damaged. Why?

The feedforward capacitor $C_{FF}$ shown in Figure 8-7 has a voltage across it in steady state. When you short the output, the feedforward capacitor cannot
discharge immediately, so its lower end gets pushed below ground (the capacitor holds the voltage across it for some time). This eventually causes an unexpected current passing through the ESD diode present at the feedback pin of the IC, in effect a sneak discharge path for the feedforward capacitor. Feedback pins are almost invariably not allowed to go more than 0.3 or 0.4V below IC ground to prevent such damage. Therefore, a few years ago, as soon
as I discovered these failures and understood their cause, we started specifically mentioning in the datasheets that you should not use feedforward capacitors larger than a certain value and/or you will need a small Schottky diode from feedback pin to ground. My battle-honed Boss, who had hitherto thought he had seen it all, was quite surprised that we ourselves had been in the position of recommending typical circuits to customers with the feedforward capacitor present, little realizing it constituted a violation of our own published Abs Max ratings on the Feedback Pin (you do expect any switcher's output to be shorted and released in its normal course, without sustaining damage—an implied expectation though).

c) Your bench power supply is set fairly close to the maximum input voltage rating of your IC. You have just changed the input ceramic capacitor of the converter from 22\(\mu\)F to 10\(\mu\)F, and the supply line still looks very clean (under steady conditions). But the part gets damaged almost every time you connect the red lead coming from your bench power supply directly to your board. Why?

The long inductances of the leads, combined with the low-ESR input capacitor and the negative input impedance of a switching converter, can produce a lethal undamped oscillatory circuit that can produce huge input swings, often exceeding the ratings of the IC. There are two ways out—either try to use only high-ESR capacitors at the input (or at least parallel a high-ESR electrolytic with the ceramic input capacitor), or increase the amount of bulk capacitance.
Therefore, a 22μF input ceramic will give a smaller input overshoot than a 10μF input ceramic. A 47μF will give even less, and so on.

Note you will not see this failure mode if you first plug in your converter to the bench power supply and then turn on the supply. Because, in that case, the output of the supply comes up very benignly as it first charges up the hefty bulk capacitors sitting inside it across its output terminals. The only way to instigate this wild input overshoot is to jam the banana plug into an already powered-up bench power supply. This produces the highest dV/dt possible at the inputs of the converter. Further, this “hard dV/dt test” is not only a tool to see the input overshoot, but it is a very good diagnostic tool in general for exposing any latent weakness in the IC. I do this almost invariably during testing. There are always surprises in store! Often, this alone can call for a significant increase in the input bulk capacitor.

d) You have a Non-Synchronous Buck switcher IC powering a load. You reduce the load to zero and then attempt to discharge the input capacitors of the converter. The IC gets damaged. Why?

If the switch is a Fet, a momentary surge current will flow from the output capacitors through its body diode, discharging the output capacitor. The device is not usually tested by semiconductor manufacturers in this mode, but neither has there been much evidence of reported field failures in this manner, unless of course the output bulk capacitance is very large and/or it is charged to a high voltage (energy in a capacitor is 1/2 × C × V^2).

If the switch is a BJT, this is a clear no-no because a bipolar attempts to block reverse voltage, but is really not designed to operate with any reverse collector-emitter voltage.

e) You have set up a Buck switcher IC with a BJT switch to deliver constant current. You intend to use it to charge a battery connected directly cross the output terminals of the converter. But you end up constantly destroying your switcher IC. Why?

For the same reasons above. Think of a battery as an infinitely large capacitor. The only way to handle battery charging with a BJT switch is to put in a blocking diode in series with the battery.

f) You have a Boost IC set to deliver 12V @ 1A from 5V. You run a spreadsheet, which suggests you use a 4.7μH inductor. So you pick a 4.7μH/1.5A inductor from the bin. But the IC fails. Why?

The average inductor current in a Buck delivering a load current of I_0 is I_0. But in a Boost or Buck-Boost, the average inductor current is equal to I_0/(1 − D). Further, the peak current in all cases is typically 20 to 30% higher.
than the average inductor current (by the normal selection criterion for
inductance). We have to calculate the worst-case peak value and use it as the
minimum rating of the inductor.

g) In an effort to improve the efficiency of your Buck design, you have picked a
Synchronous Buck controller IC simply because it has very high-current drivers.
But both the Fets blow up every now and then. Why?

Be very careful of overly aggressive drivers. Such ICs can damage themselves
in several ways. In general the fast transitions can induce spikes all over the
board, causing weird problems everywhere, including general controller
malfunction. But in modern Synchronous Buck converters, one of the strong
reasons for slowing down the Fets and picking Fets more carefully is the
phenomenon of “CdV/dt turn-on.” If you look closely at the gate of the lower
Fet (when using a controller IC), you will see a small blip on it the moment
the high-side Fet turns ON. In effect both high-side and low-side Fets are
briefly on simultaneously. What is happening here is that at the moment the
high-side Fet turns ON, it pulls up the SW node very dramatically. This
changing voltage induces a small current to flow through the Drain-to-Gate
capacitance of the Fet (as per \( I = C \frac{dV}{dt} \)), and this can turn the lower Fet ON.
Eventually, this can provoke cross-conduction, which will either be totally
destructive or, at the bare minimum, will lead to a substantial loss in efficiency.
That efficiency hit becomes especially noticeable when the converter is in
normal Synchronous mode (forced PWM mode, not cycle skipping mode) at
very light loads. My usual test is to benchmark the zero-load supply current for
a good board, and then I can easily detect excessive cross-conduction if I see
more than a few mA in excess of that level. If this is a controller IC, I also like
to compare prospective low-side Fets during the initial selection process, in
terms of the ratio \( C_{GD}/C_{GS} \) (equivalently \( C_{RSS}/C_{ISS} \)). A lower ratio makes the Fet
less susceptible, and similarly, a slightly higher threshold voltage \( V_T \) improves
the Fet’s immunity against this spurious turn-on effect. In one IC design
situation a few years ago, we actually ended up “rev’ing the silicon” one last
time just to make the drivers far “less aggressive.” The pull-up was reduced by
at least half, to slow down the turn-on. And that also saved significant silicon
area and led to a better product in general.

So, if you can access the gates of the Fets, try putting in small resistors in
series with them. If it is a switcher IC (with no access to the gates), try
inserting a small resistor in series with the decoupling capacitor of the driver
supply (usually a 0.1μF capacitor attached to the Vdd pin and/or the bootstrap
pin). Better still, pick an IC with less aggressive drive to start with. Because
otherwise it will commit suicide sooner or later.