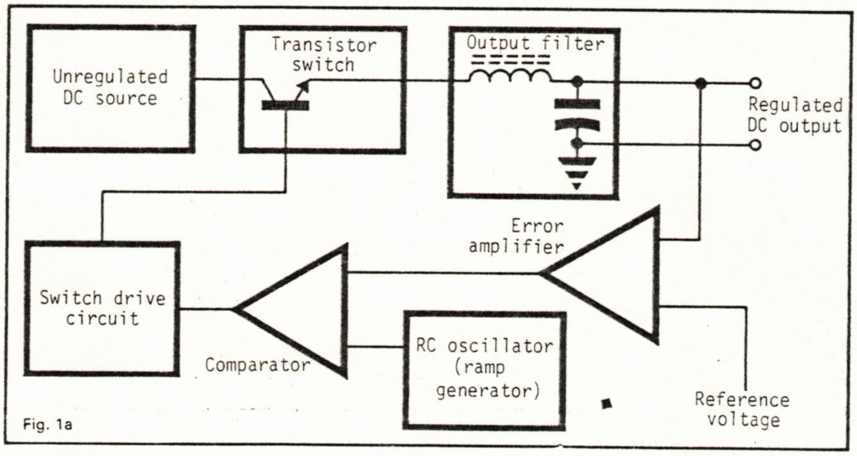
Using current control to improve SMPS regulation

Tom Simon and *Chuck Forge* of Boschert, Sunnyvale, California explain how eliminating the inductor's effect on the control loop simplifies design and improves transient response

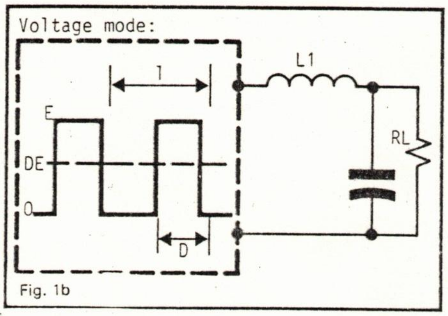
As switch-mode regulation technology matured, the power supply industry adapted voltage-mode control as its defacto standard. Long overlooked by all but flyback circuit designers, current-mode control simplifies design of the regulation loop by effectively removing the control loop lag effects of the inductor from the output filter. As a result, the designer has to contend with a simple one-pole RC circuit instead of a two-pole LC filter.

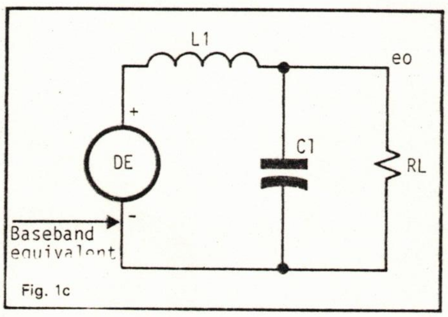


An added benefit of current-mode regulation is its ability to tolerate a wide range of input voltages, output voltages, and output currents. Not only does this increase power supply reliability in the field, it also reduces rework during the assembly process by decreasing overall sensitivity to accumulated component tolerances. With the availability of suitable control chips, current-mode control could easily displace voltage-mode control as the standard approach to switcher regulation.

All switching power supplies, whether controlled by voltage- or current mode regulation, consist of four basic function blocks: a source of unregulated dc, a high-speed electronic switch, an output filter usually consisting of an LC network, and a control loop. Regulation is achieved by opening and closing the switch in such a manner that the average input to the filter equals the desired output.

The key to switching regulation is, of course, the control loop. In a conventional pulse-width modulated switcher with voltage-mode regulation, the control loop (figure 1) consists of an error amplifier, comparator, and drive circuit. The error amplifier provides an output proportional to the difference between the power supply's output voltage and a dc reference voltage equal to the desired output potential. This error signal is applied to a comparator that overlays it on a high frequency voltage ramp produced by a fixed RC oscillator network. As the error voltage rides up and down on the ramp, the comparator performs what is in effect a voltage-to-time conversion that produces a pulse, the width of which is proportional to the error voltage amplitude (figure 2).





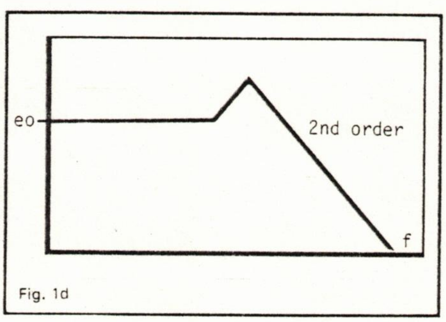


Figure 1: Simplified block diagram of typical voltage-mode regulated switching power supply consisting of an error amplifier, comparator, and drive circuit.

Because the switch is operating far above the filter's LC resonant frequency, the output filter does not respond to each individual cycle of its operation. Instead, the filter behaves as if it were connected to a constant zero-impedance voltage source the value of which is equal to the dc voltage applied to the input of the switch multiplied by its duty factor. Thus a 20V source switched at a 25% duty factor will appear to the output filter as a constant 5V input (figure 1).

The operation of a voltage-mode switch regulator is analogous to a typical SCR lamp dimmer in that the switch's duty factor is not dependent on the load current. Rather, it is controlled only by the error voltage. As a consequence, if the output voltage is drawn down by an excessively high load, the control loop will increase the duty factor to compensate for the voltage drop without regard to the current flow. Because of this, virtually all switchers built with voltage-mode regulation incorporate additional overcurrent and short circuit protection circuitry, which adds to their cost and size.

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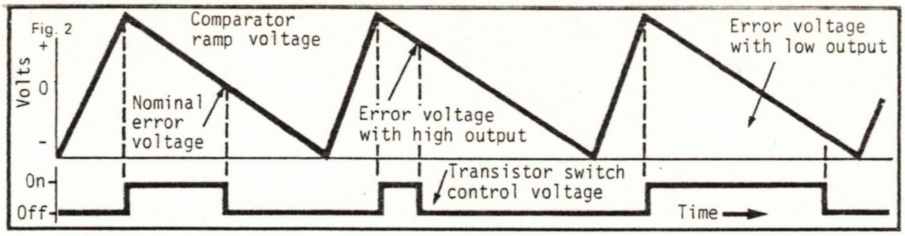
Another design problem caused by the use of voltage-mode regulation is correctly compensating the control loop for the phase shift introduced between the switch's output voltage and the error voltage by the output LC filter. Because the output filter is a two-pole device with a 180° phase shift, the control loop is inherently unstable. At best, this instability results in a tendency toward ringing in response to load steps. For this reason, most switching power supplies with voltage-mode regulation are designed with some leading-angle phase compensation built into the control loop.

The effectiveness of the phase compensation, however, depends on how closely the added phase shift compensates for the phase shift produced by the output LC filter. On paper, it is possible to obtain near perfect compensation. In the real world, however, compensation is dependent on how closely the component values approximate the design values.

Control loop instability and sensitivity to component tolerances are not the only problem associated with voltage-mode regulation, however. Since the switch's duty factor is determined exclusively by the difference between the output and reference voltages, voltage-mode regulation provides no inherent overcurrent or short circuit protection.

If the supply's terminals are short circuited and output voltage falls to zero, the control loop will hold the switch closed continuously in an attempt to restore the desired output voltage. Because of this, additional circuitry must be added to a switching power supply if overcurrent or short circuit protection is desired.

A current-mode regulator circuit is very similar to its voltage mode counterpart. The only significant difference between the two is the method used to generate the ramp voltage applied to the control-loop comparator. In voltage-mode regulation, the ramp voltage's slope and amplitude are fixed by the characteristics of a fixed RC oscillator. Current-mode regulation instead takes advantage of the output filter's inductance, which limits the rate at which current builds up each time the switch is closed. By inserting the appropriate low-value resistor in series with the inductor or across the secondary of a current



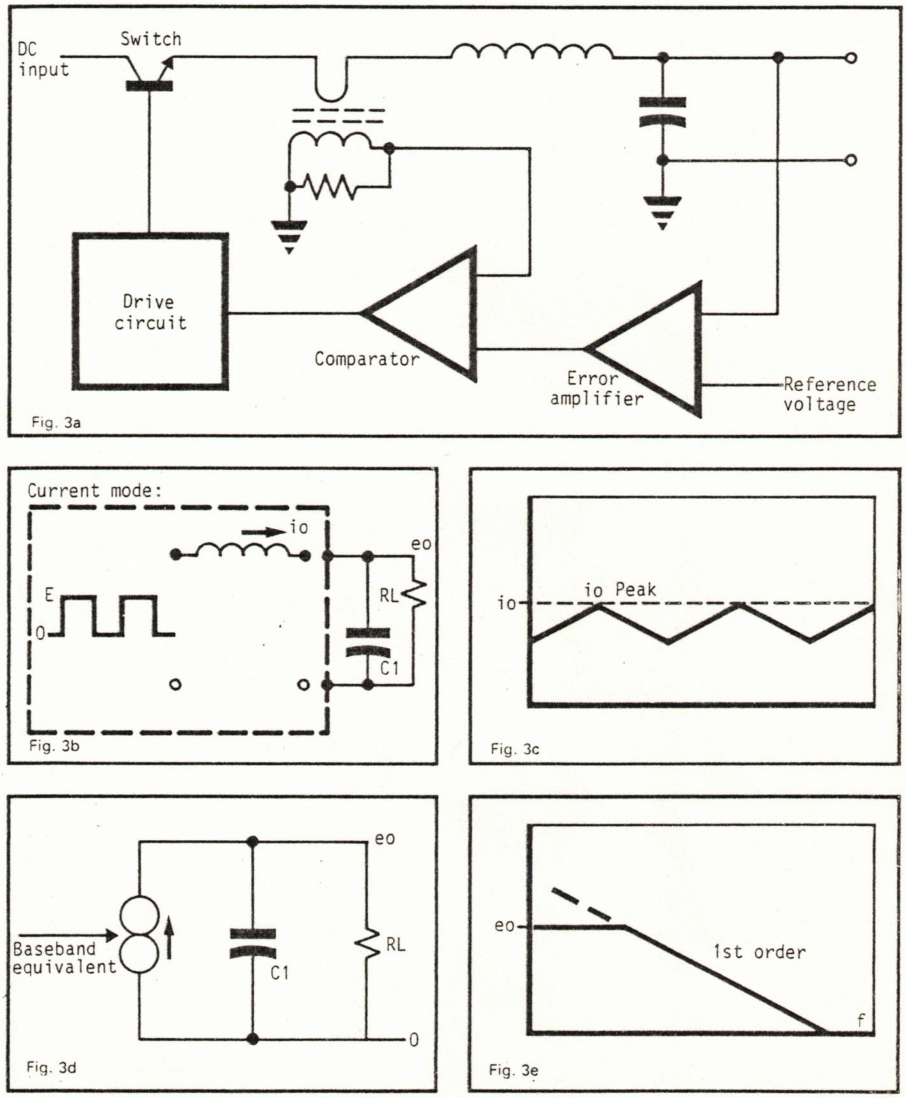


Figure 2: Switching power supplies are regulated by varying the switch duty factor. As the output voltage rises above nominal, the switch duty factor is decreased, reducing the average voltage impressed on the output filter. As the output drops below the nominal level, the switch duty factor increased, raising the average voltage impressed on the output filter.

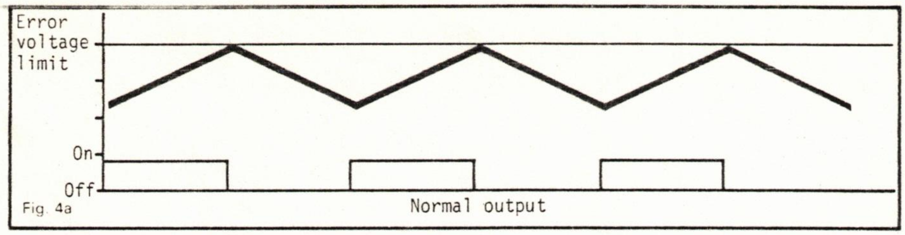
Figure 3: Fixed RC ramp generator of voltage mode regulator is replaced in the current mode regulator by a ramp that is proportional to the current flowing through the inductor. Since ramp envelope is in-phase with the inductor current, the effects of the inductor's phase shift is negated, eliminating loop instability.

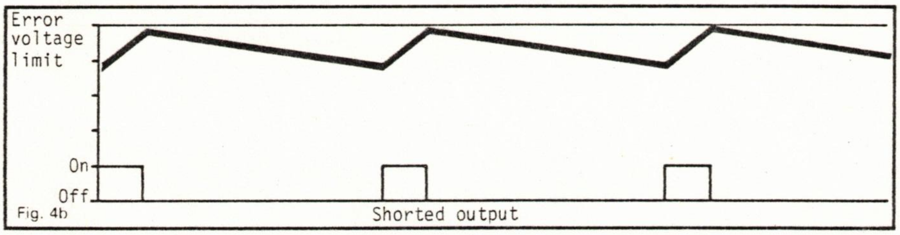
transformer (figure 3), a voltage ramp proportional to the current flowing through the inductor is obtained.

In the most commonly used current-mode scheme, the switch is operated at a constant frequency controlled by a system clock. Each clock pulse toggles a latch that closes and holds the switch. When the switch closes, the current flowing through the filter builds up at a rate determined by E/L.

The voltage produced by the current ramp flowing through the sensing resistor is applied to the comparator along with the output of the error amplifier.

Although the output voltage and, as a consequence, the error voltage





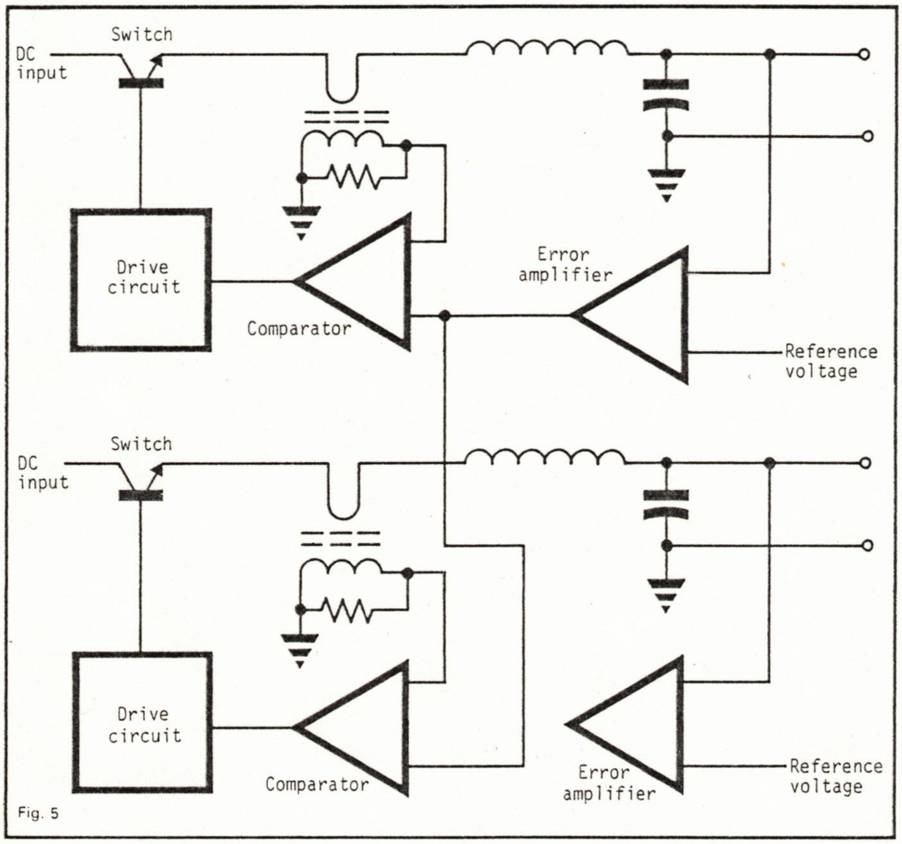


Figure 4: As error voltage shoots up with shorted output, so also does the output current. In a current mode regulated switcher, the rising current produces a steeper comparator slope which holds the switch duty factor within safe bounds — with resulting average current held to maximum design level.

Figure 5: Paralleling two current mode regulators

remains virtually constant during each switch cycle, over a number of cycles it shifts in response to changes in the level of charge on the output filter capacitor. When the load demands increased current, the difference between the higher level demanded and the current supplied during each of the immediately following cycles is supplied by the capacitor. But, as the capacitor discharges, its terminal voltage drops, increasing the error voltage and, as a result, the switch's duty factor and the current delivered to the output filter.

When the load current decreases, the excess current supplied by the switch raises the charge on the capacitor, increasing its terminal voltage and, as a result, decreasing the error voltage. As the error voltage drops, so too does the switch's duty factor and the current flowing into the capacitor.

The greatest advantage of current-mode over voltage-mode regulation is that by generating the comparator's ramp with the current flowing through the inductor, the peak ramp current follows the error voltage without phase shift. As far as the control loop is concerned, the output filter's inductance simply does not exist and, as a result, the phase shift introduced by the filter cannot exceed 90°. This means that current-mode regulation is inherently stable and that less phase compensation is needed in the control loop. From the user's point of view, this means much better transient response and freedom from chronic instability due to component ageing.

Another advantage is that current-mode regulation lends itself to a very simple form of overcurrent and short circuit protection. All that has to be done is to limit the error voltage's amplitude to a level that corresponds to the maximum safe output current level. Because the switch is turned off when the current-generated ramp voltage crosses the error voltage, limiting the error voltage causes the duty factor to decrease as the rate of current build-up increases (figure 4).

Still another advantage of current-mode regulated switching power supplies is that they can be paralleled by simply connecting the outputs together. While the paralleled supplies do not share the load equally, they are stable and exhibit the same characteristics, such as transient response, as they do when operating separately. If load sharing is required, it can be achieved by disconnecting the error amplifier in one supply from its comparator, and driving the comparator with the error amplifier in the other supply (figure 5).

Current-mode regulation is not without its own problems, however. In the constant-frequency regulator, for example, it is possible for the control loop to demand a duty factor greater than 50%. If this happens, the duty factor of the following cycle can fall below 50%. Once this divergence begins, it worsens until the switch misses a cycle and starts again.

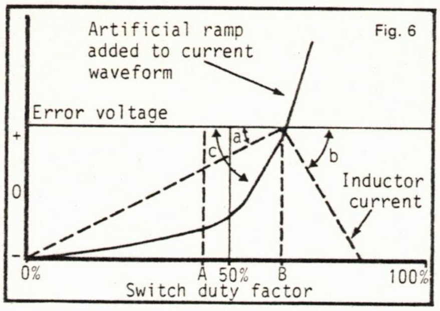
The easiest way to avoid every-other-cycle oscillation is increase the slope of the comparator ramp, either with an exponential waveform or a break in the slope (figure 6). Altering the current-generated ramp, however, produces a hybrid regulator with characteristics that are a cross between true current-mode and voltage-mode regulation. Another approach uses a constant off-time clock to fix the switch's off-time with the current-mode regulator loop determining the on-time. The advantage of this approach is that protection against duty factor problems is afforded without trading off any of the current-mode regulator's advantages.

Still another approach to preventing every-other-cycle operation is the use of what Boschert calls a double-ended current-mode regulator. With the double-ended regulator, or hysteresis regulator as some others call it, the clock is completely eliminated. Instead, the switch is closed when the current falls below one threshold, and opened when it rises above another. Not only does this approach prevent duty-factor related instability, but also provides sampling twice each cycle.

There is another problem with which the designer of current-mode regulators must deal: minimising the delay between the time the error and ramp voltages cross in the control loop comparator and the time the switching transistor actually cuts off. If the transistor cannot be cut-off quickly enough when the load impedance drops because of a short circuit or load transient, the instantaneous current flowing through the transistor may ramp up high enough to damage it, or to saturate the filter's inductor.

Although the maximum acceptable delay varies with the design and component characteristics, it shouldn't run more than a few microseconds. The actual delay experienced is due in part to the delays introduced by the comparator and transistor drive circuits. However, the largest part of the delay is usually due to the switching transistor's turn-off time. This is particularly true of devices that have been optimised for a slow turn off. Because of this, it is important that the design engineer carefully evaluate transistor turn-off time before specifying acceptable device types. If this is not done, the transistor and inductor will have to be large enough to withstand peak currents far greater than those associated with full rated output power from the supply.

The designer of a current-mode regulator must be concerned not only



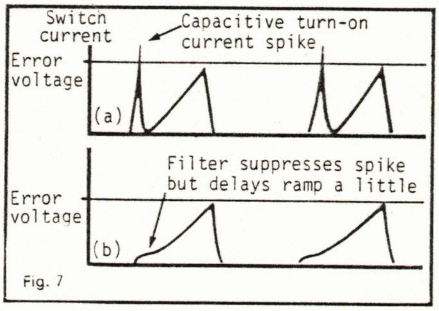


Figure 6: Every other cycle instability in current mode regulators can be prevented by holding switch duty factor to less than 50% or by artificially increasing the slope of the comparator ramp to where its angle to the error voltage is greater than that of the decaying current in the inductor. ($a < b$ *but* $c > b$).

Figure 7: When error voltage gets below spike top, switch will shut off immediately.

with the switching transistor not cutting off quickly enough, but also with it cutting off too quickly. When the switch first closes, it sees not only the filter's inductance, but also its self-capacitance as well as stray capacitances contributed by the transistor's heat sink, the commutating diodes, and other components. Because of this stray capacitance, there is a relatively large instantaneous current spike (figure 7) at turn-on that can cause the control loop comparator to command the switching transistor to cut-off.

Fortunately, the solution to the problem is straightforward. The comparator can be gated so that it ignores its inputs during the first few microseconds after it turns on the switching transistor. While this is the cleanest method of preventing premature cut-off, it is not the simplest. A low-pass RC filter can be connected to the current-sensing resistor to attenuate the fast rise-time spike before it reaches the comparator. The component values, however, must be chosen carefully so as to not introduce unacceptably long delays in the ramp waveform reaching the comparator.

Although Boschert has always used current-mode regulation in virtually its entire product line, the power supply industry has generally used current-mode regulation only in flyback switchers. Even in the case of flyback designs, however, it is more a matter of necessity than choice. In a flyback switcher, the energy-storing inductor is actually the self-inductance of the flyback transformer, which is connected to the output only during the short period of time when the switch is open. Because of this, the resonant frequency of the output filter varies over time, making it virtually impossible to close a tight voltage-mode control loop around it.

The most probable reason voltage-mode regulation has reigned so long as *the* way to regulate switchers is that the early commercial designs made use of it and manufacturers that later entered the market followed suit. Over the years, manufacturers have perfected their voltage-mode designs and have made use of the large selection of voltage-mode control chips that have appeared on the market. Unfortunately, many of these control chips are not useable in current-mode regulators because their long propagation delays permit excessively high instantaneous currents to flow when the switcher's output is shorted.

The situation is changing, however. About a year ago, Unitrode introduced its UC1846 current-mode control chip. Because of the long lead times in bringing a totally new switcher design to market, it may be another year before commercial supplies built around the UC1846 appear. Even then, there will be only a few models introduced because of the reluctance of most manufacturers to rely on a single source for a critical component. However, once the UC1846 finds a market, second sources or similar devices are sure to become available.

For those engineers who see the advantages of current-mode regulation and are just now beginning a new design cycle, there is no need to wait for second source control chips. Boschert has been building current-mode regulators economically with discrete components for years. The trick is to convert as much of the control loop as possible to equivalent circuits that use a minimum of components. □