



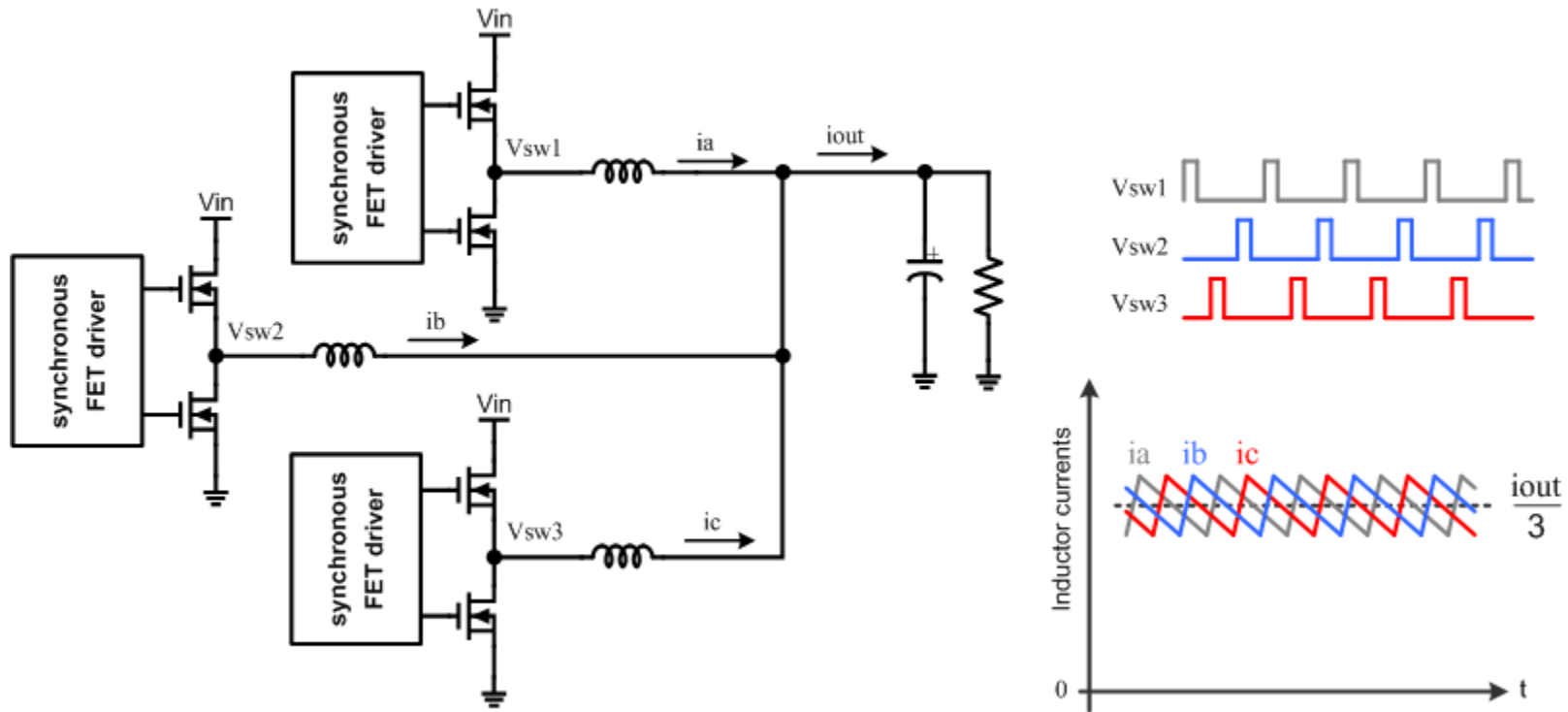
Buck Regulator Architectures

4.2 Multi-Phase Buck Regulators



Multi-phase Overview

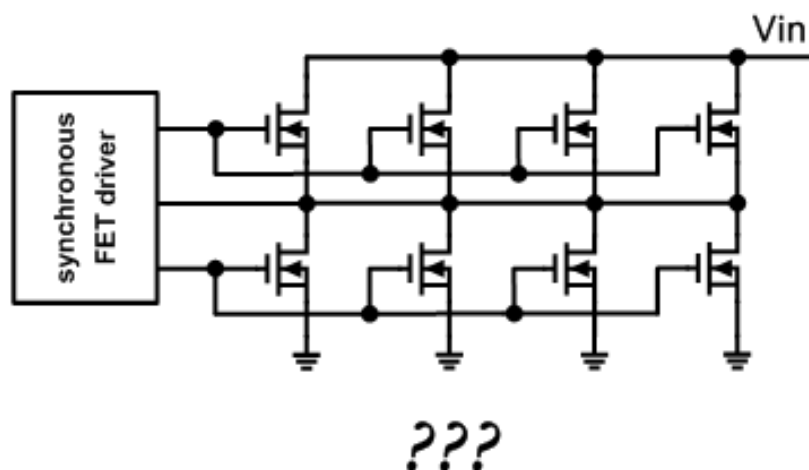
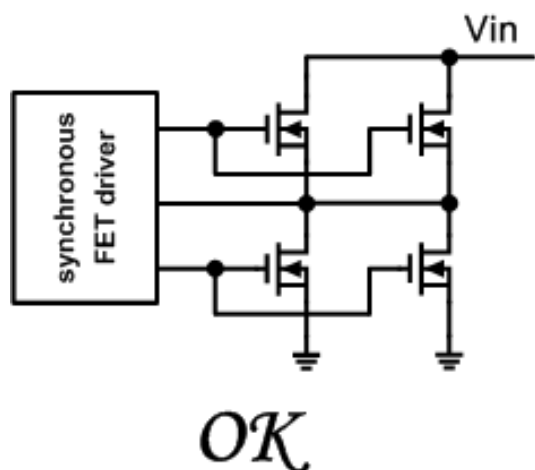
The idea of a multi-phase buck regulator is to put several buck regulators in parallel but have them operate in an interleaving manner. See figure below. The three-phase synchronous buck regulator has identical components for each phase, but the switching actions are 120 degrees out of phase.





Power FETs and Their Drivers

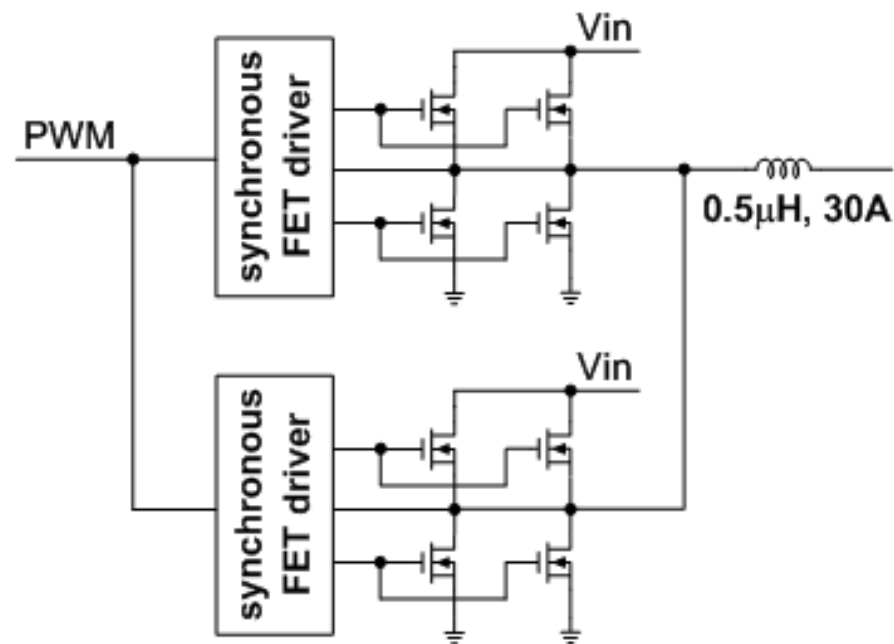
How fast a driver can turn on and turn off the power FETs has an impact on switching loss. The idea of using multiple drivers to drive FETs grouped into different phases is introduced and the benefits explained.





Power FETs and Their Drivers

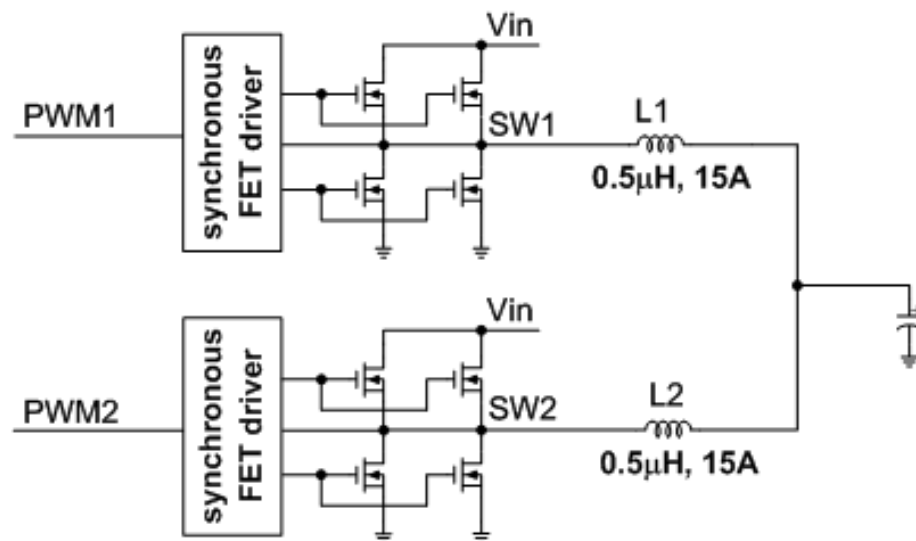
- Theoretically, we may use the same trick power FETs use, i.e. to distribute. We may drive each pair of power FETs (top and bottom) with a separate synchronous driver.
- The problem with this approach is the two groups of power FETs cannot be guaranteed to switch exactly at the same time. Therefore there can be potential shoot-through problems.





Power FETs and Their Drivers

The idea of using a separate driver for each group of FETs will work if the groups of FETs do not share the same switch node. This is precisely the case in a multi-phase configuration. Not only does each group of FETs not need to switch simultaneously with the rest of the groups, but all the groups are intentionally switched at different times to gain other benefits which we will discuss later in this course.

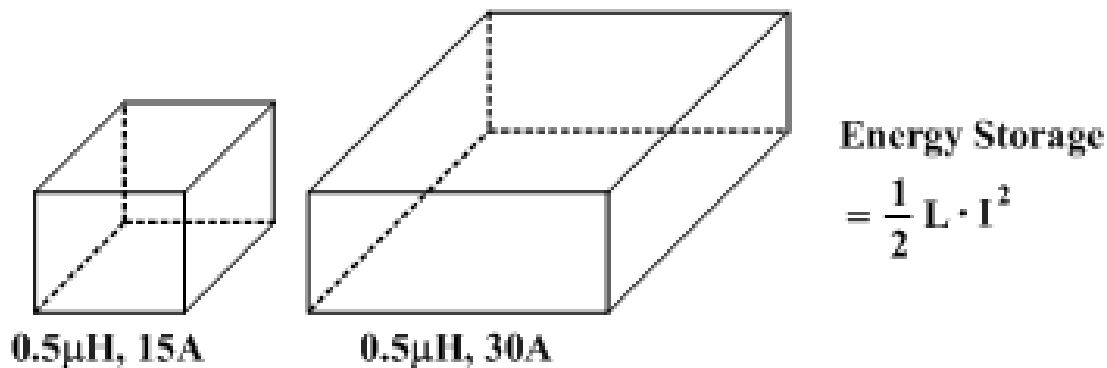




Output Filter

The output filter is a major portion of the power train and a major cost contributor. The following concepts will be explained:

- Ripple cancellation
- Physical size tradeoff
- Load transient response performance improvement

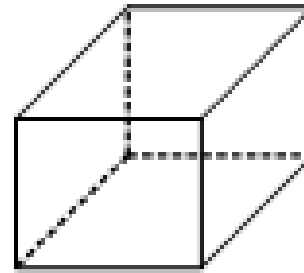




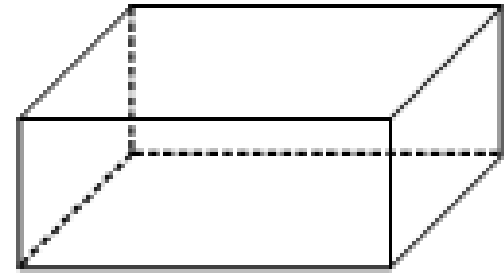
Output Filter

In reality, since the number of output capacitors typically doubles when the maximum load current doubles, the inductance value of the inductor may be cut in half without increasing the output voltage ripple.

So in many cases when the maximum load current doubles, the physical size of the inductor only needs to double and not quadruple.



0.5 μ H, 15A



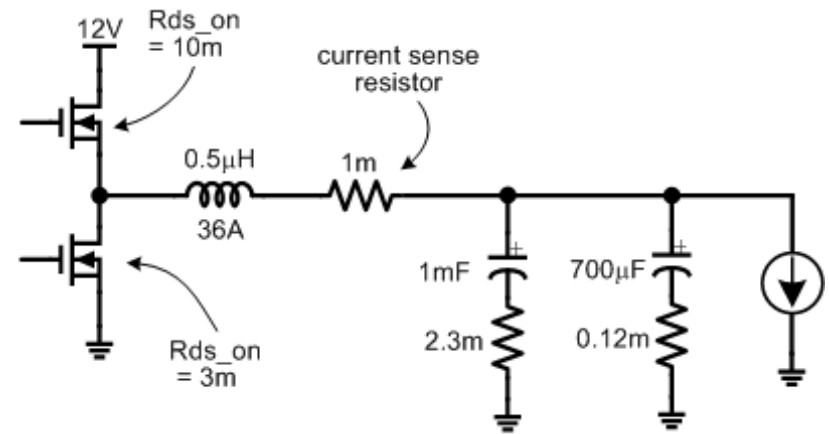
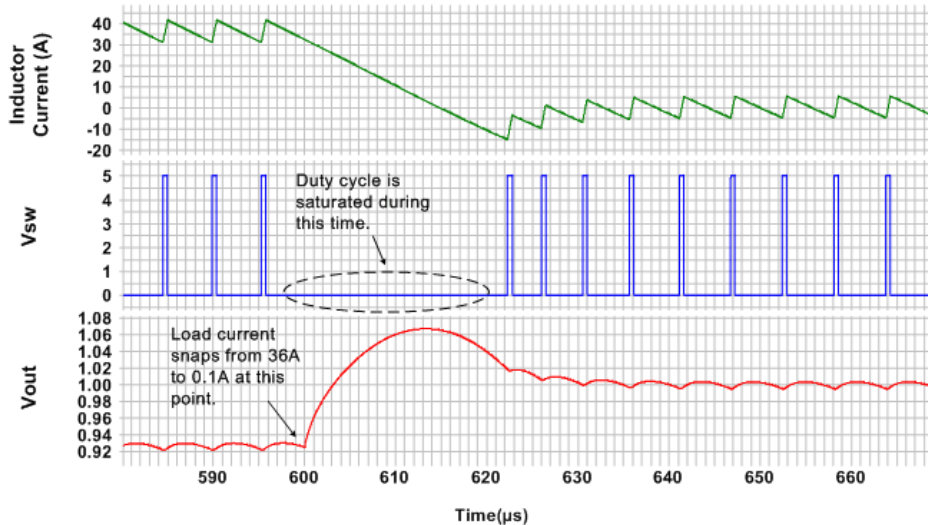
0.25 μ H, 30A

Example of Multi-Phase Benefits Using COT



A typical worst-case load transient is when the CPU current snaps from full load to no load, causing the control loop to immediately shrink the duty cycle to zero, and the energy stored in the inductor dumped into the output capacitors.

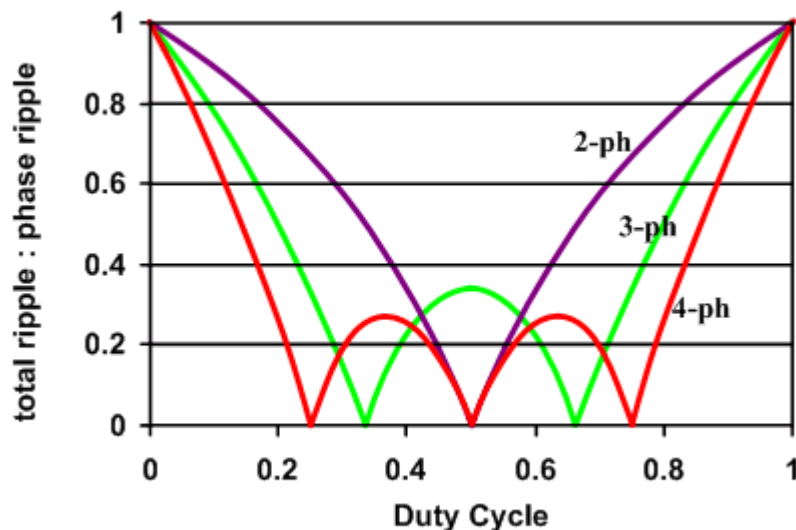
The left figure below shows such a load transient in a single-phase buck regulator where the inductor is $0.5\mu\text{H}$. Obviously the less energy stored in the inductor the fewer capacitors will be necessary. The right side is the power stage of the single-phase circuit and the control scheme is current mode hysteretic.





Choose Multi-Phase Stage

Going multi-phase has a clear technical advantage here. Let's first take a look at the combined output ripple (total ripple) current versus the ripple current in each individual inductor (phase ripple).



$$\frac{\text{total ripple}}{\text{phase ripple}} = n \cdot \frac{(D - \frac{m}{n}) \cdot (\frac{1+m}{n} - D)}{(1-D) \cdot D}$$

where $\frac{1+m}{n} \geq D \geq \frac{m}{n}$

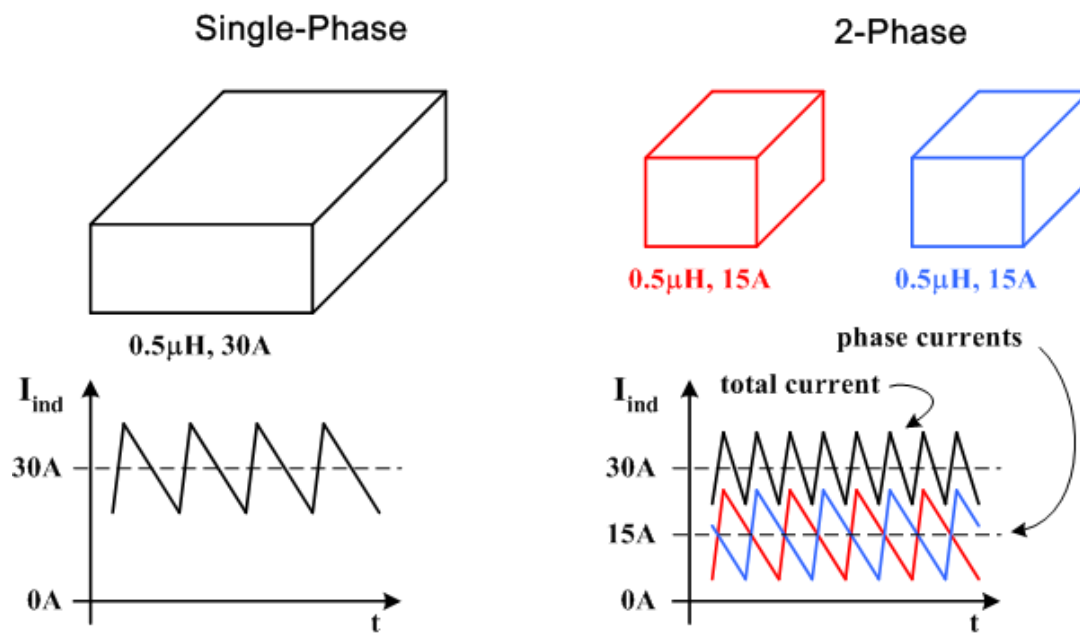
$$n > m \geq 0$$

n is the number of phases, and m is an integer.



Inductor Size Improvement

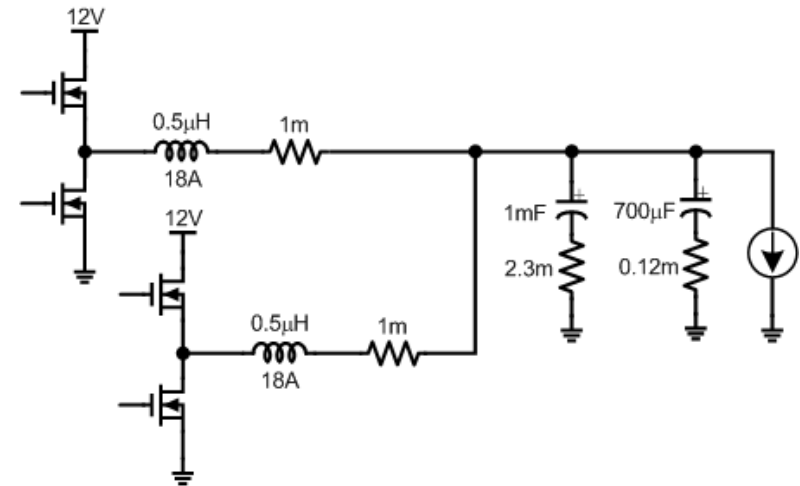
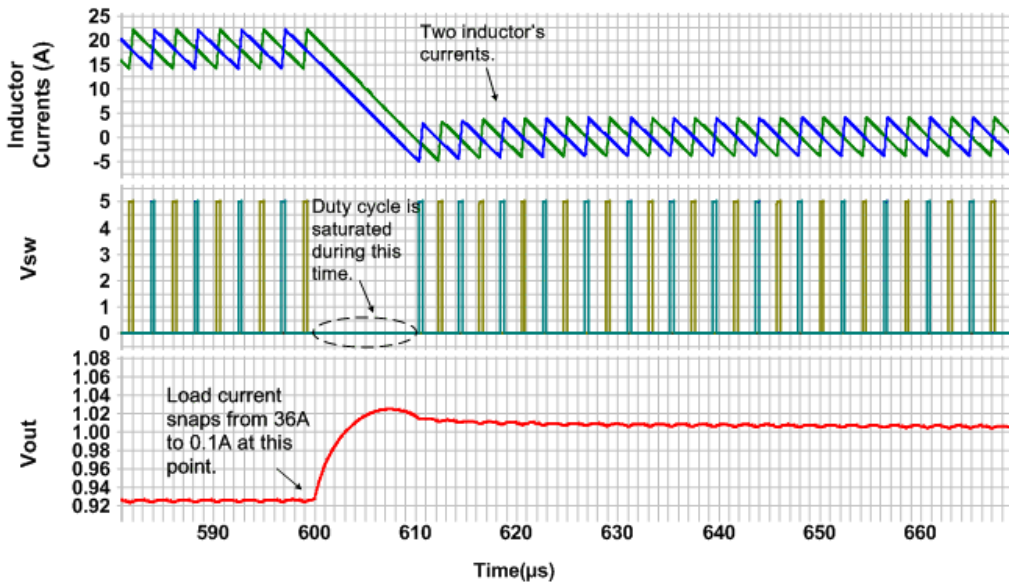
What is probably more important than achieving zero ripple at certain given points is the fact that the output ripple current is always less than phase ripple current. This means we can safely replace the single-phase inductor with multiple physically smaller inductors that are of the same inductance value, without increasing the output ripple current.



Overshoot Improvement



Load transient response also benefits from the multi-phase approach. The figure below shows the load transient response of a two-phase circuit experiencing exactly the same load step as in the single-phase example.



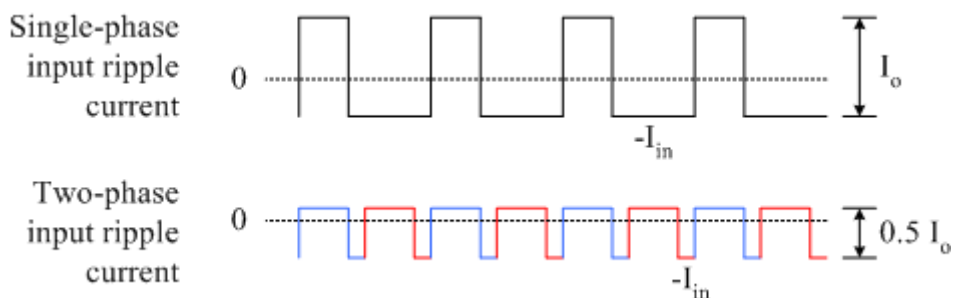


Input Capacitors

In a single-phase buck regulator, the input ripple RMS current can be calculated as follows.

$$I_{rms} = I_o \cdot \sqrt{D(1-D)}$$

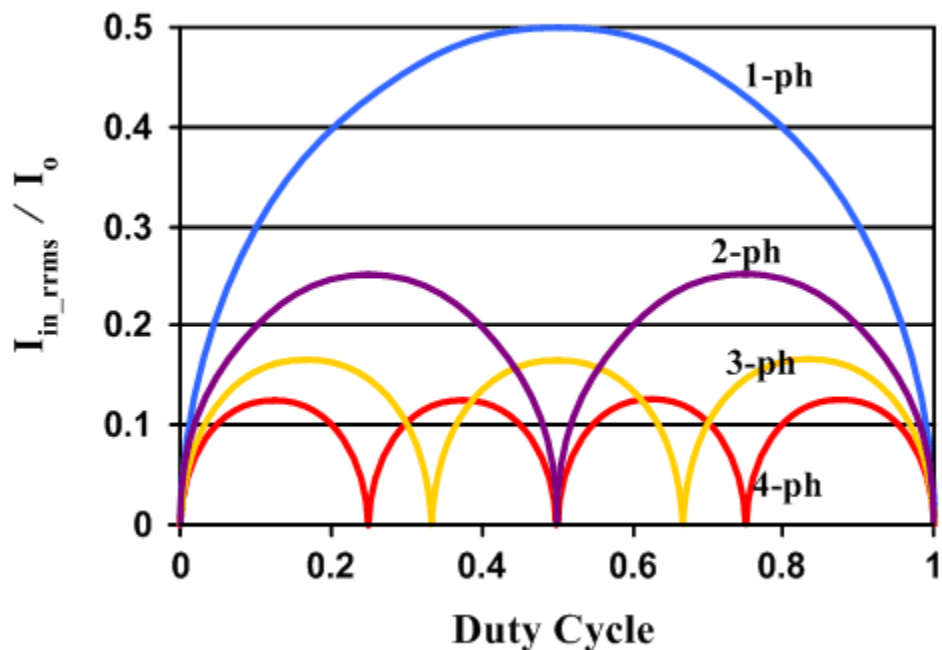
The figure below shows that if we go multi-phase, input ripple RMS current will be reduced. In the two-phase case, the magnitude of the input ripple current is half that of the single-phase solution because each phase is only carrying half the load current. Of course, there is one more current pulse each clock cycle.





Input Capacitors

The figure below shows the relationship between the duty cycle and the ratio of input ripple RMS current to the output current.



$$I_{in_rms} = I_o \cdot \sqrt{\left(D - \frac{m}{n}\right) \cdot \left(\frac{1+m}{n} - D\right)}$$

where $\frac{1+m}{n} \geq D \geq \frac{m}{n}$

$$n > m \geq 0$$

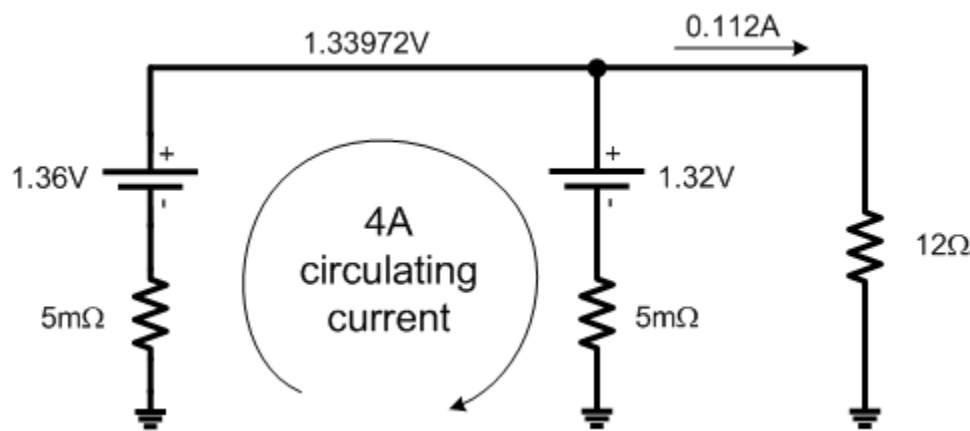
n is the number of phases, and m is an integer.



Current Sharing

Current sharing is a potential issue that is not a concern in a single-phase solution. It is also a lesson learned for the IC industry in certain applications.

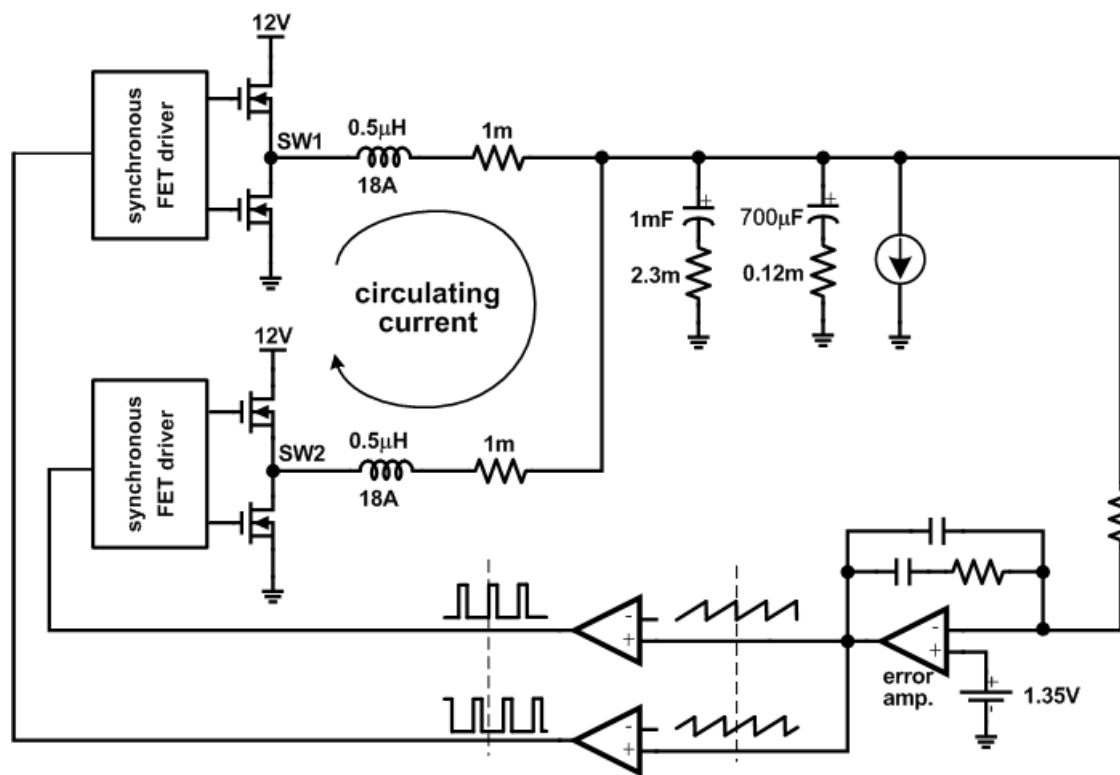
In prior discussions we assumed that in a multi-phase regulator all the phases will carry exactly the same amount of current, in other words, perfect load current sharing. In reality, that is not a given. The situation is similar to paralleling two batteries of the same type and expecting them to supply equal shares of current.





Current Sharing

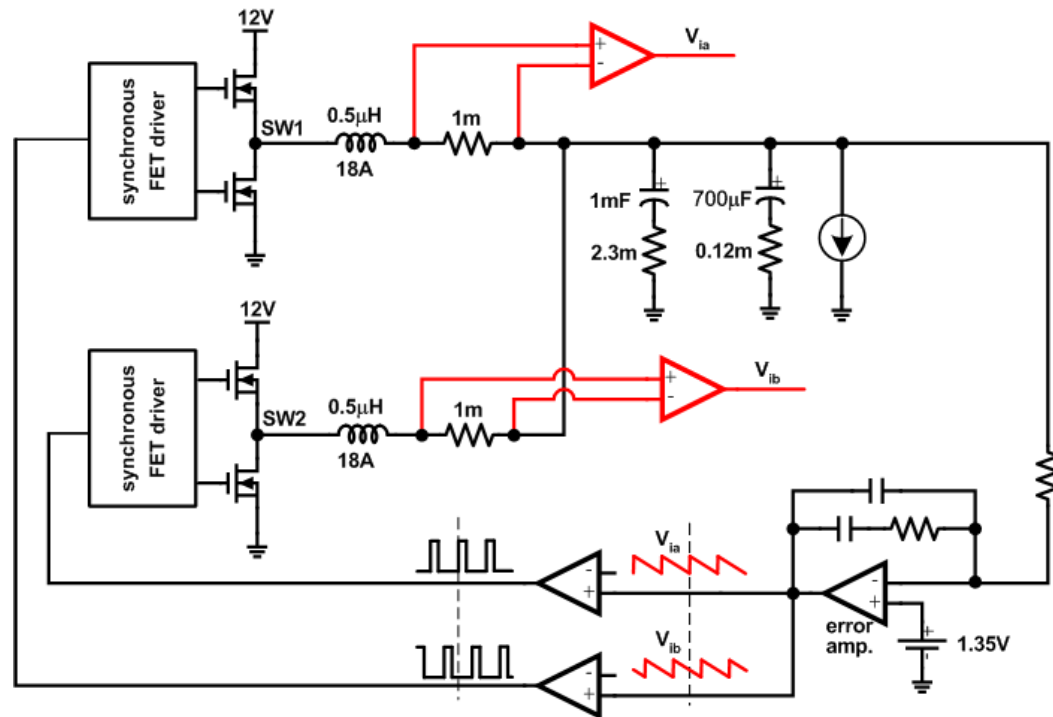
In the case of a multi-phase buck regulator, a very similar mechanism exists. The figure below shows a voltage mode two-phase synchronous buck.





Current Sharing

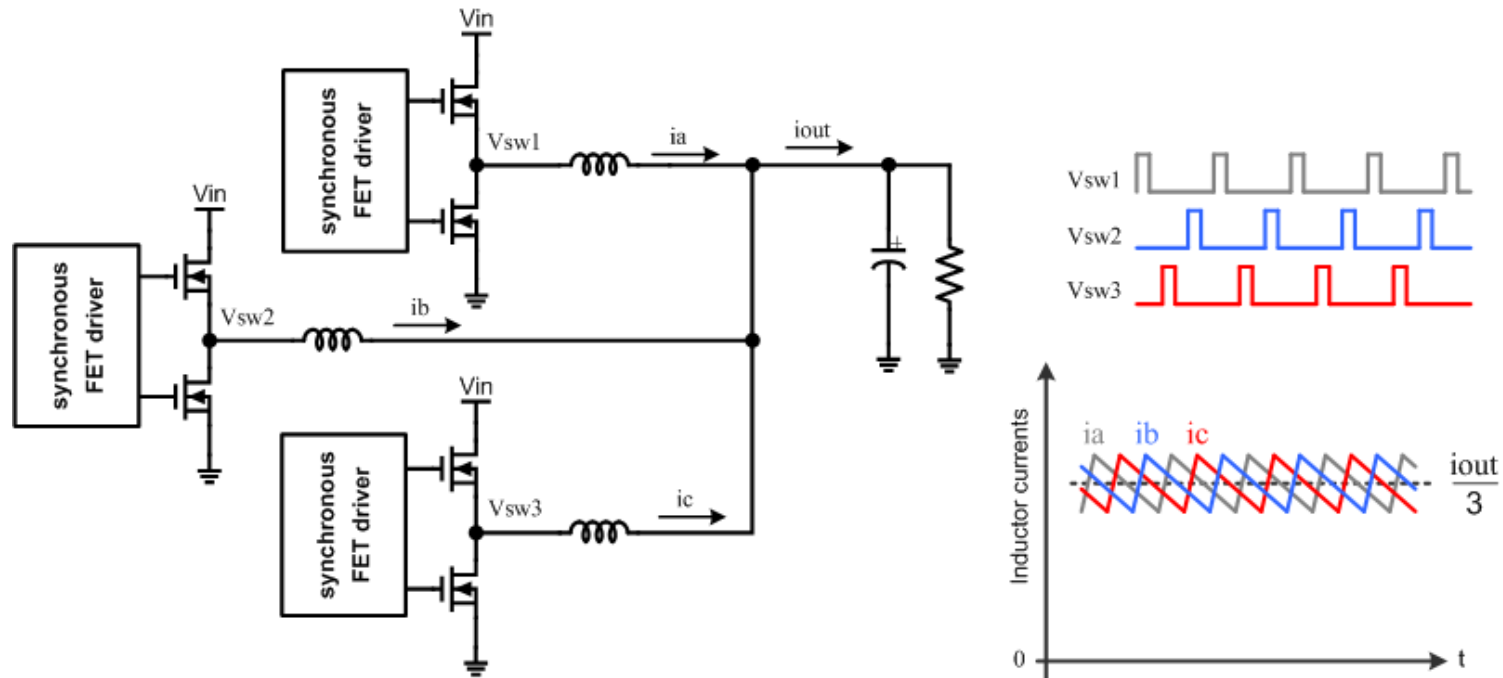
The cure for this current sharing problem is to sense the current in each phase and use some kind of feedback to force the sensed currents to be equal. The traditional peak-current mode control achieves this automatically and guarantees matching of the currents cycle by cycle.



Summary



The idea of a multi-phase buck regulator is to put several buck regulators in parallel and have them operate in an interleaving manner. The three-phase synchronous buck regulator below has identical components for each phase, but the switching actions are 120 degrees out of phase.





Thank you!