The Search for Cooler, High Power & Scalable POL Regulators in Small Footprint Packages Yields Results

3D Packaging Architecture & Clever Component Placement Resolves Thermal Issues

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The following statements will surely upset DC/DC IC and circuit designers, but the truth is that it's truer today than a few years ago. With all due respect to their complex minds and rich experiences in the art and science of designing with Bode plots, Maxwell's equations and concerns for poles and zeros to finally devise an elegant DC/DC converter circuit, IC designers often scape dealing with that one last dreaded physics topic: heat. It's the packaging engineers' job. And the packaging engineers have now far more influence in the merits of a DC/DC POL (point-of-load) regulator's thermal performance, especially those with high power housed in small packages.

A POL regulator generates heat because no voltage conversion is 100% efficient (yet). Then there is the question of how hot does the package become due to its construction, layout, and thermal impedance. Thermal impedance of the package not only raises temperature of the POL regulator, it also increases the temperature of the PCB and surrounding components as well as contributes to the complexity of a system's heat removal arrangements.

The removal of the heat from the package when it is assembled on PCB is done by two major means:

1) When surface mounted, the heat is conducted into the copper PCB layers, spreading the heat from the bottom of the package
2) The cool airflow removes heat from the top of the package, or more precisely, the heat is transferred to the cooler fast air molecules in contact with the surface of the top of the package.

Of course, there are methods of passive and active heatsinking, which for simplicity of discussion, are considered subsets of the 2nd category. So, more copper, more PCB area, thicker PCB layers, spreading out placement of components on the PCB, bigger and faster fans are some good ideas from the tool kit of thermal management to keep the whole system including the DD/DC POL regulators operating within a safe temperature value. Good ideas, may be, but are there other approaches to help with thermal management of small but high power POL regulators?

Although at first some or all the steps mentioned earlier have a significant impact in keeping a system cooler, applying these thermal remedies may diminish a system's or end product's selling competitive edge. The end product, say a router, may become larger because of the intentional separation of components on PCB, audibly noisier because of the number of fans and faster streams of airflow entering and exiting hot circuits, and perhaps at the end, render the end product inferior in a market that companies constantly compete to win on the merits of compactness, computational power, data rates, efficiency, and cooling costs. 28- 20-nm and susb-20nm digital devices are burning more power to deliver better performance, while equipment suppliers battle each other with faster, smaller, quieter and more efficient innovations. Behind the excitement of new digital technology prowess, there is also the analog and power technology's struggle to deliver more power in smaller packages with minimal contribution to the rise of a system's overall temperature. A POL voltage regulator with higher power density seems like a good choice: It's smaller but higher power.

Judging POL Regulators by the Power Density Numbers are …. for the Rookies

40W per cm squared (or cubed) POL regulator has to be better than a 30W per cm squared regulator. Marketers use power density to sell their products and system designers each year demand higher power-density regulators to position their next faster, smaller, quieter and more efficient products against their competitors. Should higher power density numbers be a deciding factor in choosing a "better" POL a regulator? Let's look at a few items.

First, forget the power density number and study the data sheet for the POL regulator. Find the thermal derating curves. A well-documented and characterized POL regulator should have many such graphs specifying output current at different input voltages, output voltages and airflow speeds. In other words, the data sheet should show the output current capability of the POL regulator under your circuit's conditions so you can judge the regulator by its thermal and load current abilities. Does it meet the requirement of your system's typical and maximum ambient temperature and airflow speed? Remember, output current derating relates to the thermal performance of the device. The two are closely related and equally important.

Second is the efficiency; not first, second. Efficiency alone is misleading and gives an inaccurate representation of the thermal characteristics of a DC/DC regulator. It is needed to calculate input current and load current, input power consumption, power dissipation, junction temperature, etc. But, to make a better sense, an efficiency number should be studied along the output current derating and other thermal data related to the device and its package. For example, a 98% efficient DC/DC step-down converter is unbelievably impressive. More impressive is when it boasts a superior power density number. Do you purchase it?

A savvy engineer should ask about the effect of the 2% efficiency loss. How does it translate into the temperature of the package? What is the junction temperature of such high power density and efficient regulator at 60degC ambient with 200LFM (linear feet per minute, airflow)? Look beyond the typical numbers that are listed at room temperature of 25°C. What are the maximum and minimum values that are measured at extreme temperatures of -40°C, 85°C or 125°C? What if the package thermal impedance was so high that the junction temperature rose beyond the safe operating temperature? Does this expensive regulator have to be derated to such low output current values that the cost of the device no longer justifies its curtailed output power capability?

The last factor to consider is the ease of cooling the POL regulator. The package thermal impedance values provided in the data sheet are key to simulate and calculate rise in junction, ambient and case temperatures of the device. Because much of the heat in surface mount packages flow from the bottom of the package to the PCB, layout guidance and discussions about thermal measurements must be articulated in the data sheet to eliminate surprises later during system prototyping.

A well designed package should be able to dissipate heat efficiently and evenly throughout the surfaces of its package to eliminate heat concentration and hot spots which degrade reliability of a POL regulator and should be eliminated or mitigated. As described earlier, PCB is responsible for absorbing and routing much of the heat from surface mountable POL regulators, however, with airflow prevalent in today's dense and complex systems, a more cleverly designed POL regulator also taps on this "free" cooling opportunity to remove heat from its heat generating components such as MOSFETs and inductors.

Guiding Heat from the Inside of the Package to the Top & into the Air

A high-power switching POL regulator depends on an inductor or transformer to converter the input supply voltage to a regulated output voltage. In a non-isolated step-down POL regulator, the device uses an inductor where the inductor and the accompanying switching elements such as MOSFETs produce heat during DC/DC conversion. About a decade ago, a new packaging advancement allowed an entire DC/DC regulator circuit including the magnetics to be designed and fitted inside a molded plastic, called modules or SiP, where much of the heat generated inside the molded plastic has to be routed to the PCB from the bottom of the package. Any conventional attempt to improve heat removal capability of the package contributes to a larger package such as attaching a heatsink to the top of the surface mount package.

However, as recent as 3 years ago, an innovative module packaging technique took advantage of available airflow to cool itself. A heatsink was integrated into the module package and over molded. Designed in a unique shape, the heatsink was connected to the MOSFETs and inductors, the heat generators, inside the package and the other end of this heatsink was a flat surface exposed on top of the package. With this new packaging and on-board heatsinking technique, the device could be cooled quickly with some airflow as the air removed heat from the top of the package where the flat surface of the heatsink was in contact with the air (see LTM4620 data sheet for TechClip videos). Another new idea in packaging to improve thermal performance of high power POL regulators, takes this concept further.

POL Module Regulator with Stacked Inductor as Heatsink

The size of an inductor in a POL regulator depends, among many factors, on voltage, switching frequency, current handling and its construction. In a module approach where the DC/DC circuit including the inductor is overmolded and encapsulated in a plastic package and resembles an IC, the size of the inductor dictates the thickness, volume and weight of the package. The inductor is also a heating element contributing to the overall internal temperature of the POL module regulator. The integrated heatsink in the package, discussed earlier, conducts heat from the MOSFETs and inductor to the top of the package and is greatly helpful in quickly transferring internal heat to outside of the package on top and finally to air, a cold plate or a passive heatsink. However, this technique is useful for smaller size, lower current inductors where they easily fit inside within the plastic mold compound of the package. For higher power POL regulators that depend on larger and higher current inductors, placement of the magnetics inside the package forces other components of the circuit to be pushed away thus expanding the PCB foot print of the package. A larger footprint means a heavier package. To keep the footprint small and to further improve heat dissipation, the packaging engineers have developed another trick: go vertical, stack or 3D (Figure 1).

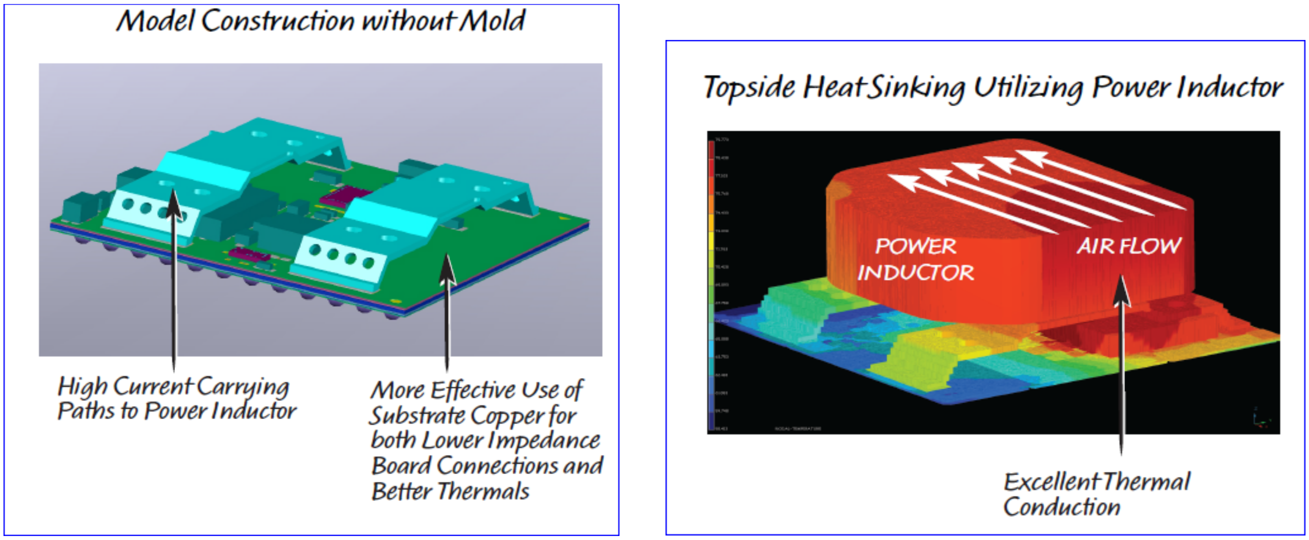

Figure 1. 3D or vertical packaging technology for high power POL regulator modules elevates the inductor and exposes it to airflow as a heatsink. The rest of the DC/DC circuitry is assembled on substrate under the inductor keeping PCB area small and improving thermal performance of the package.

3D Packaging with Exposed Stacked Inductor: Keep Footprint Small, Increase Power, Improve Heat Dissipation

Small PCB footprint, more power and better thermal performance; All three are possible simultaneously with 3D packaging a new method in construction of POL regulators (Figures 1 and 2). The LTM4636 is a µModule regulator with on-board DC/DC regulator IC, MOSFETs, supporting circuitry and a large inductor to decrease output ripple and deliver load currents up to 40A from 12V input to a precisely regulated output voltages ranging from 3.3V to 0.6V. Four LTM4636 devices can current share to provide 160A of load current. The footprint of the package is only 16mm x 16mm. If you do the numbers, power density is very good. But, let's remember not be fooled by this number. The benefits that this µModule regulator brings to system designers is in its thermal performance, a combination of its impressive DC/DC conversion efficiency and heat dispersion ability.

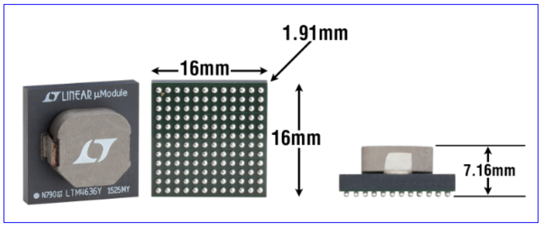

Figure 2. LTM4636 uses stacked inductor as heatsink to achieve impressive thermal performance in small footprint area

To keep the footprint small (16mm x 16mm BGA), the large footprint inductor is elevated and secured on two copper lead frame structures so that the rest of circuit components (diodes, resistors, MOSFETs, capacitors, DC/DC IC), can be soldered under it on the substrate. If the inductor were to be placed on the substrate, the µModule regulator could have easily occupied more than 1,225mm squared of PCB vs its small 256mm squared footprint. This technique rewards system designers with a more compact POL regulator layout but it has another great benefit. It demonstrates good thermal performance.

The stacked inductor in the LTM4636 is not overmolded (encapsulated) with the plastic compound. The rest of the components are. The inductor is conveniently exposed to the air and with its smooth corners and raised structure, the air flows more readily around and on top of it (minimal flow blockage).

Facts in Numbers: 40A LTM4636, Thermal Performance & Efficiency

The LTM4636 is a 40A capable µModule regulator benefiting from 3D packaging technology also referred to as Component-on-Package (CoP, Figure 2). The body of the package is an overmolded 16mm x 16mm x 1.91mm BGA package. With the inductor stacked on top of the molded section, the LTM4636's total package height, from the bottom of BGA solder balls (144 of them) to the top of the inductor, is 7.16mm.

In addition to dissipating heat from the top, the LTM4636 is designed to efficiently disperse heat from the bottom of the package to the PCB. It has 144 BGA solder balls with banks of them dedicated to GND, V_{IN} and V_{OUT} where high current flows. Collectively, these solder balls act as a heatsink to the PCB. The LTM4636 is optimized to dissipate heat from the top and bottom of the package.

At $12V_{IN}$, $1V_{OUT}$ with full load current of 40A (40W) and standard 200LFM airflow, the LTM4636 has only 40°C rise over the ambient temperature (25°C-26.5°C). Figure 3 shows the thermal image of the LTM4636 at the conditions mentioned above. Next is the derating numbers, figure 4. At 200LFM, the LTM4636 delivers full current of 40A up to 83°C ambient temperature. Half current, 20A is at very high ambient temperature of 110°C ambient. This means that the LTM4636's load current delivery is less affected by the ambient temperature when some airflow is available.

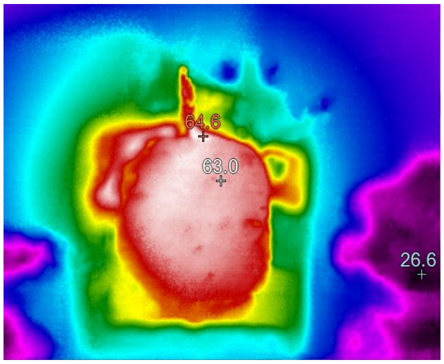

Figure 3. Only 40°C Rise at 40W – $12V_{IN}$ to $1V_{OUT}$ at 40A, 200LFM airflow

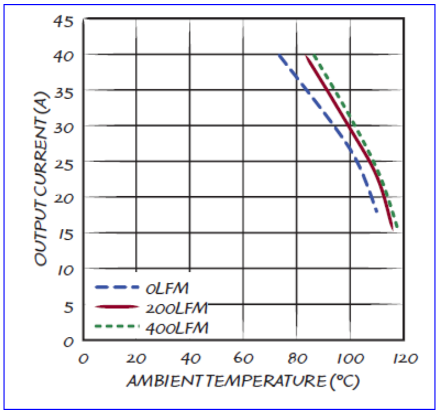

Figure 4, Full current of 40A delivered up to 83°C ambient, 200LFM

Best performance MOSFETs and strong drivers of the DC/DC controller are mainly responsible for the high conversion efficiency of the LTM4636. Here are some numbers for step-down voltage conversion from a 12Vin supply: 95% efficiency at 3.3V, 25A; 93% at 1.8V, 40A; 88% at 1V, 40A. Figure 5 summarizes the efficiency numbers from 12Vin for 1Vout to 3.3Vout.

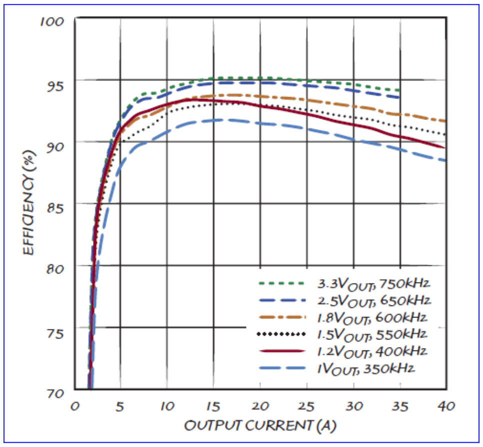

Figure 5. High DC/DC conversion efficiency from $12V_{IN}$ & various output voltages

160W, Scalable 4 x 40A µModule POL Regulator with Thermal Balance

One LTM4636 is rated for 40A load current delivery. Two LTM4636s in current sharing mode (or parallel) provide 80A and four of them up to 160A (figures 6 and 7). Current mode architecture of the LTM4636 is responsible for precision current sharing among the multiple blocks of 40A each. A precision current sharing, in return, allows for a balanced heat dissipation among 2, 3, or 4 devices in parallel (figures 6 and 7). Because of this ability, no one device will be overloaded or overheated. Another feature of this device is its ability to operate out-of-phase to reduce output and input ripple current which in turn reduces the number of input and output capacitors. For example, four LTM4636 are running 90° out-of-phase (360° ÷ 4). Clocking and phase control is included. Also, because the layout for scaling power is simple; it's a matter of copying and pasting the foot print (symbols and footprints are available).

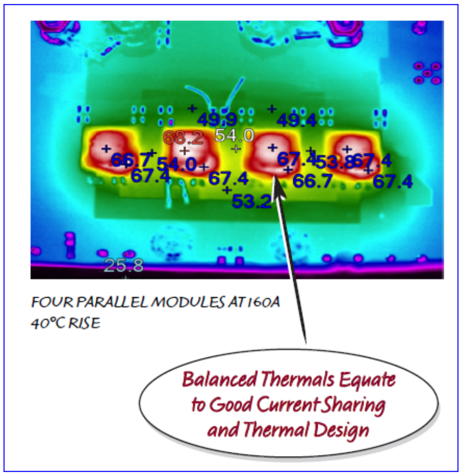

Figure 6. Precision current sharing provides balanced heat dissipation among each four LTM4636 in parallel; only 40°C rise- 12V_{IN} 1V_{OUT}, 160A, 400LFM

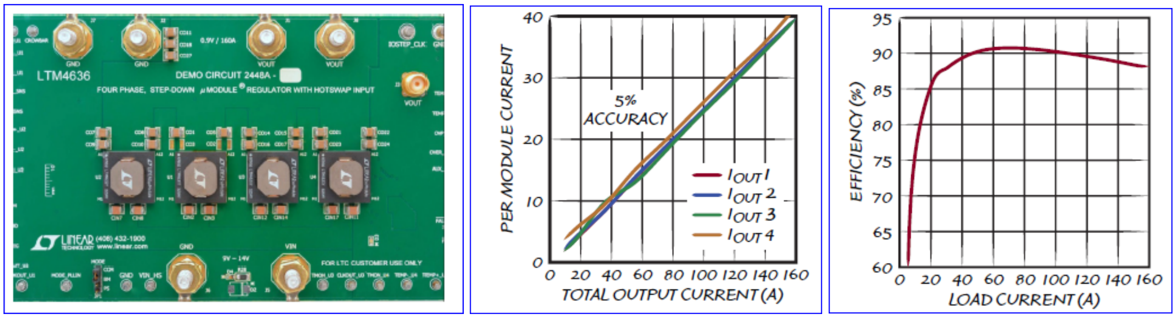

Figure 7. Four LTM4636s in parallel with precision current sharing and high efficiency, respectively- 12V_{IN} to 0.9V_{OUT} at 160A

Conclusion

Choosing a POL regulator for a densely populated system requires scrutiny beyond voltage and amperage ratings of the device. Evaluation of its package's thermal characteristics is essential as it determines an equipment's cost of cooling, cost of PCB and size. An advancement in 3D, also referred to as stacked, vertical, CoP, allow high power POL module regulators to fit on small PCB footprint but more importantly allow efficient cooling. The LTM4636 is the first series of µModule regulators to benefit from this stacked packaging technology. As a 40A POL µModule regulator with stacked inductor as heatsink, it boasts between 95% to 88% efficiency, only 40°C rise and occupies only 16mm x 16mm of PCB area. For a video description of the LTM4636, please see www.linear.com/LTM4636.