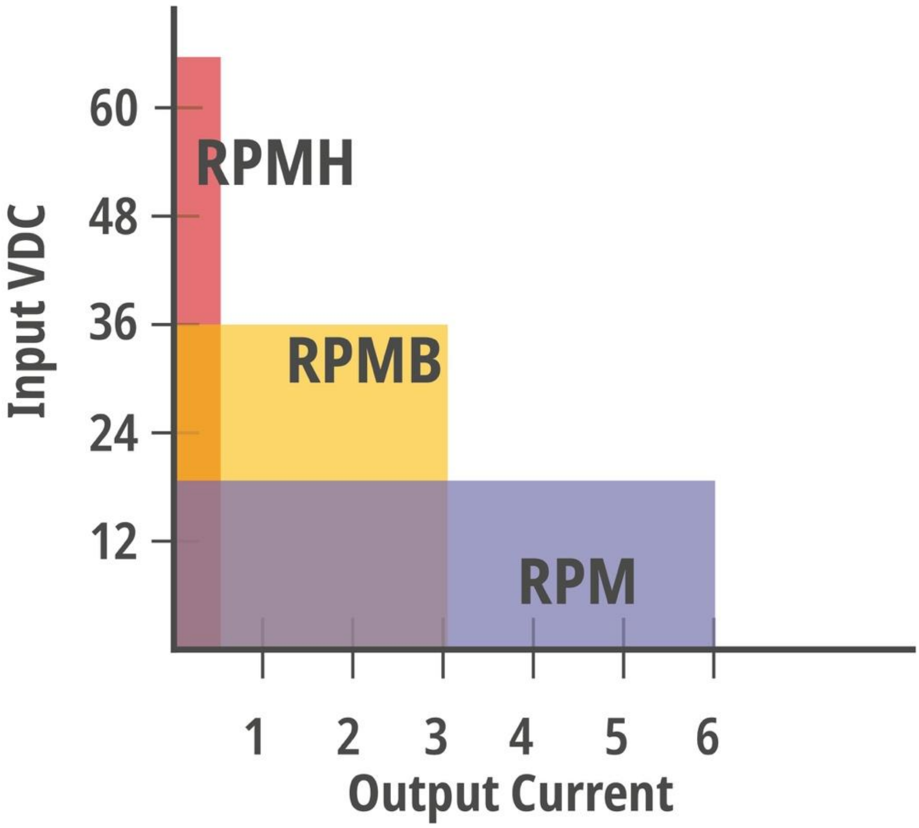
RECOM

Whitepaper

Challenges in the design of higher voltage DC/DC switching Regulators



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1 Introduction

Due to the market demand for SMD power modules, Recom has created the RPM family of compact, low profile SMD switching regulators. The RPM concept delivers fully functional power supply building blocks with the switching regulator controller IC, power inductor, voltage setting resistors and input and output capacitors included in one stand-alone part, all in a standardized size low profile metal case and with a DOSA-compatible pinout. This family of five different low voltage products (RPMxx-1.0, RPMxx-2.0, RPMxx-3-0, RPMxx-6.0 and RBB10-2.0) has been further extended with three more higher voltage series to handle increased input and output voltages (RPMBxx-2.0, RPMBxx-3.0 and RPMHxx-0.5), without deviating from the same footprint or case dimensions, permitting an easy upgrade from existing designs.

However, the new RPMH and RPMB product series are not simply modifications of the existing RPM product series. Although physically they look identical, they are internally quite different. This white paper explores some of the design and component choice decisions required to cope with higher input voltages up to 36 VDC or 65V DC respectively and higher outputs up to 24 VDC and 3 A load current.

2 Background

Switching regulators have long been the workhorse of efficient conversion of DC power rails to lower or higher voltages, either directly for the load or as part of a distributed power architecture. The first designs from the 1950s used vacuum tubes and showed dramatic improvements in conversion efficiency compared with the alternative 'linear regulator' approach and also opened up the possibility of boosting DC voltages, only practical previously with unwieldy mechanical 'vibrators'. It was only in the 1970s that the first switched-mode power supply IC controller appeared, the Silicon General SG1524, using 'voltage mode' control.

The success of this device opened the floodgates to alternatives using different control and conversion techniques. Today, there are many alternative topologies and control methodologies; from synchronous vs asynchronous, minimum on time vs minimum off time, averaged vs cycle-by-cycle current control or fixed frequency vs variable frequency designs with pulse-skipping for light loads, to name just a few examples. Although each topology has its own advantages and disadvantages, the selection and specification of the main power stage components; the switching transistor, the inductor and the output capacitor are still often key to achieving the optimum performance and the lowest possible losses under all operating conditions.

A measure of the development of the switching regulator is its conversion efficiency - over the years, the figures have been steadily climbing from around 70-80% to 97% and higher in the latest designs. Higher efficiency allows a higher power density, measured in watts/volume, representing how much power can be delivered from a given size without the converter overheating. Much of this improvement in power density is due to increasing integration; the low $R_{DS(ON)}$ switching transistor(s) are commonly integrated alongside the controller die in the same package and increasingly the inductor is also on-board. Peripheral functions such as fault monitoring, current sharing, synchronisation and sequencing have also been increasingly swept into the controller IC design. In addition, the switching frequencies are moving upwards from a few hundred kilohertz up to 1MHz or higher. Increasing the switching frequency allows smaller components to be used, but at the cost of increased power dissipation and higher EMI levels. The challenge is to find the optimum balance between physical size, thermal performance and EMC filter costs.

3 The Need for Higher Voltages

The RPMBxx-2.0 and RPMBxx-3.0 are higher voltage versions of the RPMxx-2.0 and RPMxx-3.0 respectively. The continuous input voltage can go up to 36 VDC and short excursions up to 38 VDC are permissible without causing permanent damage to the switching regulator. This input voltage range allows popular 24 VDC industrial bus power voltages to be used, accommodating any over-voltages and surges up to 150% - a condition that can sometimes occur in heavy industrial installations with long cable runs. This input voltage range also allows an unregulated 24V battery back-up system to be used to keep the system running during a power outage.

A higher input voltage range also permits a higher output voltage. The RPM series are limited to a nominal 3.3V or 5V output, adjustable from 0.9V up to 6V, which is a practical use for nominal 12V supply rails. However, with an input voltage range of up to 36V, the RPMB series also offers 12V or 15V outputs, adjustable from 9V up to 24V, as well as 3.3V or 5V outputs, adjustable from 1V up to 9V. This makes the RPMB series much more versatile. For example, the 3.3V version can be used with 5V, 12V, 24V or 36V supplies, making it a universal input power module.

A closer look at the RPMB datasheet will reveal that the converter has two sets of characteristics; the maximum input voltage remains at 36V irrespective of the output voltage, but the output voltage has two adjustment ranges: 1-9V and 9-24V. The controller IC and the topology is the same for all output voltage combinations, but a single inductor cannot cover all of the output options. To understand why this is, requires a more in-depth look into how these switching regulators work.

The RPMB uses a synchronous, peak-current-mode, constant frequency PWM controller, meaning that the on-time is adjusted to regulate the output voltage. The output current is monitored on a cycle-by-cycle basis and used to regulate for changes in input voltage and output load to keep the output voltage constant. The duty cycle is approximately the ratio of the input voltage and output voltage, once any timing delays are ignored:

$$Duty\ cycle \approx \frac{V_{out}}{V_{in}}$$

Equation 1: Buck Converter Duty Cycle Relationship

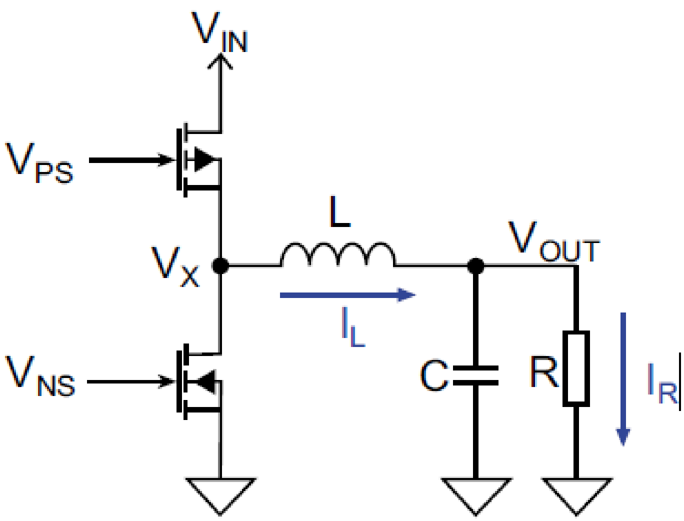

Figure 1: Simplified Synchronous Buck Regulator

(Source: Fig 1.16 DC/DC Book of Knowledge https://recom-power.com/en/support/resource-library/book-of-knowledge/book-of-knowledge.html)

So, for a 24V input and 5V output, the duty cycle would be around 21%. If the output voltage is increased to 15V, the duty cycle increases to about 64%. The worst case conditions are at 36V input and 3.3V output (smallest duty cycle of around 10%) and at 16V input and 15V output (highest duty cycle of around 94%).

The inductor value is determined by the following, more complex relationship:

$$L = duty\ cycle.\frac{V_{in} - V_{out}}{0.3 f I_{out,max}} \approx \frac{V_{in}}{V_{out}}.\frac{(V_{in} - V_{out})}{f} \text{ (for 30\% inductor ripple current)}$$

Equation 2: Inductor Value Calculation

This equation tells us two things:

1. The greater the input-to-output difference, the larger the inductor needed.

2: The higher the switching frequency, f, the smaller the inductor needed.

So for a fixed operating frequency and maximum load current and the same maximum input voltage of 36V, a larger inductance value will be needed for the lower output voltages than for the higher output voltages.

For the RPMBxx-3.0, the difference in the inductor value for the 3.3V output and for the 15V output is a factor of 7 and it makes sense to use two different inductor values; one for the lower output voltages from 1V up to 9V and another value for the higher output voltages from 9V up to 24V.

4 The Trend towards 48V Systems

There is a growing trend towards the use of 48 VDC as an industrial bus supply voltage as there are several factors that make a 48V supply more attractive than the standard 24V industrial voltage supply:

1. It is more efficient. The power losses in a wire are proportional to the square of the current flowing through it, so by increasing the supply voltage from 24V to 48V, four times more equipment can be powered using the same supply cable. This allows upgrades to be made to the existing plant without having to re-wire the power supply cabling.
2. It is more secure. The push for mild-hybrid electric vehicles (for example, city cars with a downsized fuel-burning engine that use an additional electric motor to improve the acceleration and to allow short journeys to be purely battery powered)

has meant that the cost for a Lithium-Ion 48V battery pack has fallen sharply. These maintenance-free 48V Li-Ion batteries are smaller, lighter and now often cheaper than an equivalent lead-acid battery-backed system.

3. It is safe. Operating industrial machinery on a 48 VDC supply means that the system is still classified as Safe Extra Low Voltage (SELV), meaning that additional insulation and safeguards against electrical shock are not required. This can substantially reduce the installation costs in heavy industrial applications which require more power than could be supplied by a 24V supply compared to the alternative of using mains powered equipment.

The output voltage of an automotive-grade 48V Lithium-Ion battery pack is specified by the LV148 industry norm:

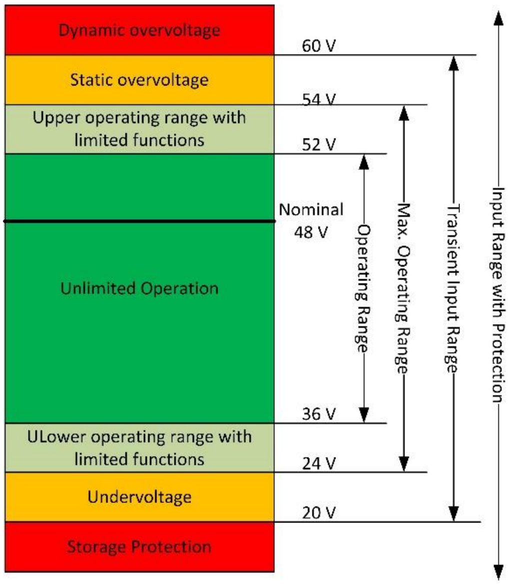

Figure 2: LV148 Voltage Levels

It can be seen from the LV148 norm that any buck regulator powered from a 48V Li-Ion battery pack needs an input voltage range of at least 20 to 60 VDC. In practice, surges can occur above the 60 V limit, although deep discharges under 20 V are to be avoided as these can damage the Lithium-Ion battery permanently.

To meet these requirements, the RPMHxx-0.5 was developed. The continuous input voltage range goes up to 65V or up to 68V for short periods of time. This allows a low cost 62V Zener diode to be used as a simple over-voltage transient limiter without it dissipating excessive heat during normal operation.

BZT52 Sel-xxx		Working voltage V_Z(V);		Maximum differential resistance rdif(Ω)		Reverse current IR (µA)		Temperature coefficient S_Z(mV/K);		Diode cpacitance C_d (pF)	Non-repetitive peak reverse current I_{ZSM} (A)
		I_Z=2 mA		I_Z=0.5 mA	I_Z=2 mA			I_Z=5 mA			
		Min	Max	Max	Max	Max	V_R(V)	Min	Max	Max	Max
56	B	54.9	57.1	375	120	0.05	39.2	52.2	63.8	40.	0.30
62	B	60.8	63.2	400	140	0.05	43.4	58.8	71.6	35	0.30
68	B	66.6	69.4	400	160	0.05	47.6	65.6	79.8	35	0.25

Figure 3: Example of Zener Diode Characteristics

The RPMHxx-0.5 has adjustable outputs up to 28 VDC, but the main applications are for direct 48V-to-3.3V and 48V-to-5V outputs. With such a large input/output voltage ratio, the duty cycle is very short (around 5%).

This means that the controller has to switch with a fast slew rate and the timing has to be very accurate. The control scheme used is constant on-time, hysteretic mode to avoid the need for external loop compensation components. The main difference between voltage or current mode control and hysteretic mode control is that the latter uses a pulse generator rather than a PWM driver, so it has more the characteristics of pulse-frequency modulation (PFM). By using PFM rather than PWM, the controller can interrupt the current pulses through the inductor if the output voltage exceeds the set limit or the load suddenly decreases, allowing a faster reaction to load transients.

This feature is especially important when the difference between the input voltage and output voltage is large. The disadvantage is that the operating frequency effective changes with load, making component selection more critical.

5 Inductor Choice for Higher Operating Voltages

What is often not appreciated is that inductors do not just have an inductance, saturation current and DCR specification but also a voltage rating. Sometimes this maximum voltage is surprisingly low. For example, a widely used inductor type for switching regulators has an iron powder core. These have the advantages of high saturation currents, soft saturation behaviour, small size and are readily available from many different suppliers.

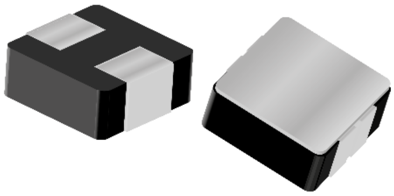

Figure 4: Example of Iron Powder SMD Inductors

The manufacturing process is also relatively straightforward and low cost - a coil made of lacquered wire is moulded into a mixture of iron powder and an organic binder, before being compressed and cured into the final product (see figure 5).

The problem here is that iron powder is an electrical conductor. The core is coated with an insulating lacquer to stop direct short circuits across the PCB terminals, but this insulation does not withstand very high voltages.

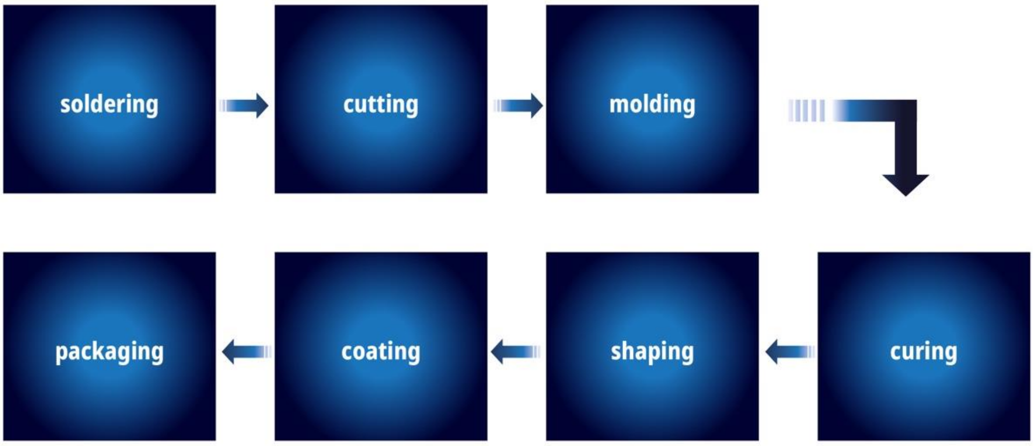

Figure 5: Typical Iron Powder Inductor Manufacturing Process

Additionally, the lacquer coating is not guaranteed not to have any pin-hole defects. An alternative to insulating lacquer would be to use triple insulated or fully insulated wire for the winding, but the coil would then become bulkier and the inductors much too big.

Pin-hole failures are not generally a problem for wire-to-wire contact within the inductor coil, as the adjacent wire is also insulated and it is highly unlikely that two pin-hole failures exactly line up, but they can be a problem for wire-to-core contact, where there is no effective isolation except the organic binder between the iron particles. For low voltage applications up to 24V, the effective resistance of the core compound is high enough that a significant short circuit current does not flow, but if higher voltages are used, then this can lead to failure. The maximum allowed voltage is not always defined in the datasheets and if it is then a healthy margin of safety must be applied as insulation damage can still occur over time.

Another issue that needs to be considered is thermal aging. The problem here is the deterioration of the organic glue binder performance over time. Due to the high frequency alternating magnetic field within the core, there is also a mechanical stress on the iron powder particles which eventually causes the binder to flex and allow adjacent particles to come into electrical contact. This increases the effective size of the conducting particles causing the internal losses due to eddy currents to increase, leading to an increase in the core temperature until thermal runaway occurs.

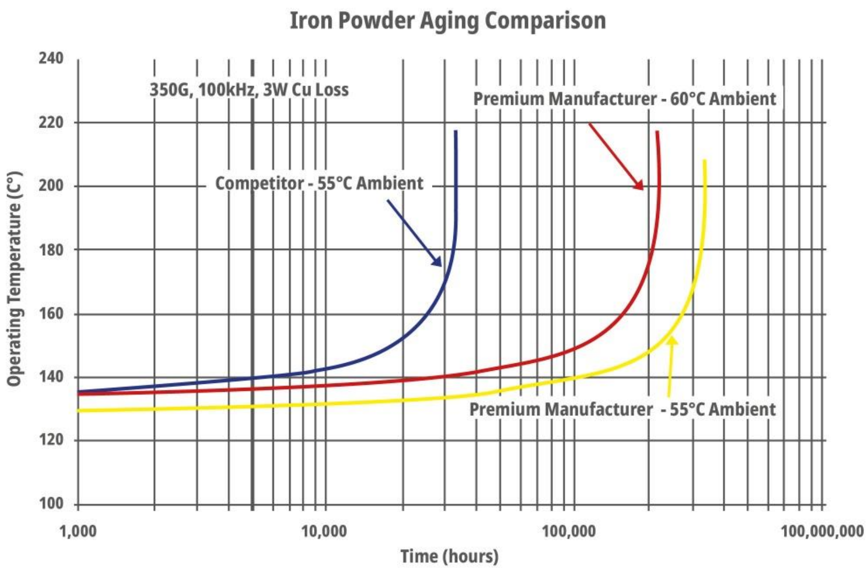

Figure 6: Example of Iron Powder Core Losses over Time

With higher operating voltages, the mechanical stress on the iron powder particles increases, so that this thermal aging effect is accelerated. The example above shows two comparable iron-powder inductors which exhibited similar initial performance, but showed remarkably different core losses over time. The difference is due to the materials used.

6 Conclusion

Switching regulators are widely used to efficiently drop higher DC supply voltages down to low voltage DC supply rails suitable for controllers, sensors and communication-bus applications. Although this technology is not new, there are a number of special techniques, considerations and component choices needed to handle input voltages of 24V or higher to ensure reliable long-term operation.

RECOM manufactures a wide-range of pre-built SMD power modules for 24V or 48V nominal input voltages, output voltages from 3.3 up to 24 VDC and output currents from 0.5A up to 3A, where we have used our extensive experience in design, component specification and component choice to make high-performance switching regulators with a long operating lifetime, even under harsh heavy industrial conditions.

Steve Roberts

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