APPLICATION NOTE

ANS024 | DC/DC Power Modules - Intelligent switching for efficient applications

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1. INTELLIGENT SWITCHING FOR EFFICIENT APPLICATIONS

The digitalization of industrial production, known as Industry 4.0 for short, relies on the networking of machines, devices and sensors with people. Data on the current status of any machine is therefore transparent and can be accessed at any time. Industry 4.0 thus enables a strategy of "predictive maintenance" of machines.

Figure 1 shows a typical application in an industrial environment for a sensor concept supporting "predictive maintenance".

The wireless MCU (cellular module with µC + power stage) records the values of temperature, vibration, shocks and humidity according to a defined time interval and sends them as a data packet to a server, which then processes it further. The data serves as the basis for "predictive maintenance" to determine the condition of the machine and then decides whether maintenance needs to be carried out. The transmitter is supplied via a dc/dc power module with 3.3 V, which draws its energy from a battery. The measurement unit consists of the functional units shown in Figure 1. A dc/dc power module, a transmitter and sensors are placed on a single circuit board. The battery and the antenna are in a housing together with the circuit board. It is precisely at this point that the power supply plays a critical role.

To get the longest lifetime out of a battery you need a highly efficient power supply. This involves both efficiency in terms of the current drawn from the battery and the heat generated by the power module, which can have a negative impact on the service life of the battery. As industrial application environments can have high ambient temperatures, the power module's thermal derating must start as late as possible to ensure full and efficient operation.

If we look at the requirements for the dc/dc converter in the applications described, they can be summarized by the following four criteria:

- Load optimized switching
- Efficient use of energy
- Power sequencing
- Full power over the entire temperature range

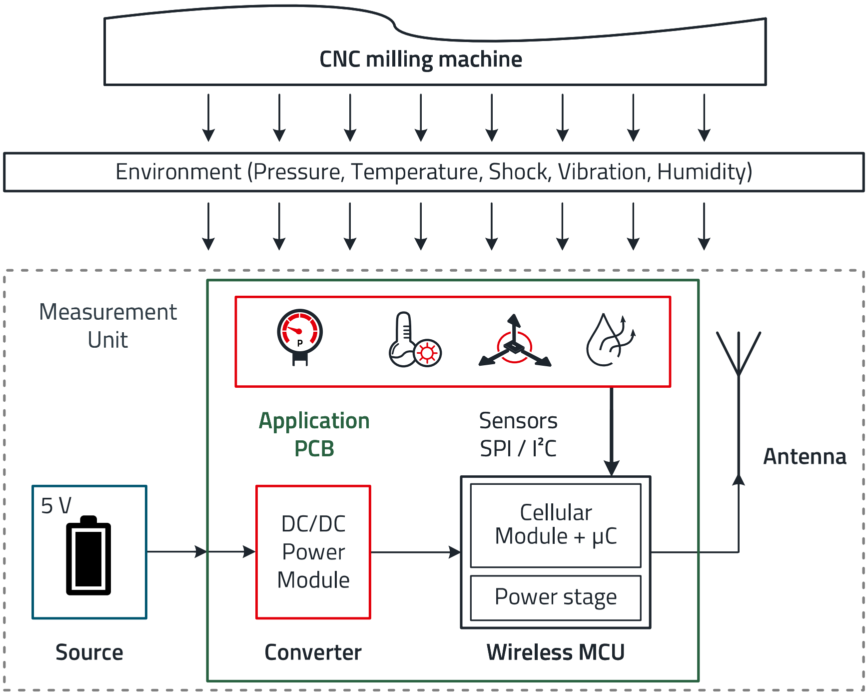


Figure 1: CNC milling machine with predictive maintenance structure.

1.1 Load Optimized Switching

Battery-powered applications, such as the one described, do not always operate under full-load conditions. For example, a measurement application has a higher power requirement during measurement and a lower power requirement between measurements.

The different load conditions can be described as follows:

- The application operates in idle or standby mode → Very low power consumption, µA range
- The application operates in light load mode → Low current consumption, mA range
- The application operates under rated power → Normal current consumption, mA-A range

Optimum switching behavior for a dc/dc power module should adapt dynamically to the load requirements.

Switching losses and line losses are the two most important influencing factors when considering the optimum switching behavior of the power module. Using the example of a buck converter, switching losses occur during the ON phase. Line losses, on the other hand, occur during the OFF phase when the load is supplied with power.

At low loads, the power module should switch little or not at all, as switching is the main cause of losses. To achieve this, adaptive switching behavior is required. Furthermore, an intelligent system must be able to switch automatically between these modes depending on the current load requirement.

Figure 2 (left) shows the "typical" behavior expected of a standard buck converter operating in pulse width modulation (PWM) mode. A variable pulse width is generated while the switching frequency remains fixed. The period duration T_S is the same for all cycles. PWM mode is widely used and is found in most industrial power supplies. This mode is satisfactory for the type of applications that operate under heavy load conditions for most of their operating life. However, applications such as sensors have a different load behavior. Here, light load operation is the predominant operating situation.

The switching behavior must therefore be adapted so that it functions optimally in this load situation. In pulse frequency modulation (PFM) mode, the frequency varies. If you compare PWM mode and PFM mode, as shown in Figure 2 (right), it becomes clear that PFM mode offers greater efficiency, as fewer switching operations take place over time and therefore the switching losses are lower. During the idle time in PFM mode, the module does not produce any unnecessary losses compared to PWM mode.

The VDLM 1710 × 560 power modules automatically transition between both modes of operation based on the load conditions. In light load conditions the module operates in PFM mode. This mode is characterized by reduced current consumption which leads to higher efficiency. For the following explanation, a buck converter as shown in Figure 3 is used as the basis.

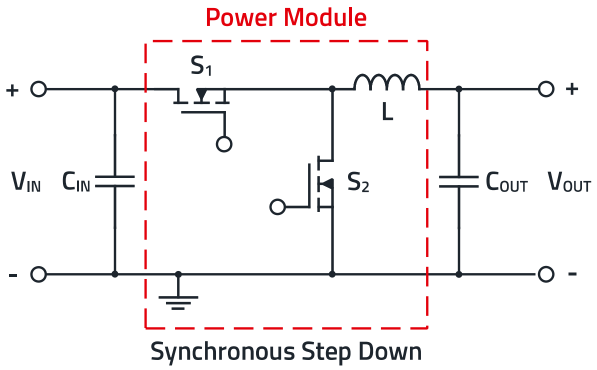


Figure 3: Synchronous Step-Down basic circuit.

In PFM mode, the power module begins by switching S_1 and S_2 as in PWM mode for a short period of time to charge the output capacitor. When the threshold for the output voltage is met, the device stops switching, leaving both S_1 and S_2 off,

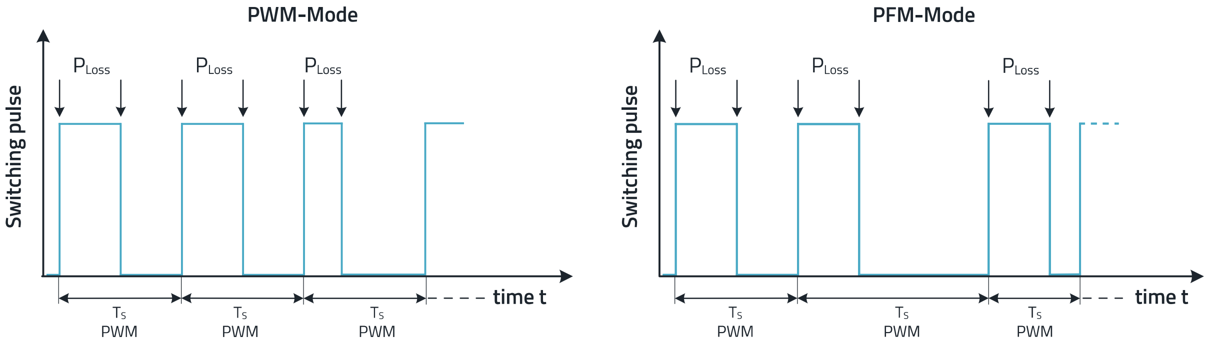


Figure 2: Different load conditions require different switching behavior: PWM mode at full load (left) and PFM mode at low load (right).

and the load is supplied entirely by the output capacitor. During this time, there are no switching or conduction losses within the power module.

While the load is being supplied, the output voltage slowly decreases according to the power consumed. The module monitors the output voltage and when a certain limit value is reached, another burst of switching is triggered, and the cycle is repeated. As the load current increases, the idle time decreases and the switching time increases until the idle time reaches a minimum threshold where the module switches to PWM mode.

1.2 Efficient Use of Energy

How does the efficiency of a power module affect an application that is powered by a battery or rechargeable battery?

The lifetime of a rechargeable battery is significantly influenced by two primary factors:

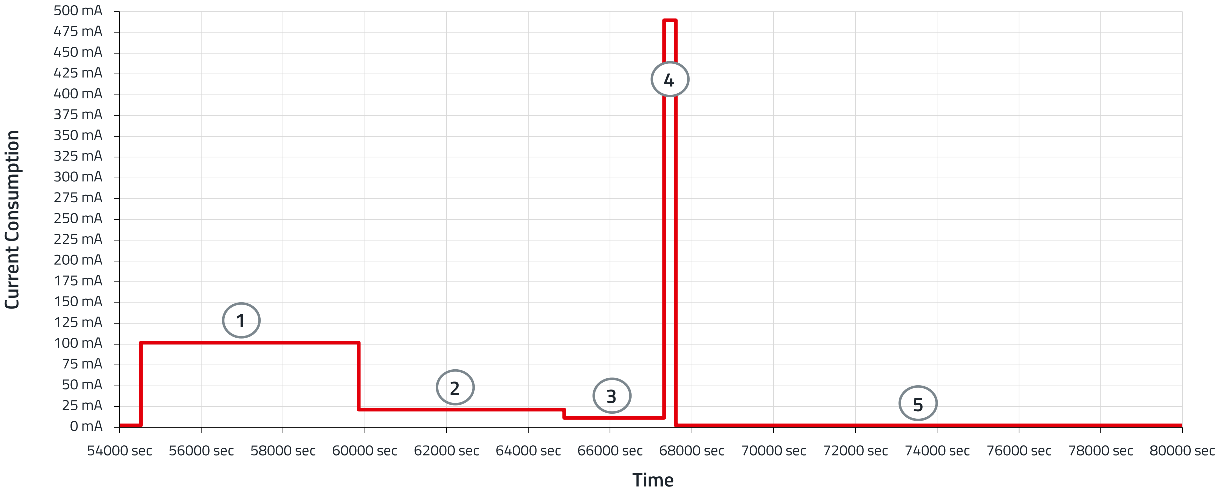
- Number of discharges and charges
- Battery temperature

The lifetime of a lithium-ion battery is strongly influenced by the number of charging cycles. A charging cycle is defined as the discharging and subsequent recharging of a total of 100% of the battery capacity, regardless of whether this is done in one or more partial discharges. In general, the capacity of a lithium-ion battery decreases with the number of charging cycles. This means that the battery can store less energy with each charging cycle.

Decreasing the number of charging cycles must be the goal for battery-driven applications to reduce costs by decreasing maintenance intervals.

Based on the power consumption shown in Figure 4 of a sensor application with a cellular module, the time after which the battery must be recharged at a specified measurement interval is calculated as an example. This is based on different efficiencies of the power module.

The cellular module used is a wireless MCU module. A wireless MCU (microcontroller unit) is a microcontroller that offers integrated functions for wireless communication. This type of microcontroller combines the computing power of a conventional microcontroller with wireless communication protocols such as LTE, Bluetooth, Wi-Fi or others.



1: MCU is ready to collect data, LTE modem is establishing a connection

2: MCU acquires the sensor data (here the temperature as an example), LTE modem is in IDLE mode

3: MCU and LTE modem are in IDLE mode and waiting for the transmission interval

4: MCU sends the data to the LTE modem and the LTE modem sends the data to the remote station

5: MCU is in shut-down mode and the LTE modem is in deep sleep mode

Figure 4: Typical power consumption of a cellular module over time.

The following is a brief description of the progression over time shown in Figure 4, described as the various modes of the MCU and the LTE modem.

Each section is represented here by an electrical charge in ampere hours (Ah). The sum of these values gives the total requirement in Ah for a complete cycle. Based on this value, it is possible to calculate how many cycles can be run before the battery is fully discharged.

Calculation example:

- Battery with 2800 mAh (2.8 Ah) capacity
- Load current of the application of Figure 4
- Power module output voltage 3.3 V
- Efficiency of the dc/dc converter

The Table 1 shows the measured values of the application shown in Figure 1. The values for the power requirement of the power module and the efficiency are based on real measurements.

The corresponding values for the required charge are based on the following equation (1).

$$Q = I_{IN} \cdot t_{IN} \qquad (1)$$

I_{IN} – Input current of the power module typ. [A]
t_{IN} – Duration of the input current of the power module [h]

Each cycle with a duration of approx. 70 seconds according to Figure 4 therefore requires 0.00015683 Ah. If we now assume a measurement interval of 60 measurements per minute, 8 hours per day for a 5-day week, this results in a consumption of 0.376403023 Ah per week.

A battery with 2800 mAh (2.8 Ah), would have to be recharged after approx. 7.4 weeks. To see the effects of efficiency on the time until a recharge would be necessary, the operating efficiencies of each section will be decreased by 2%, 5% and 10% and shown in Figure 5.

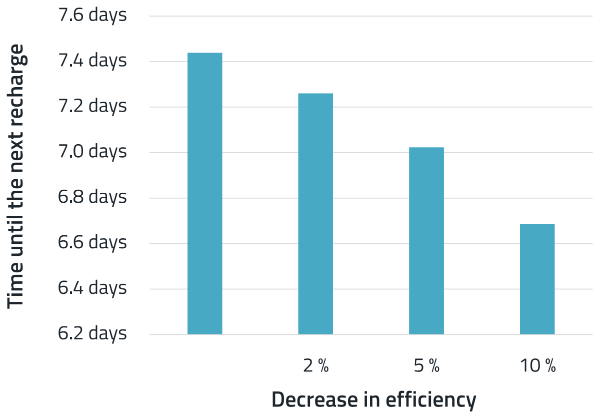


Figure 5: Dependence of the recharging time on the efficiency of a dc/dc converter.

Figure 5 thus clearly shows that the recharge interval is strongly influenced by the efficiency of the power module.

Efficiency impacts more than just charging intervals in a battery-powered system. If the efficiency in a system decreases, that means more energy is dissipated as heat. In a space-constrained application this could mean the entire system is operating at a higher temperature. Batteries are highly susceptible to heat, directly impacting service life. At high temperatures, the chemical reactions within the battery accelerate, which leads to faster ageing of the cells. This can lead to a reduction in capacity and increased self-discharge. It can also lead to degradation of the electrolytes and damage to the internal structures of the battery. In the long term, this can reduce the number of charging cycles that the battery can go through before its capacity decreases to an unusable level. To maximize the service life of a battery, it should ideally be operated and stored at moderate temperatures.

Choosing a power module with the highest efficiency provides benefits in the short-term, as shown in the time between recharges in Figure 5, as well in the long-term by decreasing aging and stress on the battery.

The efficiency curves in the data sheet for the power modules 171010560, 171020560 and 171030560 show various

Section	Charge [Ah]	Input current cellular module typ. [A]	Input current power module typ. I_{IN} [A]	Efficiency power module typ.[%]
1	0.00010464	0.10	0.0709	93.3
2	0.00002008	0.020	0.0144	91.4
3	0.00000494	0.010	0.0073	90.0
4	0.00002629	0.49	0.347	93.5
5	0.00000090	0.000009	0.000068	10
∑	0.00015683			

Table 1: The measured values of the application shown in Figure 1.

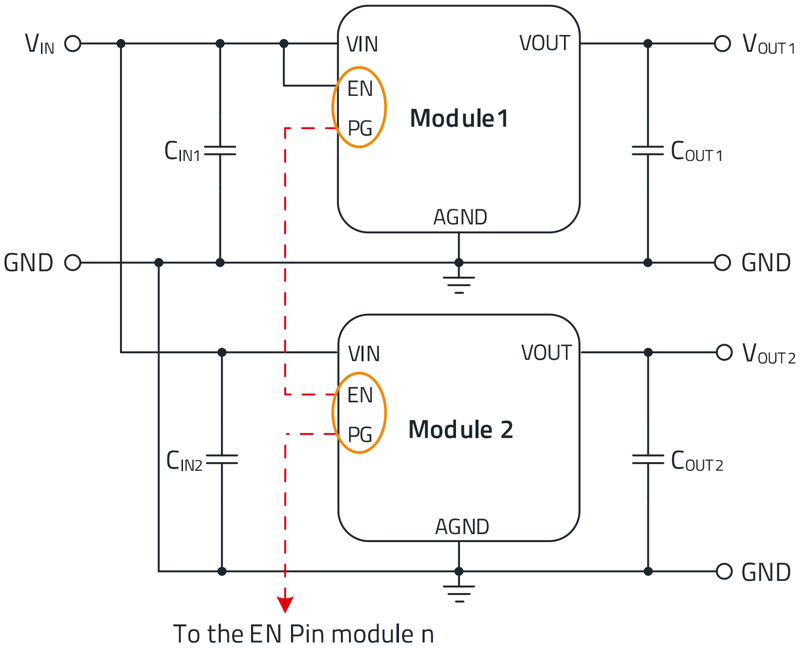


Figure 7: Typical simplified circuit for sequential start-up of the supply voltages using the 1710 × 0560 power module family.

combinations of V_{IN}, V_{OUT} and I_{OUT} in the "TYPICAL PERFORMANCE CURVES"[1].

1.3 Power sequencing

In systems that require several voltages, such as microcontrollers and DSPs, the voltages often must be provided in a specific time sequence. Figure 6 shows an example of this behavior.

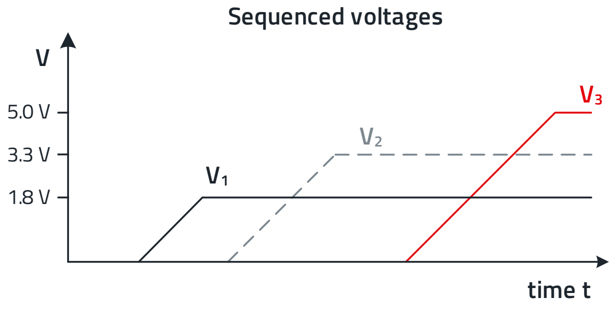


Figure 6: Sequential ramp-up of supply voltages.

The three voltages V_1, V_2 and V_3 are not applied to the load at the same time. Each of the voltages is required after a certain time period. At switch on, only voltage V1 is initiated.
The second voltage V_2 starts to rise after V_1 has reached its nominal value. Likewise, V3 waits for V2 to reach its nominal value before turning on.

To realize this type of voltage sequencing, the power module requires two functions:

- Enable function - Specifies that the converter starts switching when the threshold value is reached.
- Power-Good function - As soon as V_{OUT} is above a certain threshold value, e.g. 90%, the PG pin switches to the high state.

Figure 7 shows power module 1, which is switched on via the EN pin connected to V_{IN}. As soon as the output voltage V_{OUT1} of module 1 reaches the power good threshold, the PG pin switches to the high state. If the PG pin of module 1 is now connected to the EN pin of module 2, the PG signal from module 1 switches module 2 on. Module 2 then begins to regulate V_{OUT2}, realizing a sequential start-up of two separate output voltages.

Another positive effect of switching the modules on sequentially is that the peak input current supplied by the upstream supply, V_{IN}, is reduced. If the modules were put into operation at the same time, their input currents would add up and possibly exceed the limit value of the upstream source.

1.4 Too Hot to Handle: Thermal Derating and Heat Dissipation

Thermal performance and efficiency go hand in hand as every percent decrease in efficiency shows up as heat that must be safely dissipated. Just having a sufficient path for the heat to move away from the module is not always enough, as introducing more heat into the entire system increases the temperature stress on the surrounding components. Hence, the thermal behavior of a dc/dc converter in a space-constrained application is a critical design parameter.

A comparison of the derating curves of the VDMM 171010560 with those of an LDO (low drop-out regulator) in a similar housing design illustrates the negative influence of losses on performance.

Figure 8 shows the negative influence of the power loss on the output current capacity of the LDO.

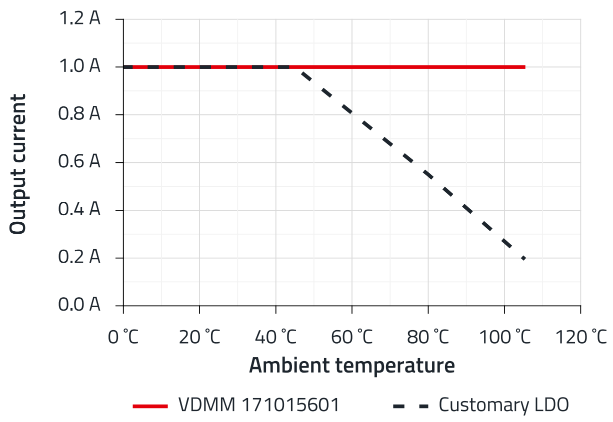


Figure 8: Derating comparison between WPME-VDMM 171010560 and LDO.

The LDO used for the comparison is designed for $V_{IN} = 5$ V and $I_{OUT} = 1$ A. The derating of the LDO already starts at an ambient temperature of 45 °C. At this conversion ratio, the power losses within the LDO are too high to allow for the full output current to be supplied above 45 °C, despite its rating as a 1 A device. Unlike the power module, additional cooling must always be provided for the operation of an LDO at higher ratios of V_{IN} to V_{OUT}.

In contrast, the VDMM 171010560 shows no derating up to 105 °C with an output current of 1 A for $V_{IN} = 5$ V to $V_{OUT} = 3.3$ V, which means that the size, weight and cost of the solution is much smaller compared to a solution based on an LDO.

Over 95% of the power fed into the 171010560 is used to supply the application. In comparison, the LDO uses only 66% of the input power for this task, which is illustrated in the following calculation:

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} \cdot I_{OUT}}{V_{IN} \cdot I_{IN}} \text{ for } I_{OUT} = I_{IN} \qquad (2)$$

$$\eta = \frac{V_{OUT}}{V_{IN}} = \frac{3.3\text{ V}}{5\text{ V}} = 0.66 \qquad (3)$$

V_{IN} = Input voltage [V]
V_{OUT} = Output voltage [V]
I_{IN} = Input current [A]
I_{OUT} = Output current [A]

44% of the power in the LDO is converted into heat, which must be dissipated by the device. The problem arises from the fact that the input and output currents of the LDO are the same and therefore the voltage drop across the LDO with its current must be completely realized as power loss.

Operation with low efficiency leads to the following disadvantages:

- Additional supply energy requirements for operating the application
- Additional cooling either passively (increasing solution size) or active (further increasing supply energy)
- Lower reliability due to the higher temperature load on the system
- Higher development effort and higher costs for thermal management

1.5 Simple, flexible and compact

In conclusion, the use of dc/dc power modules provides significant advantages to industrial and predictive maintenance applications. The ability to adapt dynamically to different load conditions enables these modules to work optimally under both full load and light load conditions. This not only leads to extended battery life, but also to a reduction in thermal stress, which increases the reliability and service life of the entire application. The VDMM series (171010560, 171020560 and 171030560) from Würth Elektronik combines these advantages and thus offers a versatile power supply solution.

A APPENDIX

A.1 Literature

[1] Data Sheets for the MagI³C-VDMM MicroModules from Würth Elektronik: https://www.we-online.com/en/components/products/MAGIC-VDMM_1

[2] Magi3C-Modules in the online simulations-Platform RedExpert: https://redexpert.we-online.com/re/5vUzzckU

A.2 Author

Timur Uludag got his Dipl.-Ing degree in Mechatronics from the University of Applied Sciences in Regensburg, Germany. He then worked for several years as a hardware engineer in the field of switched-mode power supplies and analog circuit design. Since 2015 Timur has been a Senior Technical Marketing Manager at Würth Elektronik eiSos Group in the MagI³C Power Modules business unit. There he specializes in the roadmap planning and market launch of new power modules.

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REVISION HISTORY

Document Version	Release Date	Changes
ANS024a	2026/03/20	Initial release of the application note

Note: *The current version of the document and the release date are indicated in the footer of each page of this document.*