WHITEPAPER

NEAR-ZERO-VOLTAGE SWITCHING IN DATA CENTERS

CONTEG

INTRODUCTION

The amount of data and electronics is constantly increasing, resulting in an ever-increasing need for power sources and for professional power distribution. The latter can be achieved by using PDUs (Power Distribution Units). The power distribution, for example in a data centre, can be provided with extra functionalities by applying switchable outputs in the PDUs. This makes it possible, among other things, to remotely define the start-up sequence of connected equipment, intervene in the event of a peak load or enable the reboot of IT equipment.

This White paper describes the adverse effects of switching users and how to combat these effects by using Near-Zero-Voltage Switching technology.

ADVERSE EFFECTS OF SWITCHING USERS

SWITCH-ON BEHAVIOUR

In general, electromechanical bi-stable relays are used by PDUs to switch between users. The advantage of using electromechanical relays is that the contact resistance is lower than the conductive resistance of a relay that uses a semiconductor to do the switching, thus it minimises switching losses. The advantage of a bi-stable relay is that energy is only used while switching, while a conventional relay consumes energy continuously. An electromechanical bi-stable relay is therefore the most energy-e icient choice.

Virtually all equipment that is switched has an electronic switch-mode power supply. These switch-mode power supplies feature large bu er capacitors and filters that consist, among other things, of coils and capacitors. The filters need to ensure Electro Magnetic Compatibility (EMC) between devices. EMC means that devices need to be able to tolerate each other. In other words, a device is allowed to cause limited disruption, but must also be immune to a certain level of disruption from outside. When switching on a device, the bu er capacitors and filters may generate undesirable behaviour at start-up.

SPECIFICATIONS OF INRUSH CURRENT

Capacitors can generate high switch-on surges, otherwise known as inrush currents. These capacitors are charged when switching on equipment. Although the charging is only very short, it still generates a current.

Power supply and adapter manufacturers generally indicate the inrush current of their product. This is specified as the Maximum Inrush Current. In the case of the adapter in the example below, this is specified as 70 A at 264 V, which applies with a so-called cold start. As mentioned, high inrush currents are caused by capacitors. Sometimes attempts are made to limit the inrush current with the help of resistance with a negative temperature coe icient, known as an NTC thermistor. When this NTC thermistor is cold, it has a relatively high resistance (usually around 5 Ω) and uses this to limit the inrush current. Because current travels through the NTC during operation, it heats up and the resistance decrease. In other words, if the power supply is hot when it is switched on and an NTC thermistor is used, the inrush current will be higher than when the power supply is cold. The manufacturer specifications refer to the current that starts to flow before charging the bu er capacitor. Charging of the bu er capacitor takes place in the first half of the mains voltage cycle. This specification is important in order to determine the number of users that can be connected to one group, which in turn is important for determining the value and characteristics of the fuse to be installed. What many people tend to forget, however, is that an extra EMC - also with capacitors inside - is placed in front of the NTC thermistor. These capacitors are connected directly to the mains power without a current-limiting element.

Even though these capacitors are relatively small in terms of capacity compared to the bu er capacitors, it is o en these capacitors that are the root cause of the high current spikes, as measured in the example further on. And although the current pulse only lasts around 0.5 – 1 ms, it is precisely this current pulse that is responsible for sparks in the relay and for mains distortion, as shown further on in this paper. With such a short pulse duration, there is no need to take this into account when deciding which fuses and wiring to use.

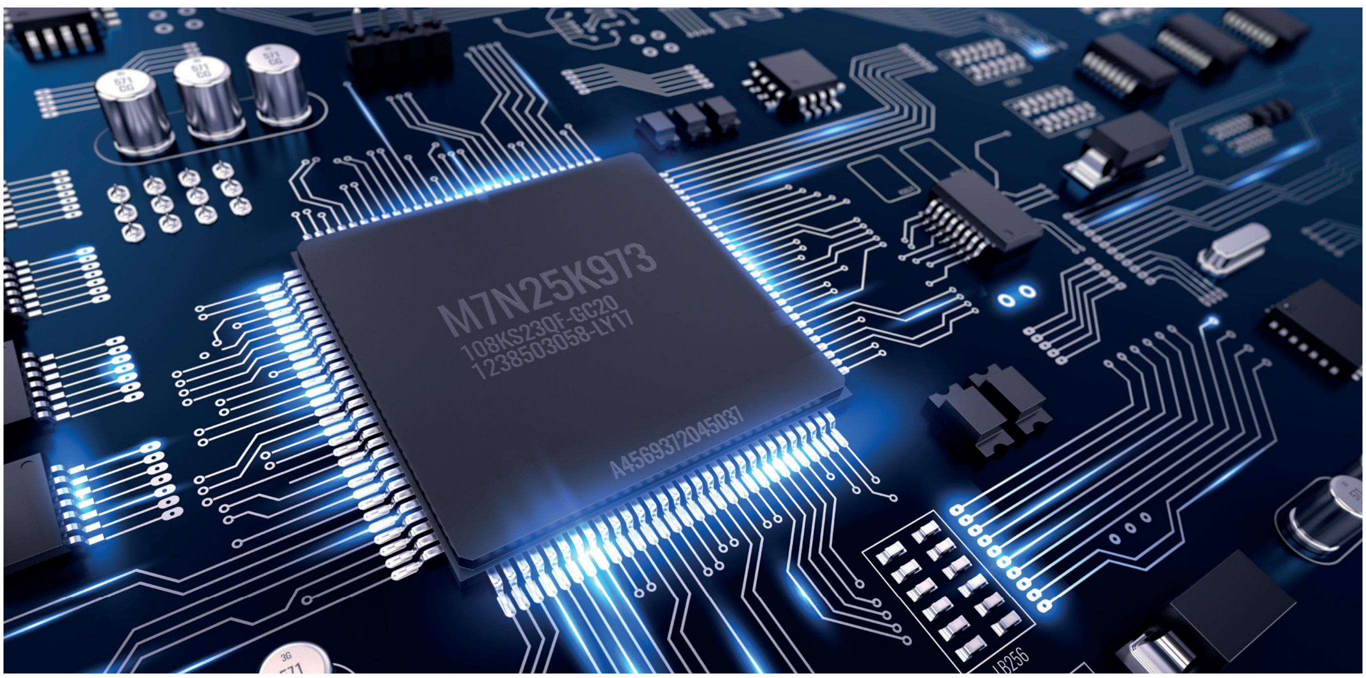
As the voltage increases during start-up, so does the charging current. It can therefore be assumed that the mains voltage is a sinusoidal alternating voltage. When the mains voltage is switched on at the top of the sine wave, the voltage will be at its highest and the current will therefore also be high. The length of the current pulse does get shorter, however. The high inrush currents can eventually have disastrous consequences for the switch relay in the PDU, but they also cause distortion on the mains power. This negatively influences the Power Quality and can disrupt other devices. With Power Quality we generally mean the total quality of the mains voltage. This is directly related to the EMC behaviour. Improving the switch-on behaviour therefore leads to better Power Quality and an improvement in EMC behaviour.

SWITCH-ON EFFECTS

As mentioned, capacitors are o en the cause of high inrush currents. When the power is switched on at the top of the sine wave, the voltage - and therefore also the inrush current - is the highest. The inrush current is lowest when switched on in the zero-crossing of the sine wave. In switch-mode power supplies, capacitors are generally the primary cause of high inrush currents.

SWITCH-OFF EFFECTS

Even switching off a user can have undesired consequences. Switching a user o can result in voltage peaks on the grid. This is caused by the coils inside the filters. When voltage runs through a coil, energy is stored in that coil. If the current is suddenly interrupted, the energy stored in the coil needs to be discharged. The voltage across the coil will then continue to rise until a current can be generated. This is done by forming sparks and continues until all energy has been discharged from the coil. The resulting voltage spikes can be extremely high. As the switch-off effect in the examples mentioned are far less dominant than the inrush effect, we will limit our explanation to the above.



TESTING OF INRUSH CURRENTS

To get an idea of the inrush currents in relation to the normal current usage of a device, tests were conducted on a laptop adapter with 65 W and a kettle with a power output of 2,200 W. Needless to say that the normal current usage of the kettle is many times higher than that of the adapter. A er all, the power of the kettle is much higher. The current usage is calculated according to the formula: $I = \frac{P}{U}$ where I is the current in Ampere, P is the power in Watt and U is the voltage in Volt. The current calculated from this formula is called the RMS current. also referred to as the e ective current. To clarify: with a sinusoidal current of 1 A RMS, the maximum value is Itop=Irms * √2.

With a 1 A RMS current, the maximum value is 1.41 A. The yield of the adapter is approximately 85 %. This means that more power needs to be added in order to reach the required 65 W. At a yield of 85 %, the input power is approximately 77 W.

Based on the formula, the usage current for the adapter is
$I = \frac{P}{U} = \frac{11}{230} = 0{,}334$ A
The peak current is then Itop=Irms x √2 = 0,334 x √2 = 0,472 A

For the kettle the current is: $I = \frac{P}{U} = \frac{2200}{230} = 9{,}56$ A
The peak current is then Itop=Irms x √2 = 9,56 x √2 = 13,52 A

For convenience' sake, these values are summarised in the table below.

	Laptop adapter	Kettle
Power (W)	77*	2200
Mains Voltage (V)	230	230
Current (A)	0,33	9,56
Calculated peak current (A)	0,47	13,52

*See explanation on the yield.

The power of the kettle is about 28 x higher than the power of the laptop adapter. We see that same factor in the relationship between the peak currents. The kettle has a large heating element and has no coils or capacitors. As a result, when we measure the inrush currents, the heating elements do not su er from the effects. The following tests shed more light on the e ect of components such as coils and capacitors.

INRUSH CURRENT TESTS OF LAPTOP ADAPTER

The size of the inrush currents are illustrated in the figures below. The images are made with an oscilloscope, which enables you to measure the voltage at the precise moment the equipment is switched on. It also allows you to measure the current that starts flowing at that moment. On the vertical axes of the images you can see voltages and currents. The horizontal axis shows the time in milliseconds per division (ms/div) or microseconds per division (µs/div). A division represents one square on the oscilloscope. Each division is divided into 10 smaller divisions. The yellow signal shows the voltage. Here, the scale is 500 V/div. The blue signal indicates the current. In this case, the scale is 50 A/div.

The following figures are measurements taken on the laptop adapter at 19 V, 65 W, which is switched on at the top of the sine wave with 230 V mains voltage. See Figure 1. The yellow line is approximately 3/5 of one division at the moment of switching on. A division is 500 V, i.e. the voltage at that moment is approximately 300 V. With 230 V on the mains, the maximum value is theoretically 325 V. The moment of switching on therefore fairly accurately approximates the top of the sine wave.

We can also see a spike in the blue line when the voltage is turned on. This spike measures 3 divisions, which indicates a current peak in this test of 150 A.

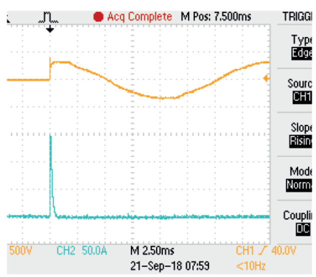


Figure 1

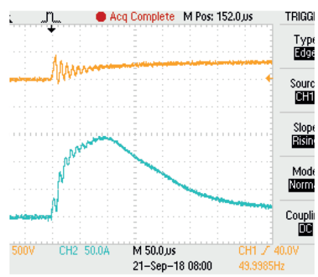


Figure 2

On figure 1 the time basis is 2.5 ms/div. Figure 2 is enlarged, the time basis here is 50 µs/div. Here it is clear that the increase of both the current and voltage is not a flowing motion, but moves in very erratic, fluctuating movements. We call this phenomenon oscillation, or ringing. Oscillation can cause mains distortion and undesirable faults in the power supply.

INRUSH CURRENT TESTS ON KETTLE

A somewhat surprising outcome is such a high inrush current on the adapter that was tested, as 65 W isn't much. The e ective current of the adapter = 0.33 A. If the current would be sinusoidal, the peak current in normal operation would be 0.47 A (see the table on the previous page). So, to measure an inrush current of 150 A is quite unexpected; more than 450 x higher than the e ective steady-state current. To put this into perspective, tests were also performed on an electric kettle. Not that a kettle is something you would normally find in a data centre, but it's the idea that counts. The kettle that was tested has a power output of 2,200 W, almost 29 times greater that the (measured) power of the adapter. The following will prove that the inrush current of such a relatively powerful appliance is actually many times lower than that of an adapter. The same tests as on the adapter were also conducted on the 2.2 kW kettle.

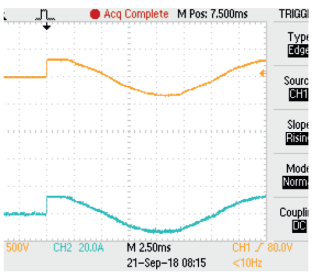


Figure 3

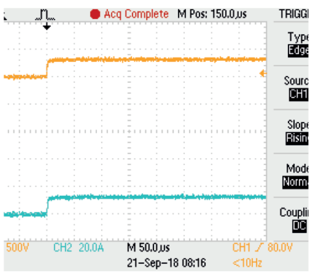


Figure 4

Figure 3 en Figure 4 show the currents of the kettle. The blue line on Figure 3 indicates the current: this is just 13 A. Figure 4 shows the same information, but enlarged. No oscillation or mains distortion can be seen here, which you do see on the adapter tests. In both cases, the device was switched on at the top of the sine wave. This clearly shows that the inrush current of the much more powerful kettle is many times lower than the low-power adapter of just 65 W.

CONSEQUENCES OF HIGH SWITCHING CURRENTS

We mentioned earlier that spikes in switching can have adverse effects. The tests of the laptop adapter show that mains distortion can occur due to oscillations. But also high current peaks can cause voltage drops on the mains. After all, because of the short-lived but high current peaks, the mains voltage can also drop for a short period as the mains also power has a certain impedance. A voltage dip, in turn, can then cause other effects such as oscillation. Mains distortion should therefore not be an underestimated consequence.

Another point is the component overload. A user, i.e. device, has several components that the total input current travels though. Think of components like cables, connectors, inlets, fuses, mains filters, coils and sometimes also rectifier diodes. Extra stress is put on all these components at those moments when they have to carry high inrush currents. This accelerates the wear on the components, reducing their service life.

The third point that shouldn't be underestimated is the impact on the relay contacts that are used to switch the user. No matter how short the switch pulse is, practical tests have proven that the high switching currents can be extremely detrimental to the relay. Contacts can 'burn in' and thus become welded together, as it were. Tests have revealed that in a few cases, the relay contacts were stuck together a er just 10 x switching a 65 W adapter. The possible consequences of high switching currents are summarised below.

Possible consequences of high switching currents:

- Deteriorated EMC behaviour
- Component overload and therefore accelerated ageing of the users
- Risk of switch relay burning in

NEAR-ZERO-VOLTAGE SWITCHING (n-ZVS)

It should be clear that preventing high switching currents offers major advantages. Preventing high switching currents leads to reduced mains distortion and therefore improved EMC behaviour and better Power Quality. It also ensures there is less chance of accelerated ageing of the user and, last but not least, leads to less wear on the switch relay with ultimately a much more reliable PDU as a result.

As explained earlier, with these types of electronic power supplies like the adapter, the inrush current is at its highest when the voltage is highest. An obvious thought would be to switch on at the moment when the voltage is at its lowest. This is the case in the zero-crossing of the alternating current. The zero-crossing can be detected by continuously measuring the mains voltage. By using smart hardware and intelligent so ware, which eliminates occurrences such as switch-on delays in the electromechanical relay, it is possible to perform reproducible switching in the zero-crossing with an accuracy of 1 ms. This technique is called: **Near-Zero-Voltage Switching** (n-ZVS). The name is derived from a similar technique used in switching power supplies.

The effect of switching near the zero-crossing by means of Near-Zero-Voltage Switching is illustrated below. The test is conducted on the same 65 W laptop adapter. This time, however, the adapter is switched on around the zero-crossing, as seen in the figures below. Figure 5 shows the switch-on effect when switching on at the zero-crossing.

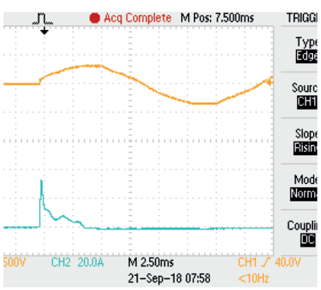


Figure 5

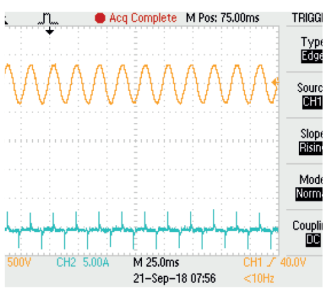


Figure 6

We can see on Figure 5 that switching on takes place a fraction later than the moment of the zero-crossing. The current is now approximately 35 A, which is a huge di erence when compared to the earlier measurement of 150 A. **Also note that the divisions here have been adapted in relation to the previous tests: 20 A/div on the le and 5 A/div on the right.** Figure 6 shows the current and the voltage during continuous operation of the adapter at full power of 65 W. The peak currents at normal, full-capacity operation are around 3 A. The RMS value of the current in Figure 8 is consistent with the calculated value of 0.33 A from the table on page 4. Based on these tests, the advantage of Near-Zero-Voltage-Switching is self-evident. The inrush current of 150 A that was measured earlier has now been reduced to 35 A.

For the sake of completeness, Figure 7 shows the voltage and current when the kettle is switched on in the zero-crossing. We can see that no switch-on spike appears in Figure 7. The current increases proportionately with the voltage, which was to be expected. Figure 8 shows the situation of the 2,200 W kettle in continuous operation.

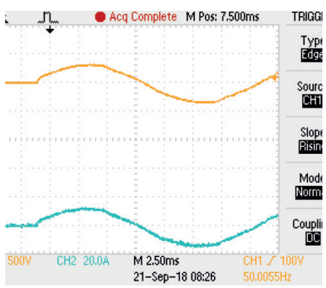


Figure 7

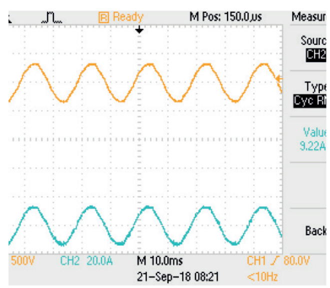


Figure 8

The measured RMS current in continuous operation is 9.22 A (Figure 8). This results in 2,120 W at 230 V, which approximately corresponds to the what it says on the nameplate.

SUMMARY

This whitepaper discusses the adverse effects of switching equipment in a data center. Using practical examples, the term inrush current is clarified and the damaging consequences of high inrush currents are explained in detail. The EMC aspect is discussed, as is the impact on the service life and reliability of both the PDU and of the devices and components that are connected. It is also explained how to combat these adverse effects. Clarification is also given on what happens when an electrical appliance is switched on at the mains. The effect of switching on at the zero-crossing or at the top of the sine wave is illustrated. It is explained what happens when an electrical appliance is switched on in the zero-crossing of the mains power. The technology used, Near-Zero-Voltage Switching, is discussed in further detail.

CONTEG

CONTEG is a Czech manufacturer of IT racks, cooling units and data center accesssories.
The rack PDUs are built to customer specifications as OEM products. You can compare the configuration and production processes with Lego®: a limited number of building blocks can create an unlimited number of final products.
CONTEG rack PDUs are adapted to suit the electronic infrastructure of your data centre instead of the electronic infrastructure being adapted to the rack PDU. You can find more information at www.conteg.com

CONCLUSION

The switch-on behaviour of electronic power supplies often brings with it unexpected and undesirable effects. Inrush cur rents, although short in duration, are o en much higher than one might think, and are also o en much higher than the ma nufacturers' information suggests. By switching more intelli gently, these high inrush currents can be significantly limited. Switching in the zero-crossing, for example, offers many ad vantages. It reduces the risk of failure in the relay or connected equipment that is switching, and can also lead to less mains distortion, improved EMC behaviour and the associated better Power Quality. N-ZVS: Near Zero Voltage Switching is the techno logy best suited to accomplish this.

Publication: July 2019

CONTEG, spol. s r.o.
Stetkova 1638/18
140 00 Prague 4

Czech Republic

Tel.: +420 565 300 358
info@conteg.com
www.conteg.com

CONTEG