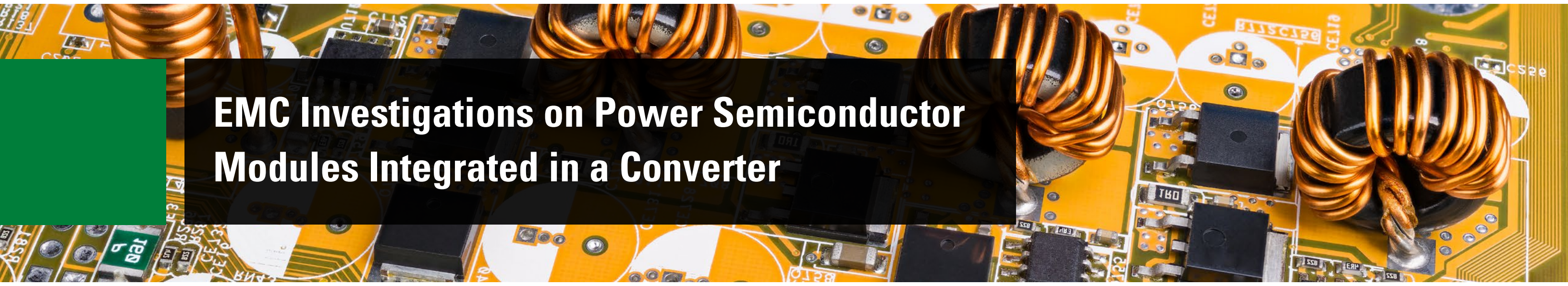

EMC Investigations on Power Semiconductor Modules Integrated in a Converter

Objectives

This document deals with electromagnetic compatibility regarding power semiconductors and converter setup, and summarizes the electromagnetic effects on rectifier topologies, which shall be considered during the converter design phase.

Applications

- AC-DC-Conversion
- Industrial Drives
- Switch-Mode Power Supplies (SMPS)
- Uninterruptible Power Supplies (UPS)

Target Audience

This document is intended for engineers involved with and interested in designing power electronic converters.

Contact Information

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Abstract

Power electronic devices are transmitters and receivers of electromagnetic disturbances. This application note aims to give an insight into some of the core aspects of parasitic capacitive coupling on several circuits between different voltage levels. For the investigation, simulations were carried out and measurements conducted in power semiconductor modules and on power and control terminals which are difficult to do during a common converter's development phase. Further investigations deal with the emission of electromagnetic disturbance by different input rectifiers. In this way, the potential of noise reduction by semiconductor technology is analyzed. Finally, some applicational hints are offered for choosing an appropriate topology when designing a converter.

1. Introduction

The subject of Electromagnetic Compatibility (EMC) has gained importance due to recent technical developments. Most electrical devices to be sold in the European Union must meet EMC requirements. To keep interference between electronic devices under control and avoid malfunction, it is important and economical to consider aspects of EMC during the entire process of development and production.

According to the standard IEC 61000, a phenomenological proceeding has been chosen for the investigations described here. Several kinds of disturbances have been simulated and measured. This approach reveals qualitative relationships determined by physics and tendencies useful for designing power electronics. The shape of the signals applied to the test samples does not necessarily correspond to the standard's requirements. Standardized tests only make sense when carried out with a particular converter for a certain application, completely equipped including case and filters. European generic standards and product standards then define which products must be able to pass specific tests and the levels that must be used for them.

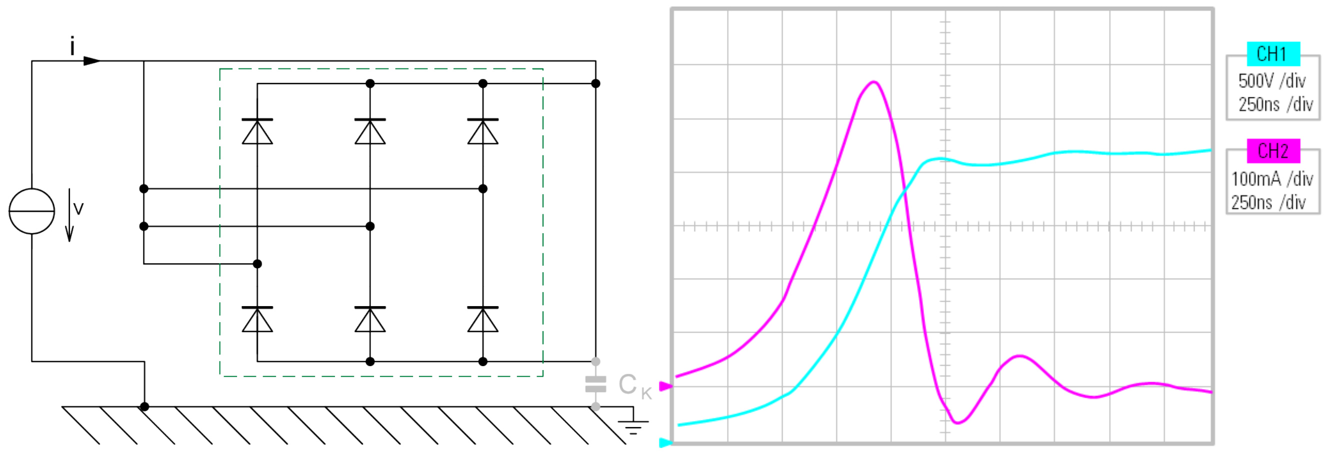
The data presented here is intended to be reproduceable; however, results may differ due to different conditions. When measuring parasitic effects, the coupling by the measurement equipment must be avoided. Therefore, the arrangements and test setups were carefully designed, especially with reference to the ground connections. Where possible, additional reference measurements have been conducted.

2. Experimental Results and their Consequences for Designing for Converters

This section describes some parasitic effects occurring within the converter and gives suggestions on how to evaluate and avoid consequences on the performance.

2.1. Parasitic Capacitive Coupling between Terminals and Heatsink

The setup chosen to demonstrate parasitic capacitive coupling between the terminals and the heatsink is a three-phase rectifier module connected to a basic heat sink. All terminals of a three-phase rectifier are joined and connected to the positive pole of a voltage source with Voltage (V). The heatsink the module is mounted on is connected to the negative pole and grounded. Thus, conducting a capacitive displacement current through the parasitic Coupling Capacitance (C_K) towards the heatsink can be observed. **Figure 1** holds the schematic of the arrangement used and the measured results.



(a) Schematic (b) Measurement

Figure 1: Capacitive Coupling between Terminals and Heatsink

The current can be estimated using **Equation 1**:

$$i = C_K \cdot \frac{dv}{dt}$$

Equation 1

The measurement of voltage and current is plotted on the right side of **Figure 1**. The voltage rises to 2500 V with a maximum change rate of dv/dt = 5 kV/µs and a current value of i = 0.56 A occurring at the same time. Using **Equation 1**, the coupling capacity can be calculated to be:

$$C_K = \frac{i}{\frac{dv}{dt}} = 112\ pF$$

Equation 2

This is the coupling capacitance (C_K) between the power terminals and the heatsink of the rectifier module. If the heatsink is connected to ground, the capacitance to ground is determined this way. The size of this coupling capacitance is an important parameter to dimension input filter capacitors, especially Y-capacitors. A comparative measurement took place using an RCL-Meter. The coupling capacitance has been determined as C_K = 125 pF which is in the same range as in **Equation 2**.

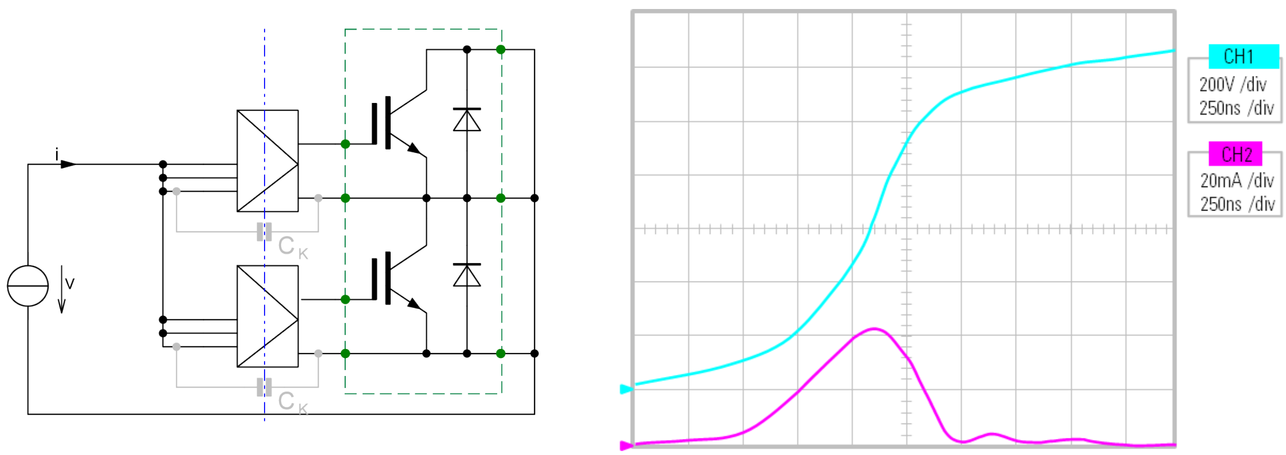
As all material parameters and the geometry of the power module are known, the coupling capacitance (C_K) can also be calculated. The module is insulated from the heatsink by an aluminum-oxide ceramic substrate with an area of A = 25 · 34 mm²,
a thickness d = 0.63 mm and a relative dielectric constant of εr = 9.5. Considering the similarities, the setup can be interpreted as being a plate capacitor. With **Equation 3**, this capacity can be calculated to be:

$$C_K = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} = 114\,pF$$ **Equation 3**

This simple calculation is suitable to determine the range of coupling capacitance of a power semiconductor module and is preferred in comparison to **Equation 2**. In case the DCB substrate is not visible due to a metal base plate, it can be assumed that the DCB is slightly smaller than the case, which may be helpful for this evaluation.

2.2. Parasitic Capacitive Coupling between Power Terminals and Control Terminals

Another parasitic capacitive coupling occurs between the power circuit and the control unit on the driver board, for being the interface between the low- and high-voltage sections. Although common gate-drivers require galvanic insulation, the control unit is influenced by the power section due to capacitive coupling. This is independent of the driver scheme in use if galvanic insulation as sketched in **Figure 2** is involved:



(a) Schematic (b) Measurement

Figure 2: Capacitive Coupling between Power and Control Terminals

The driver board includes galvanically insulated power supplies and signal transmission. Physically, this represents an interface between the control unit operating at low-voltage logical signals and the high-voltage side of the power circuitry. For the measurement, all terminals of the low-voltage side as well as all terminals of the high-voltage side are connected. In this way, the sum of all coupling capacities including the ones from the DC-DC converters and the hardware to feedback fault signals are measured. The pulse-voltage (V) and Current (i) are plotted in **Figure 2**.

The voltage change rate dv/dt exceeds the values to be expected during regular operation. The coupling capacitance can again be derived from **Equation 2** and results in C_K = 33 pF according to **Equation 4**.

$$C_K = \frac{i}{\frac{dv}{dt}} = \frac{42mA}{1.25\frac{kV}{\mu s}} = 33\,pF$$ **Equation 4**

The value gained from a comparative measurement by a RCL meter is lower but again in the same range. High dv/dt can create an issue with high displacement currents being forced through the insulation in the coupling capacitance according to **Equation 1**. With a voltage change rate of 100 kV/µs, a 10 pF barrier capacitance would pass one ampere of current, circulating through the primary side of the gate drive circuit, potentially creating heat and disturbances. For these reasons, reducing the coupling capacitance to the lowest possible value is favored.

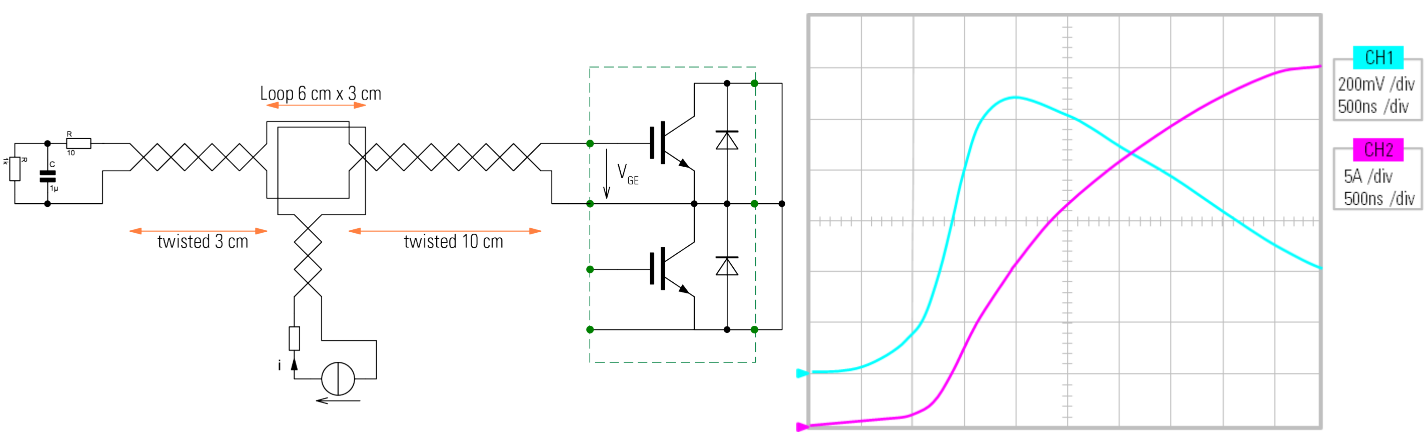
2.3. Parasitic Coupling into the Wires between Driver and IGBT Module

It is considered best practice to stick to a few golden rules in designing power electronic applications and testing power electronic components, including, but not limited to:

- Use of short wires to connect the gate driver
- Use shielded cables or at least twisted pair wires with a minimum of space in between
- Use wires with a sufficiently low resistance able to carry the expected currents or current peaks without too big a voltage drop
- Provide sufficient insulation as the wires might touch any conductor at high voltage levels
- As semiconductor devices to be driven are sensitive towards electrostatic discharge, provide sufficient means for avoiding high voltages, which is usually done by connecting anti-serial Zener-diodes in parallel to the gate-emitter or gate-source terminals

Of course, this short list does not intend to replace more detailed manuals about the design of converters. The experiment carried out, depicted in **Figure 3**, underlines the necessity of following these rules and shows the consequences when these concerns are dismissed.

An IGBT is connected to a driver circuit supplied by 0 V with a realistic impedance. For the connections, twisted pair wires are used as recommended. Additionally, there is a loop formed between the wires as seen in **Figure 3** and in parallel, there is a second overlapping loop, carrying a current. The parasitic coupling of the galvanically isolated circuits in this arrangement is mainly inductive. The effect of the inductive coupling when applying a Current (i) is clearly visible in **Figure 3.** The Gate-Emitter voltage (V_{GE}) of the IGBT has been measured inside the module of a nearby IGBT chip and is illustrated in **Figure 3** at Channel 1 (CH1) while Channel 2 (CH2) represents the current causing the effect.



(a) Schematic **(b) Measurement**

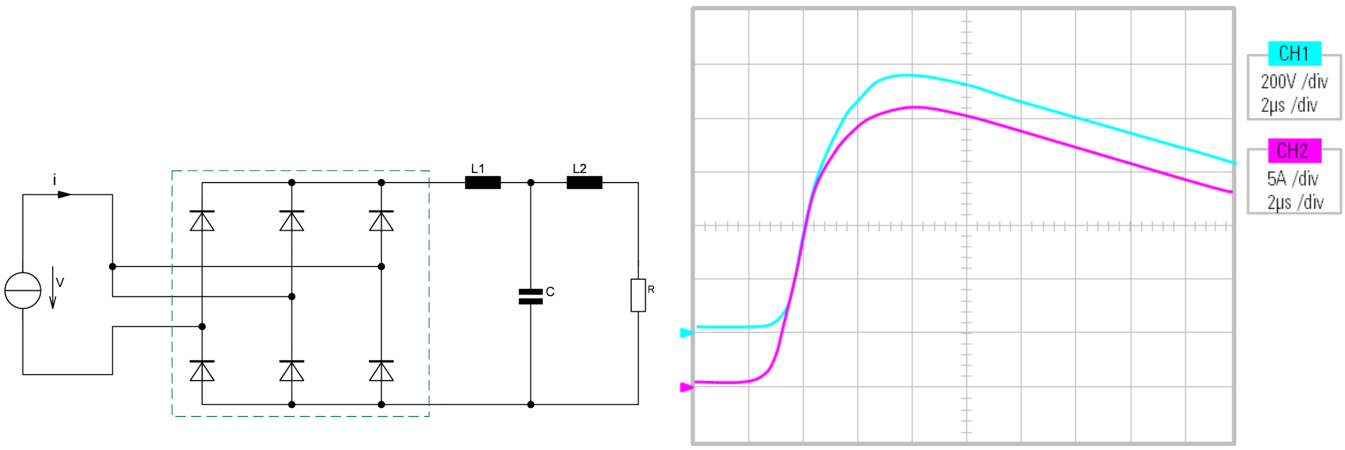
Figure 3: Coupling into the Wires between Driver and IGBT-Module

The measurement verifies common concerns. A voltage peak of $V_{GE,pk}$ = 1.1 V occurs in the Gate-Emitter voltage, displayed in **Figure 3** Channel 1 (CH1). At first glance it might appear as not much but when considering that the power terminals of the IGBT module were terminated by a low impedance, it becomes obvious that the boundary conditions during real-world operation are different. In a worst-case scenario, the switching state of the transistor may no longer be controlled by the gate driver but by electromagnetic distortions. In addition, gate emitter voltages may not correspond to the desired value. Handling faults like over currents can get more challenging and higher switching losses may occur.

The value of the Gate Emitter threshold voltage ($V_{GE(th)}$) specified in the IGBT data sheets helps to evaluate the intended and tolerable gate emitter voltages. However, the sensitivity for disturbances by electromagnetic radiation must always be minimized and care must be taken for an appropriate design of power sections including the gate drives and the surrounding interconnections.

2.4. Effect of Disturbances in the Grid to the Input Rectifiers

The standards IEC 61000-4-4 and IEC 61000-4-5 describe tests to evaluate whether a device is sufficiently resistive against the phenomena of burst and surge. Correlating tests are carried out by applying high voltage peaks onto the lines, especially the supply lines of a device. The supply lines for this experiment described here, are the inputs to a three-phase rectifier bridge. A voltage source has been connected to the input terminals of the bridge. The load at its DC terminals consists of a resistor, a capacitor, and inductances as seen in the schematic in **Figure 4**. Variable configurations have been tested; one plot with a resistive-capacitive load, which means the inductances were zero, is given in **Figure 4(b)**.



(a) Schematic, $L_1 = L_2 = 0$, $C = 11nF$, $R = 47\ \Omega$ **(b) Simulation**

Figure 4. Simulation of Disturbance in the Grid for a Rectifier

This simulation shows that the change rates dv/dt and di/dt along the rectifier diodes are small, which means that diodes are not a critical component being easily damaged. There must, however, be a current sink somewhere on the AC– or the DC–side to prevent the voltage from rising to a level exceeding nominal voltage on the semiconductors. With respect to the current peaks, possibly only limited by the internal resistance of the voltage source, diodes usually provide a high overcurrent capability as specified in their datasheets. If the impedance of the DC load, the inductance on the AC side, and the level of voltage to be applied are known, a dimensioning of the input rectifier is possible. In general, only a few problems may arise here.

Of course, the electronic circuitry on the DC–side must as well be capable of withstanding the disturbances passing through the rectifier. It is important to consider that during operation, additional commutations might be caused by voltage peaks being higher than the voltage of the grid. In this case, the switching losses of the diodes increase, and input voltages may be distorted by the commutations similar to a transient effect described in section 2.5. Depending on the rise time of the voltage peaks, which for burst and surge measurements according to the standards is shorter than applied here, it may be advantageous to use fast recovery diodes.

IEC 61000-4-11 describes tests for voltage interruptions, drops, and variations. Depending on the internal energy storage in the DC–Link, these effects may cause malfunctions. The input rectifier can be concerned in two ways:

- In case the DC-Link has some energy stored, the control current will rise when voltage decreases, which leads to higher conduction losses of the rectifier. The possible overcurrent can be calculated and thus, an estimation of how to dimension the rectifier is easily done.
- In case the voltage reaches its nominal value after a short period of grid damp, an overcurrent through the rectifier due to charging the DC–link may occur. This is the subject which must be considered anyway during power up.

Correlating tests again mainly concern the electronics on the DC–side while the input rectifier proves to be quite rugged.

2.5. Emission of Disturbances to the Grid by Input Rectifiers

The emission of voltage harmonics to the grid is specified in the standard IEC 61000-6-3. Usually, an input rectifier is the interface of a device towards the grid. Especially during commutation, the recovery phase of the diodes causes current and voltage peaks. So, a test has been carried out according to **Figure 5**.

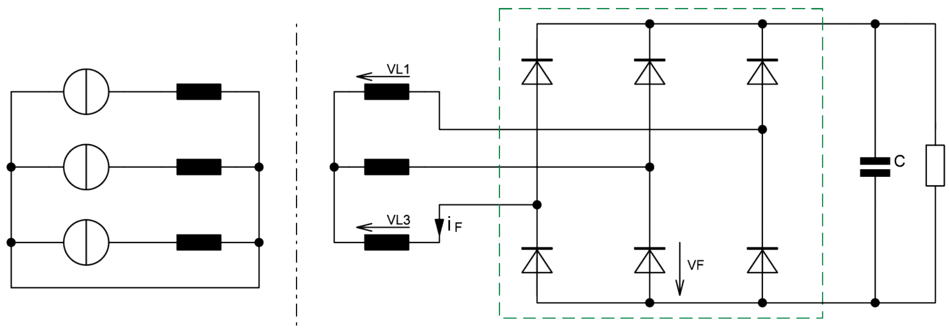
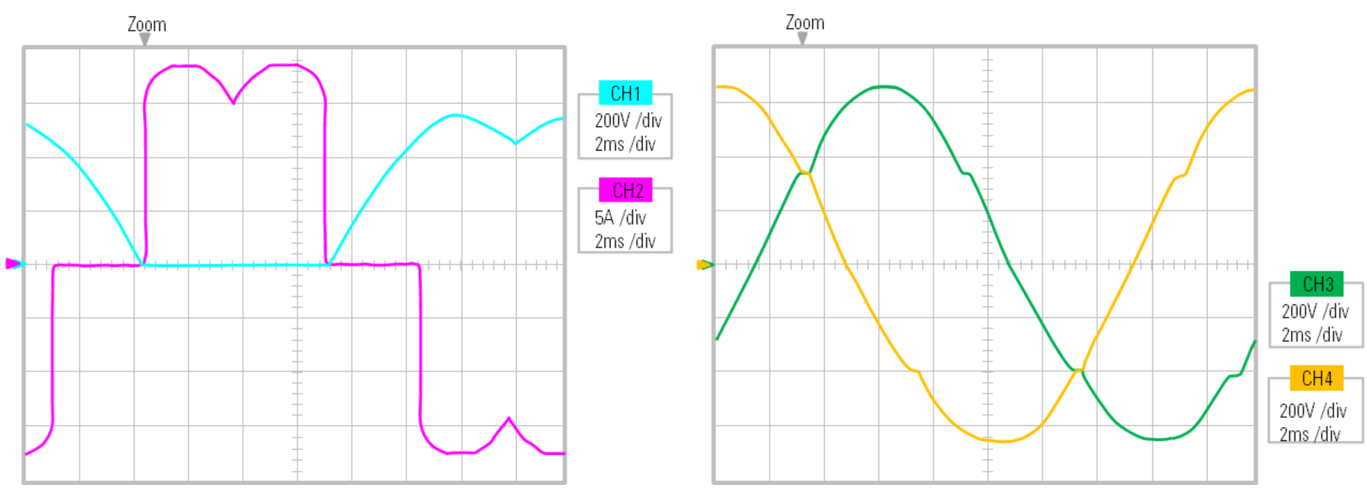


Figure 5: Schematic of an Input Rectifier with a Transformer providing a defined Impedance; C = 22 nF

The grid, symbolized by three voltage sources in **Figure 5**, is connected to a transformer with unity transfer ratio. On its secondary side, there is a three-phase system of 400 V, 50 Hz with a defined impedance mainly determined by the transformer. This way, voltage harmonics can be measured according to standardized measurement conditions, independently from the impedance of the grid. A three-phase rectifier module is connected to the transformer – on its DC side there is a small DC-link-capacitor and a resistive load resulting in a power output of Ptot = 9 kW. The measurements are taken under the rectifier's nominal operational conditions.

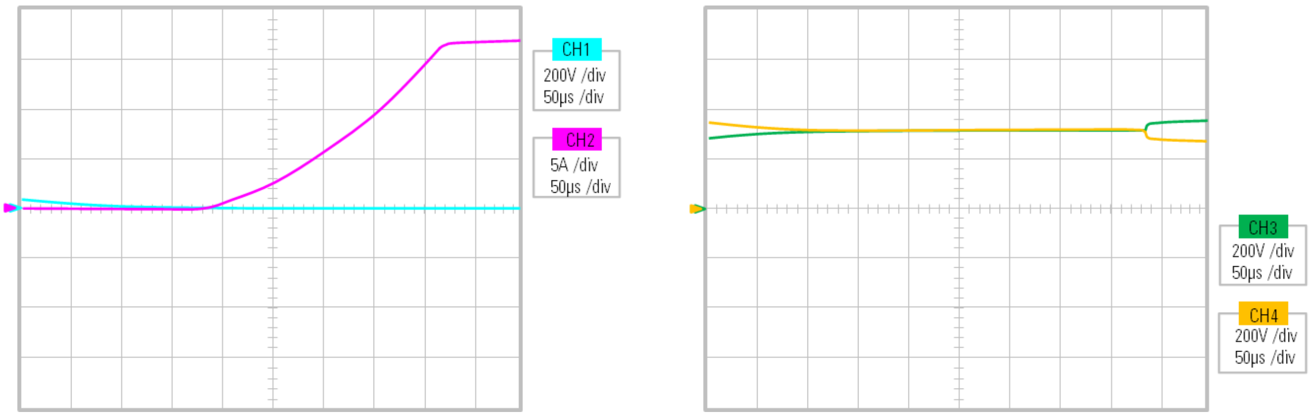


(a) Measurement of the Voltage and Current of the Input Rectifier Diodes **(b) Source Voltages on the Transformer Windings**

Figure 6: Measurements on the Transformer and Input Rectifier Diodes

Figure 6(a) depicts the Voltage (V_F) and the Current (i_F) through the diodes. The voltage (V_F) cannot be negative, as in that case the diode becomes conductive, and the voltage drops to the diodes forward voltage (V_F). The plots for the other diodes in the rectifiers bridge would be identical, but phase-shifted for reasons of symmetry. The phase voltages VL1 and VL3 according to **Figure 5** are depicted in **Figure 6(b)**.

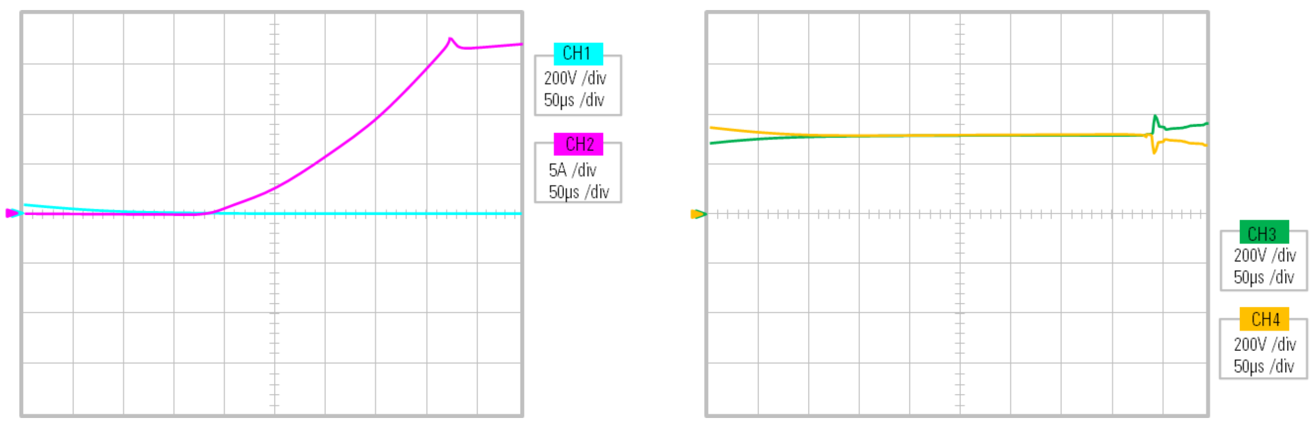
The plots in **Figure 7** and **Figure 8** detail the interval in which the current commutates, marked as Zoom in **Figure 6**. The measurement in **Figure 7** examines the behavior of Fast Recovery Epitaxial Diodes (FRED), in contrast to the measurement in **Figure 8** which has been done with a module equipped with standard rectifier diodes. There is no difference seen in the current rise-time between those technologies as the current change rate di/dt is mainly determined by the external inductances. In both cases the inductance is given by the transformer and the wires to the power section, which both remained identical.



(a) Voltage V_F and Current i_F (b) Voltages VL1 and VL3 on the Transformer Windings

Figure 7: Zoom on Measurement of Figure 6 using Fast Diodes (FRED)

However, there is a difference in reverse recovery of the diodes: The FRED recovers as fast and as softly as desirable and does not have any transient peaks at all according to **Figure 7**, whereas the standard rectifier diode's turn-off features a peak of reverse current which is added to the forward current of the conducting diode. The effect of reverse recovery as described above can be seen here as well: There are voltage peaks during reverse recovery of the standard rectifier diodes, seen in **Figure 8**.



(a) Voltage V_F and Current i_F (b) Source Voltages VL1 and VL3 on the Transformer Windings

Figure 8: Zoom on the Measurement of Figure 6 using Common Rectifier Diodes

These results have been confirmed by measurements of EMC emissions taken according to the IEC 61000-6-3 standards with identical packages, one being equipped with a standard rectifier diode, the other with FRED technology. Emissions of voltage oscillation were significantly lower with the FRED–based rectifier. Thus, expenses for filtering can be minimized by using power semiconductors of an appropriate technology. The relationship between the increase in forward voltage using FREDs compared to the decrease in emissions will help determine the type of rectifier to use.

Littelfuse standard rectifiers of the type VUO and FRED rectifiers of the type VUE are offered in the same package. The designer has the advantage of complete compatibility of both families and thus can easily adapt his products to the requirements.

3. The Importance of Choosing an Appropriate Topology

This subject is discussed with special regard to input rectifiers, for which different applications may require a suitable topology. Each of them has specific characteristics, both economically and technically. Regarding semiconductor modules, because there are only a few external connections, there is no need for galvanic insulation to the heatsink; cost intensive work for construction and mounting is therefore minimized. In addition, there are important technical advantages – for example, the low inductance of the electric connections inside the modules, including the ones between paralleled semiconductor chips. For these reasons, power semiconductor modules for general applications are an advantageous solution.

There are several possible topologies for input rectification to be considered.

3.1. Single or Three-phase Rectifier Bridge

Static rectification as in **Figure 5** is the most basic solution. The rectifiers are quite rugged and don't need any control. Depending on inductances and capacities in the circuit, the startup setting must be adjusted to avoid destructive current peaks when connecting to the grid. Here, a voltage source is connected to capacitors in the DC-link being a voltage source as well. The main disadvantage of this topology is the high harmonic content in the AC currents. It can be estimated by spectral analysis of the currents with the assumption that the diodes are ideal switches. The harmonic content of line currents can only be reduced by filters, which may get quite big, depending on the power levels to be handled. The effects of commutation as described in section 2.5 are an additional aspect.

Rectifier diodes are available as discrete components or in a variety of rectifier modules.

3.2. Rectifier Bridge with Thyristors

Replacing half or all of the diodes in **Figure 5** by thyristors offers the opportunity to control current flow and DC-voltage respectively. Evidently, there must be a control unit for the thyristors, within which the feature for startup must be integrated. The problems of harmonic content and voltage distortion remain. Furthermore, the circuit consumes additional reactive power when the thyristors are triggered with delay. Again, there may be a high expense for filters, at least for the input inductance.

The construction of a rectifier bridge can be done with discrete power semiconductors or with thyristor– and thyristor–diode modules.

3.3. Self-commutated Rectifier Bridge

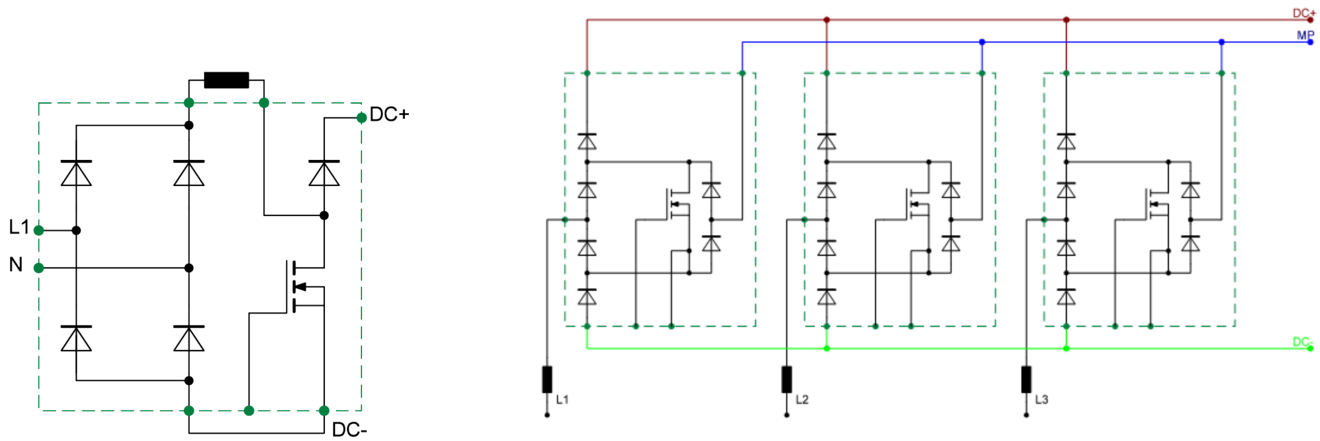
Adding transistors anti-parallel to the diodes in **Figure 5** leads to the schematic of a self-commutated rectifier bridge. With an appropriate control unit, this circuit can operate as a rectifier with unity power factor and with a low harmonic content in AC currents, depending on control strategy and switching frequency. On behalf of the latter, measures of filtering for conducted and non-conducted high frequency emissions may be necessary. Compared to filters for mains frequency, these components usually are quite small but not always easy to design.

The diodes used need to be fast diodes; often, FREDs as described in section 2.5 are preferred. Usually, the transistors are MOSFETs or IGBTs. All of them are available in discrete versions and in a variety of standard modules. This type of module can be used in inverters and DC-DC converters as well and thus, is very universal.

3.4. Rectifiers for Power Factor Correction (PFC)

Static rectifiers require reactive power from the grid, which is detrimental, and on an industrial scale may even be expensive. Reactive power is involved whenever the power factor in the AC–supply is different from “1”. While the self-commutated bridge can be used to create unity power factor, it requires controlling six power semiconductors.

There are other solutions that are simpler to control than the self-commutated bridge with comparable operational behavior and superior in relation to the diode and thyristor–diode-bridges. The schematics for a single–phase and a three–phase solution are presented in **Figure 9**.



(a) Single-phase (b) Three-phase, known as Vienna Rectifier

Figure 9: Schematics for Power Factor Correction

Both circuits operate in continuous current mode which is favorable considering lower electromagnetic emissions due to lower current transients in the lines. The principles of operation cannot be explained here in detail; the single-phase configuration is well documented in References [1] and [2], while the three-phase circuit is documented in References [3], [4], [5], and [6]. The VUM 24-05 in **Figure 10**:**(a)** and the VUM 25-05 in **Figure 10**:**(b)** are single-phase versions, which can be controlled by a custom IC with a minimum of peripheral components.

(a) Single-phase PFC-module VUM 24-05N (b) Vienna Rectifier Phase-leg VUM 25-05E

Figure 10: Cost-efficient Solutions for Single-phase or Three-phase Rectification and Power Factor Correction

In this manner, a cost-efficient solution for an input rectifier of high quality is achieved. Littelfuse also manufactures modules containing one bridge for the three-phase rectifier, which are easily paralleled on the DC-side to achieve the circuit shown in **Figure 9**.

As mentioned in section 2.5, certain applications must meet IEC 61000-6-3 standards, which specify harmonic content of line currents and voltages to the grid. The decision regarding the rectifier topology to be used depends on the technical requirements and on cost. In addition, devices like welding machines often benefit from allowing supply via a standard plug of 230 V, 16 A. The device is best matched to this condition if it operates with unity power factor and a very low harmonic content of line current because reactive power consumption would superfluously reduce nominal power due to the current limit. In this and comparable cases, solutions with power factor correction as mentioned in section 3.4 are advantageous.

Similar considerations concern questions of topologies other than rectifiers. There is a variety of possibilities; for example, considering resonant circuits with zero voltage or zero current switching. A profound discussion would however exceed the limits of this application note. The users of power semiconductors are asked to contact their semiconductor manufacturers. This cooperation offers the opportunity to get informed about approved and new approaches.

4. Summary

Investigations on electromagnetic compatibility have been carried out. The results ascertain that many questions can be answered by quite simple calculations or estimations based on well-known physical laws. Following some simple rules in the design of converters is very helpful in achieving appropriate operational behavior. Finally, it is important to use power semiconductors in a circuit that is adequate for the application. Due to the variety of discrete power semiconductors and semiconductor modules, the selection may be challenging but when well done, will lead to results favorably matched to each application.

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