Investigations on Electromagnetic Compatibility of Power Semiconductor Modules Integrated in a Converter

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Abstract

Power electronic devices are transmitters and receivers of electromagnetic disturbances. In this paper investigations on some aspects of this subject are described: The effect of external disturbances on several circuits has been evaluated; some measurements have been taken inside power semiconductor modules which usually is impossible during development of a converter. Further investigations deal with the emission of electromagnetic disturbance by different input rectifiers; this way the potential of noise reduction by semiconductor technology is shown. Finally some applicational hints are given for choosing an appropriate topology when designing a converter.

1 Introduction

The subject of electromagnetic compatibility EMC becomes more important due to the recent technical development. Most electrical devices to be sold in the European Union have to meet the requirements of EMC which is conformed by the sign "CE". To avoid malfunctions of a device or the disturbance of other devices it is important and economic to consider aspects of EMC during the whole process of development and production.

According to the standard IEC 1000 a phenomenological proceeding has been choosen for the investigations described here: Several kinds of disturbances have been simulated and measured. This approach shows qualititive relationships determined by physics and tendencies useful for designing power electronics. The shape of the signals applied to the test sample however does not necessarily correspond to the standard; 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 which tests and what levels have to be used for them.

The measurements presented were not easy to take: To measure parasitic effects additional coupling by the measurement equipment has to be avoided. To achieve this the arrangements were carefully designed, especially referring to the ground connections. If possible, additional reference measurements were taken. Thus the data presented here is intended to be reproduceable, but however results may differ if they are obtained under different conditions.

2 Experimental Results and their Consequences Designing Converters

2.1 Parasitic Capacitive Coupling between Terminals and Heatsink

Figure 1 shows the schematic of the arrangement used:

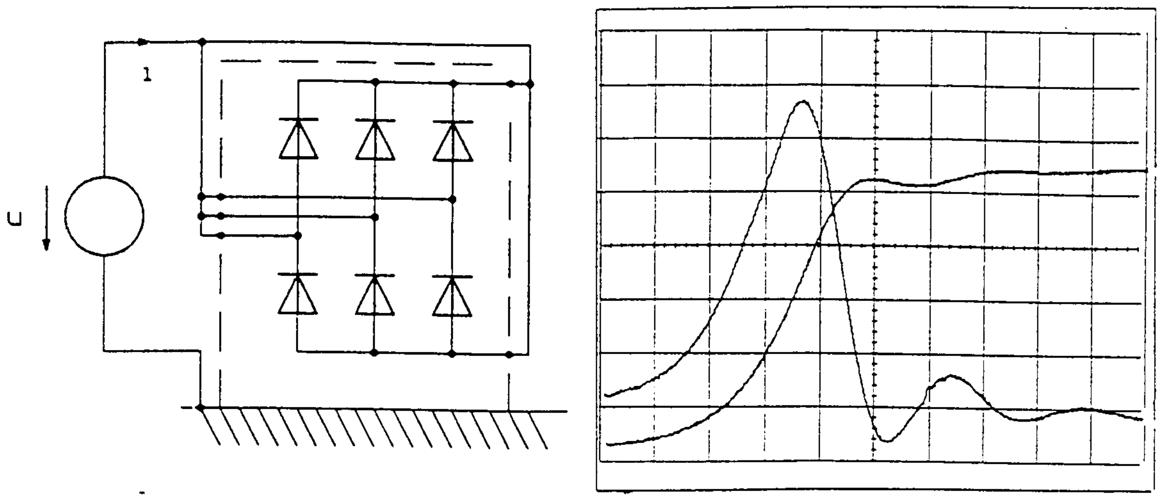

Figure 1: Capacitive Coupling between Terminals and Heatsink; left: schematic; right: voltage u (lower trace, 500 $\frac{V}{div}$), current i (upper trace, 0.1 $\frac{A}{div}$), 250 $\frac{ns}{div}$

All terminals of a three-phase rectifier have been shortened and connected to the positive pole of a voltage source with the voltage u; the heatsink the module is fixed on is connected to the negative pole. Thus a current i can flow through the coupling capacity C_K towards the heatsink according to:

$$i = C_K \cdot \frac{du}{dt} \tag{1}$$

The measurement of voltage and current is plotted on the right of figure 1: Voltage rises to about 2500 V with a maximum $\frac{du}{dt} = 5\ \frac{kV}{\mu s}$. With the value of $i = 0.56\ A$ occuring at the same time equation 1 results in:

$$C_K = \frac{i}{\frac{du}{dt}} = 112\ pF \tag{2}$$

This is the coupling capacity between the power terminals and the heatsink of the rectifier module. If the heatsink is connected to ground, the capacity to ground is determined this way. The size of this coupling capacity is important to know for being able to appropriately dimension filter capacitors, especially Y-capacitors.

With a RCL-Meter coupling capacity was determined as $C_K = 125\ pF$ which is in the same range. However it is even possible to calculate C_K without an electrical measurement: The module is isolated to the heatsink by a aluminium-oxide ceramic substrate with the area $A = 25\ mm \cdot 34\ mm$, the thickness $d = 0.63\ mm$ and a dielectric constant of $\varepsilon_r = 9.5$. With the formula for a plate condensor the value

$$C_K = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} = 114\ pF \tag{3}$$

is obtained. This simple calculation thus is favourable to determine the range of coupling capacity of a power semiconductor module as the comparison of equations 2 and 3 shows. If the direct copper bonded DCB ceramic substrate is not visible due to a metal base plate the assumption that DCB is some smaller than the case may be helpful for this evaluation.

2.2 Parasitic Capacitive Coupling between Power Terminals and Control Terminals of an Intelligent IGBT Module

Besides the effect of the capacity between the power terminals and the heatsink as described in section 2.1 there is another coupling between the power circuit and the control unit. Usually they are galvanically insulated but however the control unit might be unintentionally influenced by the power section due to capacitive coupling. Thus coupling capacity should be minimized. It is usually located in the drivers being the interface between low and high potential.

The configuration used for the experiment is shown in the schematic of figure 2:

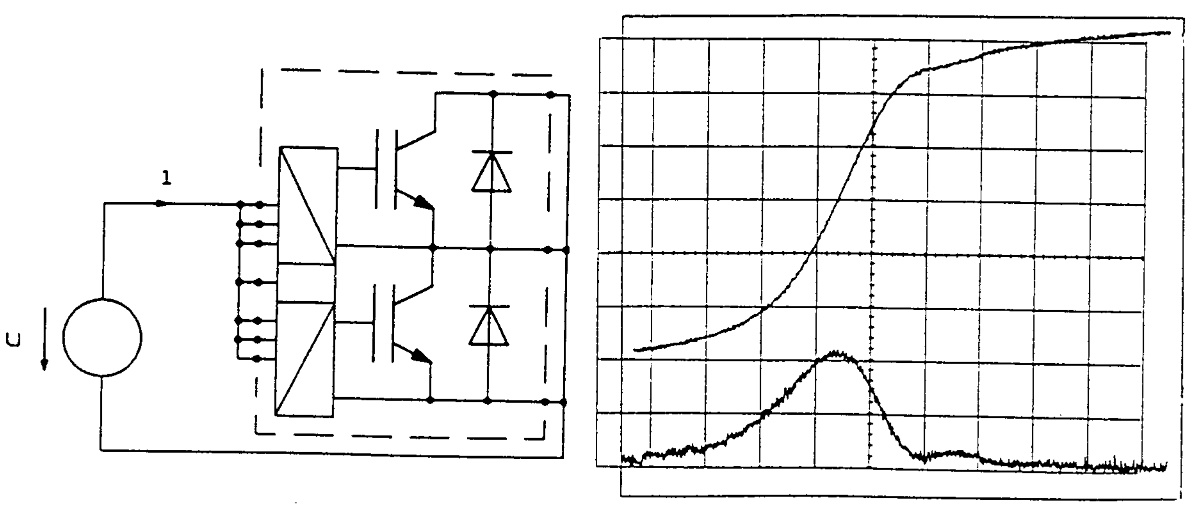

Figure 2: Capacitive Coupling between Power and Control Terminals; left: schematic; right: voltage u (upper trace, 200 $\frac{V}{div}$), current i (lower trace, 20 $\frac{mA}{div}$), 250 $\frac{ns}{div}$

An intelligent IGBT module of the IXYS ISOSMART® family has been used. The drivers including their galvanically insulated power supplies are integrated in the module. Thus this module provides an interface between control unit operating with low voltage logical signals and the potential of power circuitry. For the measurement all terminals of low voltage side are short circuited as well as all terminals of the high voltage side. This way the sum of all coupling capacities including the DC-DC-converter and the feedback for fault signals is measured. Voltage u and current i are plotted in figure 2. The rates of u and $\frac{du}{dt}$ exceed the values to be expected during operation.

A calculation according to equations 1 and 2 results in a coupling capacity of $C_K \approx 22\ pF$; the value measured with a RCL meter this time is lower but again in the same range as mentioned in section 2.1. This coupling capacity being such small is favourable for the reasons mentioned above.

2.3 Parasitic Coupling into the Wires between Driver and IGBT Module

A lot of hints how to design the connections between the drivers and the power transistors are well known by the staff concerned with the development of converters, as for example:

- Use short wires.
- Use shielded cables or at least twisted pair wires with a minimum of space in between.
- Use wires with a sufficiently low resistance being able to carry the expected currents or current peaks without a too big voltage drop.
- Provide a sufficient insulation if the wires might touch any conductor on high potential.
- If the semiconductor device to be driven is sensitive for electrostatical discharge provide some 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.

This short list of course does not intend to replace more detailed manuals about the design of converters. An experiment carried out according to figure 3 underlines the necessity to obey these rules:

An IGBT has been connected to a kind of driver circuit supplying it with $0\ V$ with a realistic impedance. For the connection twisted pair wires have been used as recommended above. There however is a loop between the wires as shown in figure 3 and in parallel there is another loop carrying a current. The parasitic coupling of the galvanically insulated circuits in this arrangement is mainly inductive. Gate emitter voltage of the IGBT has been measured inside the module nearby an IGBT chip.

The effect of a voltage being applied by the voltage source driving a current i as shown in the plot in figure 3 is clearly to be seen: There is a voltage peak at the gate. Some $1.1\ V$ is not much but taking into account the power terminals of the IGBT module were short circuited the boundary conditions are very harmless. During operation there would be additional transients. If the gate emitter voltage of an IGBT does not correspond to the desired value faults in overcurrent detection or higher losses may occur or, even worse, the switching state of the transistor may not be controlled by the gate driver all the time.

The value of gate emitter threshold voltage $V_{GE(th)}$ specified in the data sheets of IGBTs helps to evaluate the intended and tolerable gate emitter voltages. The sensitivity for disturbances by electromagnetic radiation however should always be minimized by an appropriate design of power section including the gate drives and the interconnections.

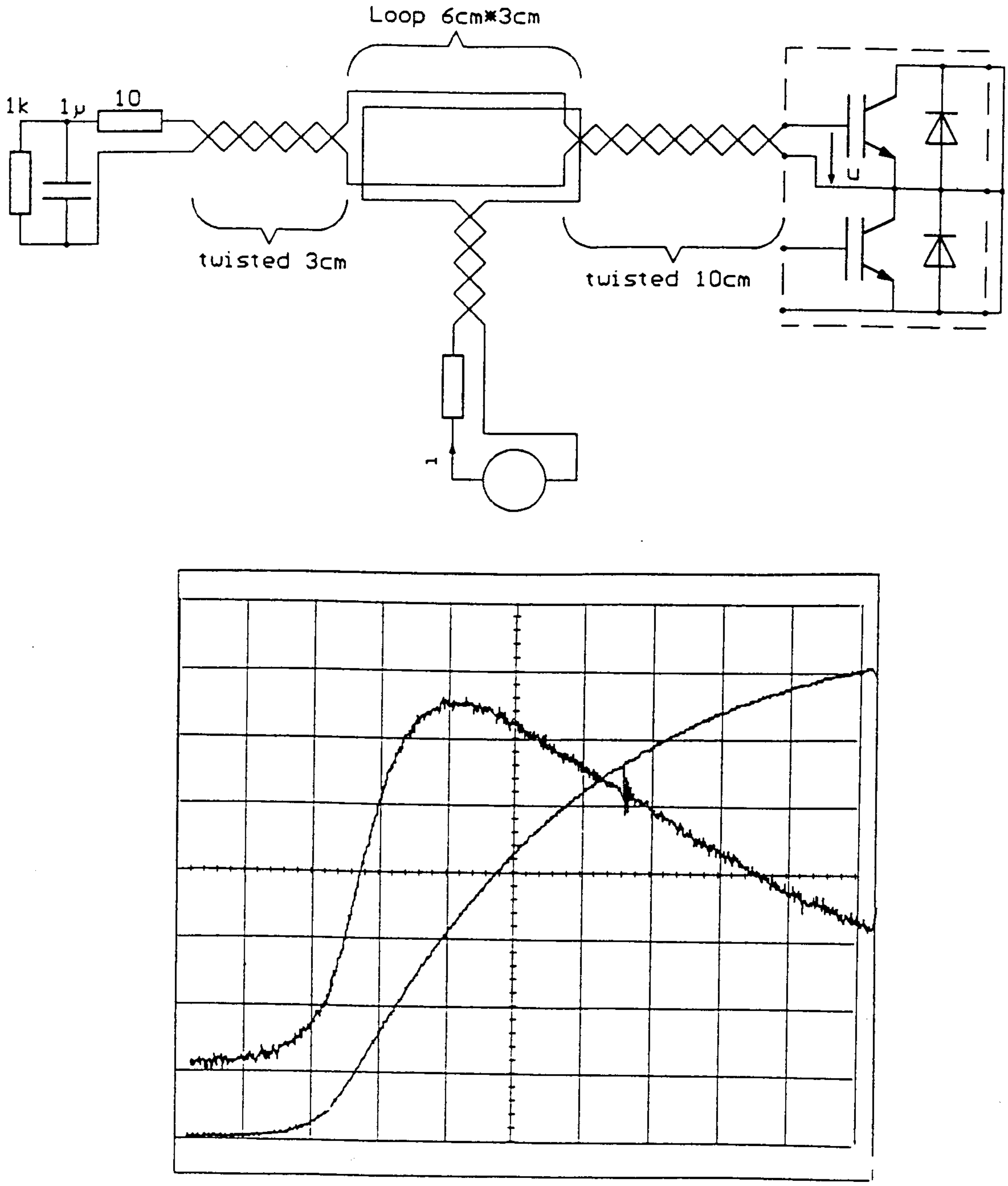

Figure 3: Coupling into the Wires between Driver and IGBT-Module; above: schematic; below: voltage u (upper trace, 0.2 $\frac{V}{div}$), current i (lower trace, 5 $\frac{A}{div}$), 500 $\frac{ns}{div}$

2.4 Effect of Disturbances in the Grid on Input Rectifiers

The standards IEC 1000-4-4 and IEC 1000-4-5 describe tests to evaluate whether a device is sufficiently resistive against the phenomena of burst and surge. Most of the tests are carried out by applying voltage peaks onto the lines, especially the supply lines of a device. For supply lines are usually equipped with a rectifier a three-phase rectifier bridge has been used for the experiment described here. A voltage source has been connected to the input terminals of the bridge according to figure 4. The load at its DC terminals consists of a resistor, a capacitor and inductances as shown in the schematic. Variable configurations have been tested; one plot with a resistive capacitive load, which means the inductances were zero, is given on the right of figure 4:

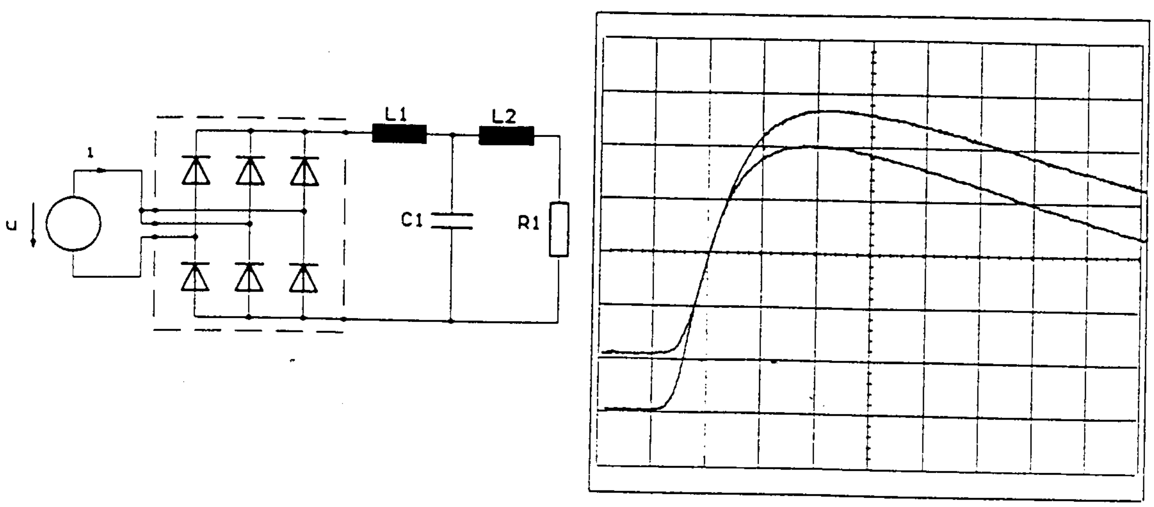

Figure 4: Simulation of a Disturbance in the Grid for a Rectifier; left: schematic, $L_1 = L_2 = 0$, $C = 11\ nF$, $R = 47\ \Omega$; right: voltage u (upper trace, 200 $\frac{V}{div}$), current i (lower trace, 5 $\frac{A}{div}$), 2 $\frac{\mu s}{div}$

The experiments showed that the disturbances pass by the rectifier which means that the rectifier is not a critical component being easily damaged. There must however be a current sink somewhere on the AC or the DC side to prevent voltage from rising to a level exceeding nominal voltage of 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 data sheets. So if the impedance of the DC load, the inductance on the AC side and the level of voltage to be applied are known an evaluation how to ruggedly dimension an input rectifier is possible. In general few problems will arise here.

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

IEC 1000-4-11 describes tests for voltage interrupts, drops and variations. Depending on the internal energy storage in a device these effects may cause malfunctions. The input rectifier can be concerned in two ways:

- If the device has some power control current will rise when voltage decreases which augments conducting losses of the rectifier. The possible overcurrent can be calculated and thus an estimation how to dimension the rectifier is easily done.
- If voltage reaches its nominal value after a period of low voltage there is an overcurrent through the rectifier due to the charging of the capacitors on its DC side. This is the subject of power up which has to be considered anyway.

So these tests again mainly concern the electronics on 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 limited in the standard EN 50081. Usually an input rectifier is the interface of a device towards the grid. Especially during commutation when diodes have to recover a rectifier may cause current and voltage peaks. So a test has been carried out according to figure 5:

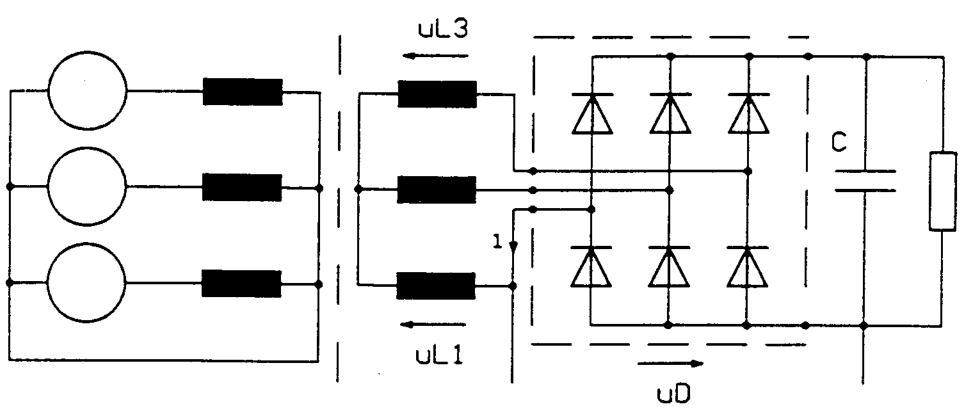

Figure 5: Schematic of an Input Rectifier with a Transformer Providing a Defined Impedance; $C = 22nF$

The grid — symbolized by three voltage sources — is connected with a transformer with unity turns ratio; thus 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 quite independently from the impedance of mains which is similar to the standardized measurement conditions. A three-phase rectifier module is connected to the transformer; on its DC side there is a small snubber capacitor and a resistive load

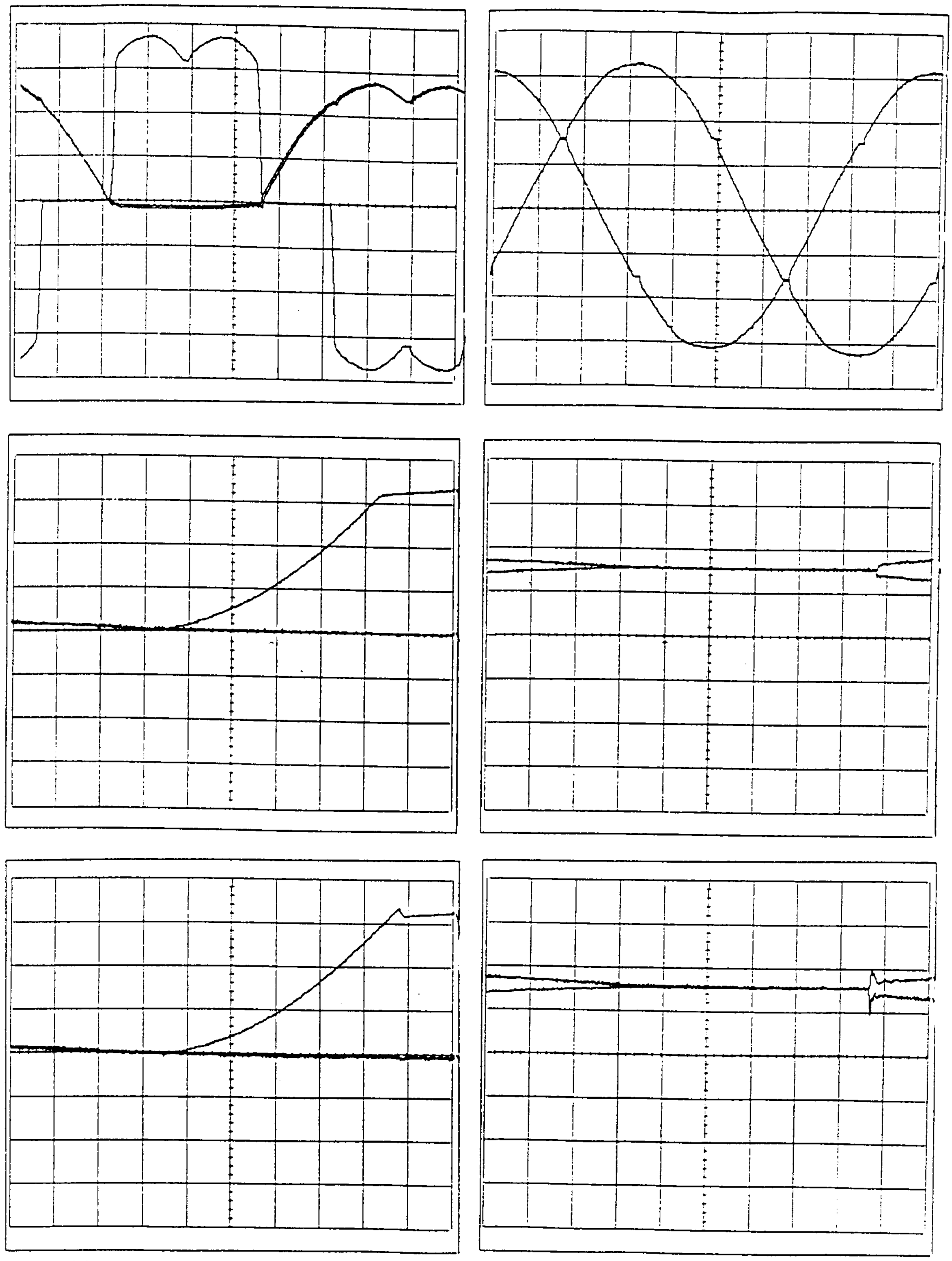

Figure 6: Plots taken at different Input Rectifiers; above: one period (20 ms), center: zoom of commutation interval of Fast Recovery Epitaxial Diodes FRED (50 $\frac{\mu s}{div}$), below: zoom of commutation interval of Rectifier Diodes (50 $\frac{\mu s}{div}$); left: voltage u_D (asymmetrical, 200 $\frac{V}{div}$), current i (symmetrical, 5 $\frac{A}{div}$), right: voltages u_{L1} and u_{L3} (100 $\frac{V}{div}$)

of some 9 kW. So the measurement is taken under the rectifier's operational conditions. Several plots are shown in figure 6:

Left on the top the voltage u_D and the current i are given. u_D cannot be negative because the lower left diode in figure 5 becomes conducting; thus the current while $u_D = 0$ is carried by this diode. The plots for the other diodes of the rectifiers would be identical for reasons of symmetry. The plots in the center and below on the left in figure 6 show the interval the current rises in detail. While the plot on the bottom is taken with a module equipped with standard mains rectifier diodes the plot in the center shows the behaviour of fast recovery epitaxial diodes FRED. There is not much difference in the current rise mainly determined by the external inductances — the transformer and the wires to the power section which were identical for both experiments. There is however a difference in reverse recovery of the diodes: While the standard rectifier diode's switching off shows some peak of reverse current which is added to the forward current of the conducting diode, the FRED recovers as fast and as soft as desirable — there is no peak visible at all.

On the right of figure 6 the phase voltages u_{L1} and u_{L3} according to figure 5 are shown, again over one period on the top and for a commutation interval in the center — the plot taken with the FRED rectifier — and below — taken with a standard rectifier. 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 while the curves taken at the FRED are smooth.

These results have been confirmed by measurements of EMC emissions taken according to the EN standards with identical electrical devices one being equipped with a standard rectifier respectively one with a FRED rectifier. Emission of voltage oscillation was significantly lower with the FRED rectifier. Thus expend 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 determine the decision which type of rectifier shall be used. IXYS standard rectifiers of the type VUO and FRED rectifiers of the type VUE are offered in the same package. So the designer has the advantage of complete compatibility of both families and thus is able to easily adapt his products to the particular requirements.

Additional regulations for emissions to be applied on certain products are given in the standard EN 60555. The subject of current harmonics is discussed in section 3:

3 The Importance of Choosing an Appropriate Topology

This subject shall again be discussed with special regard to input rectifiers as an example for an application different topologies can be used in. Each of them has specific characteristics, both economically and technically. Economic aspects often favour solutions with semiconductor modules — there are few external connections left, there is no need for galvanic insulation to the heatsink, cost intensive work in construction and mounting is minimized. Besides there are important technical advantages as 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 or particular applications are an advantageous solution.

The following list gives examples for possible topologies of input rectifiers:

1. single or three-phase rectifier bridge — see figure 5:

   This is the most simple solution. The rectifiers are quite rugged and don't need any control. Depending on inductances and capacities some start up facility must be provided to avoid destructive current peaks when switching the grid — which is a voltage source — onto capacitors in DC-link being a voltage source as well. The most important disadvantage of this configuration is the high harmonic content in AC currents which is mostly determined by physics; it can be estimated by spectral analysis of the currents with the assumption the diodes being ideal switches. The harmonic content of line currents can only be reduced by filters which may get quite big depending on nominal power. The effects of commutation as described in section 2.5 are an additional aspect not considered here again.

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

2. rectifier bridge with thyristors:

   Replacing half or all of the diodes in figure 5 by thyristors offers the opportunity to control current flow or DC voltage respectively. Evidently there must be a control unit for the thyristors; some feature for start up can be integrated there. The problems of harmonic content and voltage distortion remain similar to those mentioned under point 1. Furtherly the circuit consumes additional reactive power when the thyristors are triggered with delay. So there may again be a high expense for filters, usually at least input inductances. This conservative solution however has a quite rugged operational behaviour, too.

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

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 often are FREDs — see section 2.5; the transistors usually are MOS-FETs or IGBTs. All of them are available in discrete versions and in a variety of standard modules. This type of module can as well be used in inverters and DC-DC-converters and thus is very universal.

4. rectifiers for power factor correction:

   There is another solution being more simple to control than the self commutated bridge as described under item 3 and having a comparable operational behaviour, superior in relation to the diode and thyristor diode bridges as described under items 1 and 2. The schematics are shown in figure 7, above for a single-phase, below for a three-phase solution:

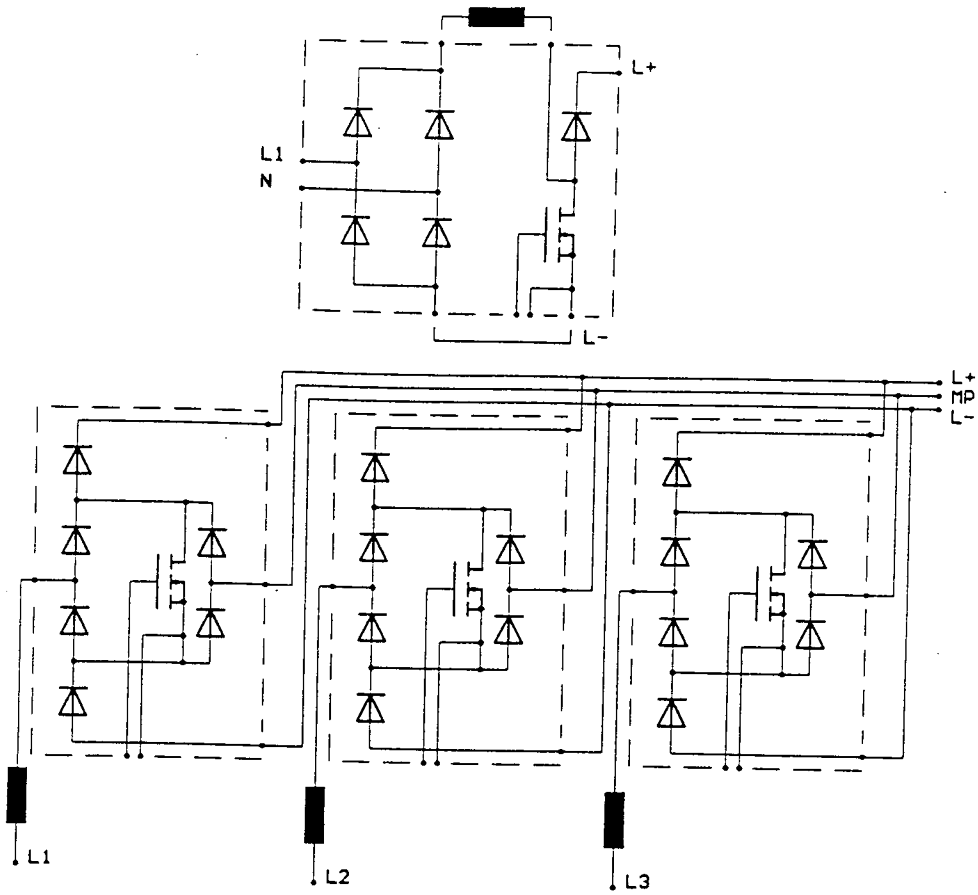

Figure 7: Modules for Power Factor Correction; above: single-phase, below: three-phase

Both circuits operate in continuous current mode which is favourable on behalf of 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 for example documented in [1] and [2] while the three-phase circuit is documented in [3], [4], [5] and [6]. The VUM 24-05 and VUM 33-05 — which are single phase versions — can be controlled by a custom IC with few peripheral components; this way a cost effective solution for an input rectifer of high quality is achieved. IXYS also manufactures modules containing one bridge for the three-phase rectifier — easily to be paralleled on the DC side to achieve the circuit shown in figure 7 below.

The decision which type of rectifier shall be used depends on the technical requirements and on costs. The former can for example be standards: As mentioned in section 2.5 certain devices have to meet EN 60555 which limits harmonic content of line currents and voltages. In addition for a lot of devices, for example welding machines, it is desirable that they can be used with 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 above under items 3 and 4 are evidently very advantageous.

Similar considerations concern questions of other topologies 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 paper. Anyway — the users of power semiconductors are asked to contact their semiconductor manufacturers. This cooperation offers the opportunity to realize approved and new approaches.

4 Conclusion

Investigations on electromagnetic compatibility have been carried out. The results show that many questions can be answered by quite simple calculations or estimations based on well known physical laws. Obeying some simple rules in the design of converters is very helpful to achieve an appropriate operational behaviour. Finally it is important to use power semiconductors in a circuit being adequate for the application. Due to the variety of discrete power semiconductors and semiconductor modules the selection may be not easy but well done it will lead to results favourably matched to each particular application.

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