35 kW Active Rectifier with Integrated Power Modules

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Abstract

Front end converters for high power generators e.g. for plasma applications as well as for induction heating applications, are currently mostly designed with uncontrolled bridge rectifiers feeding a dc-link capacitor. Line current harmonics can cause operating problems by distorting the mains voltage. To overcome this issue an active rectifier based on Vienna Rectifier topology has been developed. High power factor and nearly constant dc link voltage are other advantageous characteristics of such an active power factor correction unit. Two 17.5 kW stages comprised of low profile SP6-P power modules from Microsemi are operated in parallel to achieve the output power of 35 kW.

Introduction

Industrial power supplies, such as for plasma applications or induction heating applications may feed back inadmissible harmonic currents into the mains due to the currently widely used uncontrolled input rectifier in combination with a capacitive dc link circuit. The resulting mains voltage distortion can affect other devices and may even cause their malfunction.

To avoid these drawbacks, a mains input stage with sinusoidal current consumption has been developed. The following shows the main specification requirements:

- Input voltage range 360 - 523 VAC
- Output voltage 800 VDC
- Output power rating 35 kW
- Power factor > 0.99
- Efficiency > 97 %
- Installation volume approx. 4.5 dm^3
- Constant output voltage (DC intermediate circuit voltage as input voltage for the subsequent switching stage) independent of mains voltage fluctuations
- Negligible output voltage ripple compared to the remaining ripple of the uncontrolled rectifier (without extensive filtering)

The three-phase active rectifier in center point configuration 'VIENNA Rectifier' was chosen from the multitude of known switching topologies for the medium and high performance range. A fundamental reason for this decision was the ability to access extensive knowledge and practical experience according to [1] and thus the ability to keep the risks of a fast technical implementation up to series production under control.

VIENNA Rectifier topology

References [2] and [3] introduced a unidirectional, three-phase / three-level PWM pulse rectifier system with only three turn-off power semiconductors under the name 'VIENNA rectifier' (see Fig. 1).

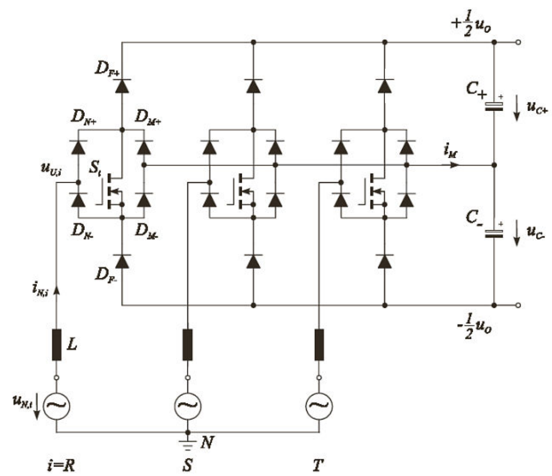

Fig. 1 Three-phase / three-switch / three-level pulse rectifier system – VIENNA rectifier.

The technical and economic advantages of the system compared to alternative concepts were analyzed in detail in [4] and [5]. The main advantages are:

- only one turn-off power semiconductor (MOSFET or IGBT) per phase,
- Three level characteristic of the bridge branches, resulting in a low voltage stress on the power semiconductors,
- continuous, uninterrupted input current with comparably low switching frequency components,
- two divided output voltages that may be loaded asymmetrically [6],
- high reliability, as no bridge or output voltage short circuit can occur, even in the case of a control failure.

The disadvantage of the system is that it cannot invert power into the mains, which would be required in a motor drive solution, for example.

With suitable PWM control of the power transistors S_i (i = R, S, T), a pulse-shaped three-phase rotating current system $u_{U,i}$ can be created at the system's input. Its voltage difference to the mains voltage $u_{N,i}$ (which shows a fully sinusoidal characteristic) occurs across the input inductors and affects the most sinusoidal current consumption of the system possible [7]. At this point, we refrain from explaining futher details about the controller. See [1…8].

Switching topology for higher power

For higher powers (the current limit is at an output power of about 10kW), the higher losses require parallel connection of the switches S_i of the switch topologies in Fig. 1.

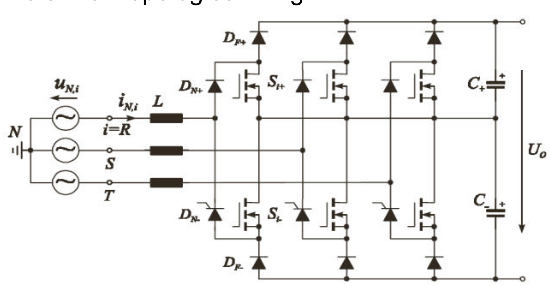

Fig. 1 Three-phase / six-switch / three-point / pulse rectifier system

As soon as this is the case, the topology in Fig. 2 is preferable, as the center point diodes D_M become surplus to requirements. This requires, however, not three but six gate driver circuits. The functioning of the two systems is equivalent; the switches S_{i+} and S_{i-} are operated by the same control signal s_i .

For the practical implementation, two (circuit technology) alternatives were considered:

A) Single 1x 35 kW PFC unit, using 3 branch modules, e.g., in the Microsemi SP4 module:

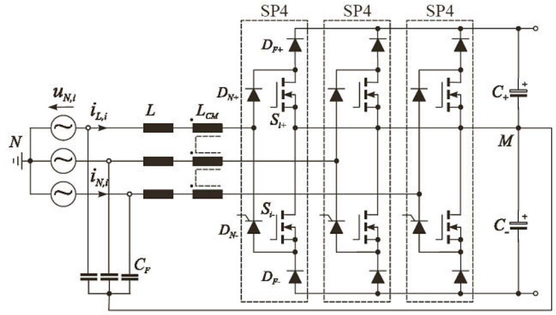

Fig. 2 Topology based on 3x SP4 branch modules

B) Parallel operation of 2x 17.5 kW PFC stages with phase-shifted driver, 2 'full bridge modules'.

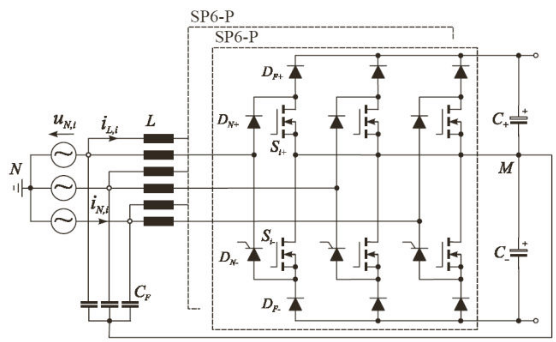

Fig. 3 Topology based on 2x SP6-P rectifier modules

The 2x 17.5 kW option was selected, even though both options are technically feasible. This option has a number of advantages:

- the common mode suppressor choke L_{cm} of option A is surplus to requirements
- the phase shift of 180° in switching frequency of the drive signals of the two partial systems partially compensates the ripple of the choke currents in the mains current
- no parallel connection of COOLMOS™ 1) transistors in the power module is required
- modular design: may be scaled down to 17.5 kW output power by removing one of the two paralleled PFC stages.

A disadvantage is the increased hardware requirement resulting from the additional current transducers and driver amplifiers. However, the positive features outweigh the negatives.

Low profile power module integration

The electrical configuration of the 3-phase Vienna rectifier is built from a significant number of individual devices from different technologies (6 fast recovery diodes, 6 MOSFETs, 3 thyristors and 3 standard rectifier diodes). The circuit configuration using discrete devices would spread over a very wide area to achieve the complete power function.

Interconnecting all the power semiconductors together is not only complex from a layout point of view but also introduces high parasitic wiring inductances and resistances that increase the voltage stress of the power semiconductors and limit at the same time their switching speed. The consequent long wires between devices generate inevitable parasitic ringing or oscillations that are difficult to cancel and/or damp out and these may affect the stability and EMC performance of the system. Therefore it makes eminent sense to integrate the whole power function inside a single package to achieve the power conversion module of the 3- phase Vienna Rectifier according to Fig. 4.

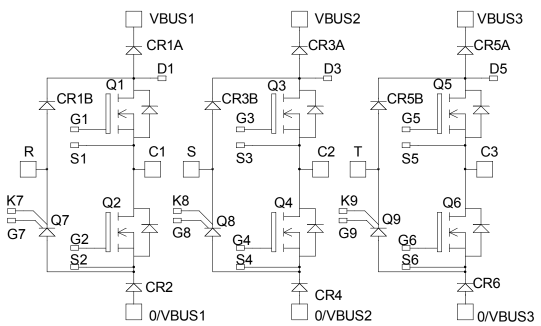

Fig. 4 Power module electrical diagram

The Vienna rectifier is a 3-level topology that reduces the voltage stress and allows 600V MOSFETs and FREDs to be used from 400V line to line mains systems.

600V transistors and diodes offer much better conduction and switching losses than the equivalent 1200V components.

The phase control thyristors feature V_{RRM}=1200V, I_{TAV}=30A, V_{T0}=0.85V, R_T=10 mΩ. The mains rectifier diodes CR1B, CR3B and CR5B feature V_{RRM}=1200V, I_{FAV}=40A, V_{T0}=0.8V and R_T=6.5 mΩ.

The Super Junction MOSFET switches are made of 600V ultra low RDSon COOLMOS™ devices.

With 45 mOhms, these devices offer outstanding RDSon per chip area. This contributes to increase the power density level and offer the highest possible efficiency. With very low input capacitance and ultra low gate charge they allow high frequency operation in the range of several hundred of kHz with minimum conduction losses at high output power. The fast recovery diodes CR1A, CR2, CR3A, CR4, CR5A and CR6 feature 30A/600V. These diodes belong to the latest DQ generation type from Microsemi PPG (formerly APT) and exhibit low recovery charge and time to decrease the turn on loss in the power switches and minimize the recovery loss in the diode. The DQ diodes, with an optimized epitaxial design offer much softer recovery characteristics without sacrificing speed. This results in less stress on the switches and generates much less switching noise. The quiet behaviour of the diodes makes it easier to meet EMI/RFI noise emissions limits.

The moderate forward voltage provides a good balance between switching and conduction losses. With avalanche rating characteristics the DQ diodes contribute to a more rugged system.

All MOSFET devices as well as the SCR's are provided with command signals taken directly from the dice such that the corresponding Kelvin connections do not interfere with the power circuit to further reduce the amount of noise in the control circuit. This enhances the quality of the control signals, improves the safety of operation and facilitates filtering operation without affecting the speed of the system.

With platinum doping, the DQ diodes offer less degradation of performance at elevated temperatures such that they can be specified up to 175°C maximum junction temperature.

Consequently the state of the art super junction MOSFET devices can operate at their full speed without significant de-rating on the switched current up to junction temperatures of 125°C.

On the other hand, the highly doping level of the base region of COOLMOS™ transistors allows higher temperature operation than with conventional silicon transistors having the same blocking voltage. COOLMOS™ devices could be safely operated up to 200°C. It has also to be noted that both the COOLMOS™ transistors and DQ diodes exhibit very low leakage current as temperature increases, thus minimizing the power losses and improving the reliability over the entire junction temperature range varying from -55°C to 175°C.

Fig. 5 shows a picture of the power module with all power devices soldered onto ceramic substrates. Alumina substrates have been specified first, to minimize the module cost. Three identical substrates are used within the package to offer perfect design symmetry. The substrates are soldered to a copper base plate for best heat transfer to the heat sink.

Fig. 5 Picture of the open Microsemi power module

Each leg of the bridge is provided with independent Vbus and 0/VBus connections. This offers the advantage to further reduce the parasitic inductance, proportionally to the number of connections. The power connections are also placed as close as possible to the power semiconductors to minimize layout stray inductances, shorten high frequency loops and facilitate outside decoupling with capacitors placed outside the power module directly across the output terminals. The power connections are made of short and large lead frames terminated by pins to facilitate the connection to a top PCB.

The module is potted with silicone gel and completed with a plastic cover (Fig. 6).

The SP6-P power module exhibits a footprint of 108 mm x 62 mm with a height of only 12 mm.

All the power function, with multiple components packaged in die form into the very low profile SP6-P package from Microsemi allows the advantage of the full speed characteristics of the power semiconductors to be taken without introducing any parasitic elements in the power circuit.

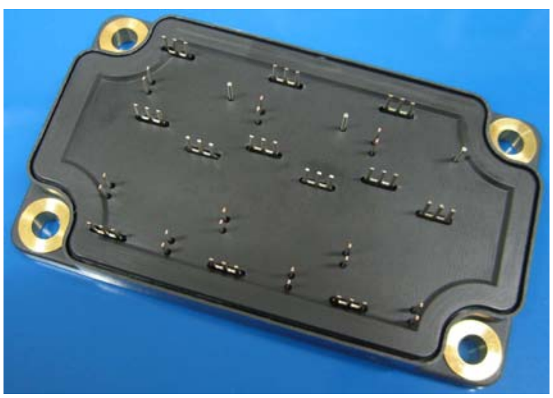

Fig. 6 Photograph of the complete SP6-P Microsemi power module

The module thermal performance has been further improved by about 25% with the substitution of alumina substrates by Aluminium nitride ones having a much better thermal conductivity. This allows higher output power or longer life time at same output power while lowering the amplitude of variation of the power semiconductors junction temperature.

Temperature cycling is another limitation of power modules life time. Fast transients of case temperature between two extremes cause mechanical stresses at the level of the solder joints between the different materials or even inside the materials. The stress is proportional to the difference of Temperature Coefficient of Expansion (TCE) of the two assembly materials brazed together. Replacing the standard copper base plate by aluminium silicon carbide (AlSiC) base plate having a TCE of 7 ppm instead of 16 ppm significantly increases the module lifetime thanks to more closely matched TCEs with the substrates and dice soldered to it.

Design

The following figure shows the main functional elements of the PFC unit:

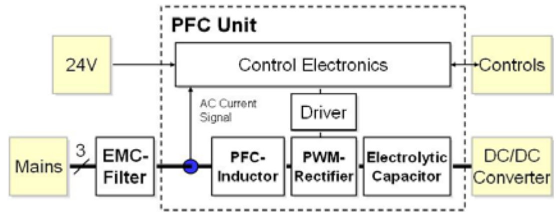

Fig. 7 Block diagram

All phase currents are captured with active converters and fed to the controller. The controller has the following main tasks:

- creating the PWM - driver pulses for the MOSFET transistors following the principle of three-phase multiplier-free regulation [8],
- controlling the start-up stage when the mains voltage is connected,
- regulating the DC output voltage to a constant value, independent of mains voltage fluctuations and load current changes
- protective functions (over-current, over-voltage)
- data exchange with the central controller of the DC plasma power supply.

When dimensioning the PFC assembly, the characteristics of the mains must be taken into account:

- mains input voltage range
- mains impedance
- harmonics content of the mains voltage
- brownouts and interruptions
- phase failure
- line-based EMC,

as well as possible interactions with the DC/DC converter connected to the output of the PFC:

- additional current load caused by the DC/DC converter
- load impedance changes, i.e., fast changes of the current drain during both load increase and load shedding.

Operating temperature and temperate gradients during cyclic operation are the crucial variables for dimensioning the components according to the required lifetime. See, e.g, [9].

For the mechanical construction, a volume of only about 4.5 dm^3 was available.

$$Powerdensity = \frac{35kW}{4.5dm^3} = 7.8\frac{kW}{dm^3}$$

To achieve this construction volume, all active and passive components were arranged on printed circuit boards. This meant that no wiring was required for the assembly and an exactly reproducible geometry was achieved. The following figure shows a 3D-CAD design:

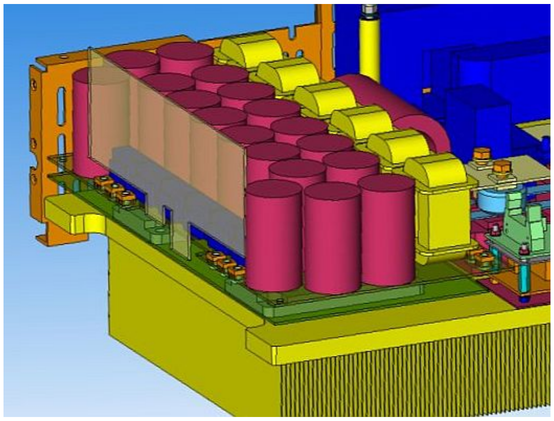

Fig. 8 3D CAD design of the PFC unit

Both power modules are arranged on the heatsink and are connected by a circuit board that also accommodates the driver and other components directly associated with the power electronics. In the level above it, a further PCB accommodates the current converter, electrolytic capacitors and the mains input chokes. Since two PFC stages operate in parallel, 6 mains input chokes are required.

On the left of the figure, the vertically arranged electronics controller of the PFC assembly is visible.

Test Results

Due to the chosen control process, the PFC behaves approximately like a resistive load on the mains. That is, the mains current tracks the mains voltage (including its harmonics). This can be seen on the oscilloscope:

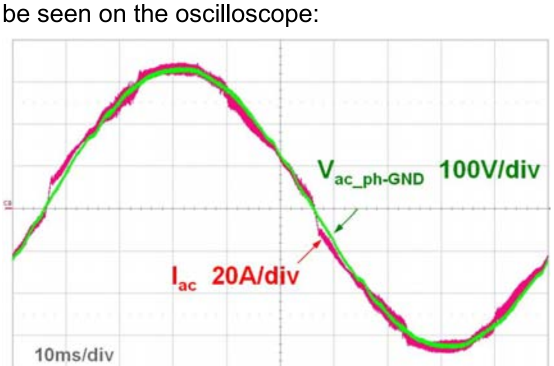

Fig. 9 Current and voltage traces at rated power

The high-frequency components of the PWM switching frequency visible on the oscilloscope are attenuated by the EMC filter to below the current limits.

Sudden load jumps are regulated within approximately 50 ms. In case of a power-ON transition from zero to rated power the voltage dip is about 100V, as shown in the following oscilloscope picture:

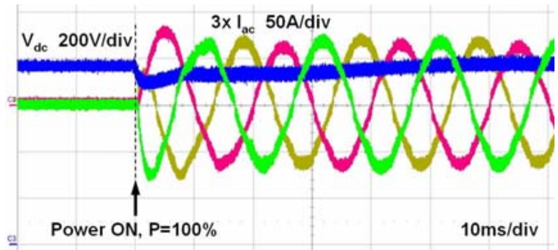

Fig. 10 Transient at a load jump from 0 kW to 30 kW

A high dynamism of the regulation is required in particular to avoid overvoltages as a result of sudden load shedding, as these may cause voltage overload of components.

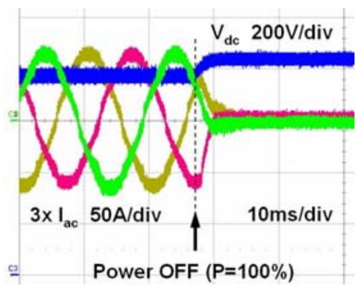

Fig. 11 Power-OFF transition from full load to zero. Voltage overshot of about 100 V (V.peak < 900 V)

During nominal operation, the following data was measured with a network analyzer:

U1	396.08 V	I1	47.83 A
U2	398.34 V	I2	47.97 A
U3	397.27 V	I3	48.21 A
Uave	397.23 V	Iave	48.00 A
P1	10.93kW	S1	10.94kVA
P2	10.99kW	S2	11.00kVA
P3	11.08kW	S3	11.09kVA
Psum	0.0330MW	Ssum	0.0330MVA
Q1	- 0.43kvar	PF 1	-0.9992
Q2	- 0.44kvar	PF 2	-0.9992
Q3	- 0.44kvar	PF 3	-0.9992
Qsum	-0.0013Mvar	PF sum	-0.9992

Fig. 12 AC input values during operating at rated power of the DC plasma power supply

The measured power factor is almost at 1.0 and thus above the specified value required. High power factor values could also be demonstrated in low-load operation. Even below 20% of the rated power onwards, the measured value is greater than 0.99. The results of the investigation are shown in the following diagram:

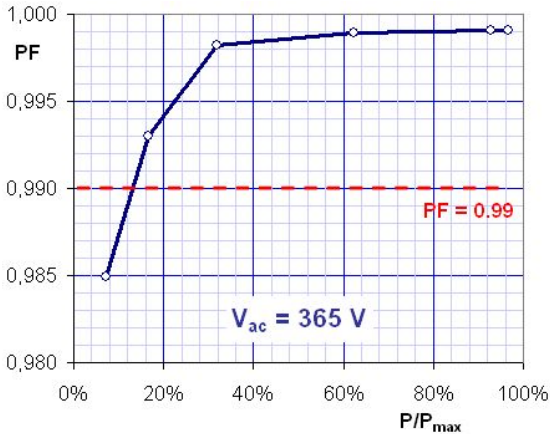

Fig. 13 Power Factor curve over the relative output power

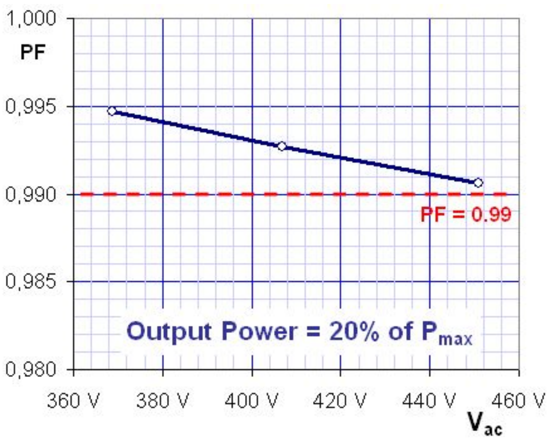

Fig. 14 Power factor curve depending on the ac input voltage at 20% output power

Summary

Based on the VIENNA rectifier topology, a compact 35 kW PFC unit has been developed. Fundamental features are the use of integrated 17.5 kW modules, which contain all of the power switches of the active rectifier bridge, and the two-stage construction with phase-shifted operation.

It was demonstrated that the VIENNA rectifier can also be used successfully in the medium load range, considerably above 10 kW.

Outstanding stationary performance and dynamic operating characteristics were achieved. The main feature is the high power factor in both nominal and the low-load operation.

[1] "COOLMOS™ comprise a new family of transistors developed by Infineon Technologies AG. "COOLMOS" is a trademark of Infineon Technologies AG".

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