Total harmonic distortion reduction add-on unit for three-phase diode rectifiers

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An active add-on option for 208 V_{LL}/60 Hz passive three-phase rectifiers is presented. The active optional circuit is implemented as 'centre-tapped' full-bridge stage and guarantees low-harmonic input currents and unity power factor. The active unit is able to operate for a wide frequency range and therefore applicable for high- (e.g. >100 kW) and low-power applications. Some basic considerations such as principle operation, duty cycles, voltage/current stress of switches and design of inductors are discussed and additionally supported by simulation results. Applicability of emerging wide bandgap power devices such as silicon carbide MOSFETs, which improve converter efficiency and power density, is furthermore briefly discussed.

Introduction: During the last couple of years harmonic current pollution is becoming more and more important. If AC-to-DC three-phase rectification is required (i.e. for DC power supply, motor applications or adjustable speed drives) passive diode bridge rectifiers are emerging as an attractive solution due to low cost, simplicity and robustness. In addition, no active switches are required, which results in very low complexity of the system. These rectifiers, however, highly tend to pollute the AC power grid due to their high input current harmonics ($3f_N$, $5f_N$, …).

Numerous rectifier systems, offering unidirectional powerflow and regulated output voltage, have been presented up to now (as e.g. the VIENNA-rectifier [1]). If, however, controlled output voltage is not mandatory, hybrid rectifiers based on the third harmonic injection principle (described in [2]) seem to be the more attractive solution. Multitudinous rectifiers have been proposed in these fields which consider passive current injection and passive current shaping [3], passive injection and active shaping [4], active injection and passive shaping [5] and active injection and active shaping [7]. Especially those regarding active injection and active shaping are either facing issues as high complexity [6], increased the number of switches [6] or only operable for constant output loads or higher switching frequencies [7].

A novel low-frequency harmonic suppression unit (depicted in Fig. 1) has, hence, been introduced recently (cf. [8]) which stands out due to simplicity, low number of switches and applicable for both high- and low-power applications. It is stated in [8], that a line-to-line voltage of 400 V requires 1700 V switching devices and has therefore not been further investigated. Detailed analyses, however, revealed that the proposed third harmonic injection network is very well suited for 200–220 V_{LL}.

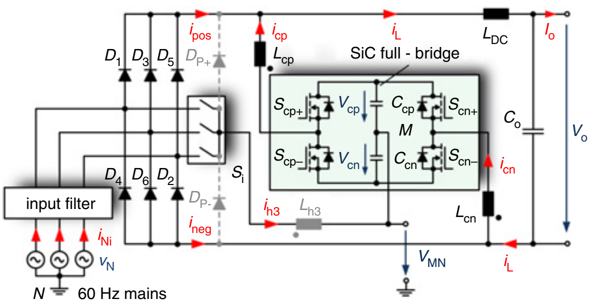

Fig. 1 *Passive three-phase diode bridge rectifier system employing a 'centre-tapped' silicon-carbide full-bridge converter (C_{cp}, C_{cn}), considering either a two (L_{cp}, L_{cn}) or a three inductor (L_{cp}, L_{h3}, L_{cn}) arrangement*

Topology description and full-bridge characteristics: Due to its low complexity the full-bridge converter is an attractive power electronics topology which is a common standard in industry applications. Active components are available as combined power modules from several manufacturers. The full-bridge topology is, furthermore, integrated in well-known power stages as the dual active bridge or AC–DC multi-cell arrangements. The full-bridge converter, therefore, appears to be attractive to serve as active current suppression *extension*/*option* for three-phase low-voltage applications. An already existing passive rectifier can hence be equipped by the optional active third harmonic circuit without redesigning the B6 rectifier.

Fig. 1 illustrates the proposed hybrid rectifier system (equipped with optional full-bridge enhancement) based on the third harmonic injection (THI) principle. The basic idea of the THI is (as discussed in [2]) to extend the passive three-phase rectifier by an additional circuit consisting of a current injection and a current shaping network. The current injection device consists of three bidirectional switches [S_i, e.g. standard MOSFETs/IGBTs (insulated-gate bipolar transistors)in back-to-back configuration or a parallel arrangement of reverse-blocking IGBTs] which are injecting the third harmonic current i_{h3} into the appropriate AC side mains phase which shows 0 A gaps due to passive rectification. The current injection network, hence, forms the interconnection between the AC side of the passive diode bridge rectifier and the DC side located current injection cell. Additional diodes ($D_{P\pm}$, connected to the positive and negative busbar of the rectifier) are highly recommended to be integrated as they are offering an alternative current path to prevent either irreversible damage of coil or injection network, if the injection device is forced to stop operation due to some kind of fault detection.

The current shaping network is designed as simple 'centre-tapped' full-bridge stage and injects some amount of current i_{cp} and i_{cn} into the positive and negative busbars of the rectifier (cf. Fig. 2). The DC link of the converter is formed by two capacitors C_{cp} and C_{cn} in series with midpoint M directly connected to the injection device (S_i). Considering line-to-line mains voltages of 200–220 V_{rms} a maximum DC-link voltage of 600 V is fully sufficient. Each capacitor C_{cp} and C_{cn}, therefore, has to endure 300 V which allows utilisation of 400 V/450 V electrolytic capacitors (no additional series connection of capacitors required). Furthermore, 900 V/1200 V IGBTs or silicon carbide (SiC) MOSFETs are applicable as both positive and negative switches are stressed with 600 V DC voltage. As GaN switching devices are only available for 650 V up to now, the utilisation of this technology is not possible for the third harmonic injection network at the moment. As, however, discussed in [9], 900 V/1200 V GaN high-voltage/high-power devices can be expected to be commercially available within the next years.

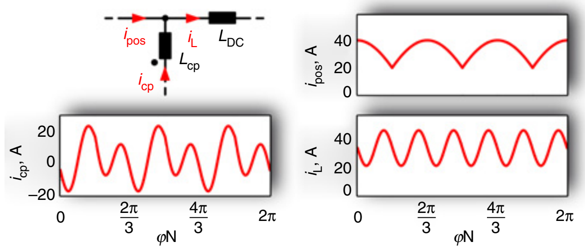

Fig. 2 *Calculated current waveforms i_{pos}, i_{cp} and i_L of the hybrid rectifier full-bridge topology*

As indicated in Fig. 1 a third inductor L_{h3} can be implemented and is directly located between the midpoint M of the full-bridge stage and the third harmonic injection device. This additional inductor advantageously allows a volume reduced design, if the three independent coils are formed as one coupled (e.g. iron) three-phase choke.

In the following, some basic considerations regarding operation and design of the proposed topology are discussed. The system specifications are defined as

- Mains characteristic: 208V_{LL}/60 Hz,
- DC-link voltage: $V_{cp} = V_{cn} = 300$ V,
- Switching frequency: $f_s = 10$ kHz.

A rather low-switching frequency of 10 kHz has been chosen for improved efficiency of the system. The duty cycle of the positive switch S_{cp+} assigned to the injection choke L_{cp} can be assessed by

$$\delta_{cp,L_{h3}} = \frac{1}{2}\left(1 + \frac{v_{pos} + v_{L_{cp}} - v_{h3}}{V_c} + \frac{v_{L_{h3}}}{V_c}\right) \tag{1}$$

The appropriated duty cycle for the dedicated lower switch (S_{cp-}) can be easily calculated by $1 - \delta_{cp,L_{h3}}$. V_c is the overall DC voltage $V_{cp} + V_{cn} = 600$ V. $\delta_{cp,L_{h3}}$ is the duty cycle of S_{cp+} considering an additional inductance L_{h3}. This additional coil results in an additional voltage drop $v_{L_{h3}}$ which has to be compensated by both half-bridges.

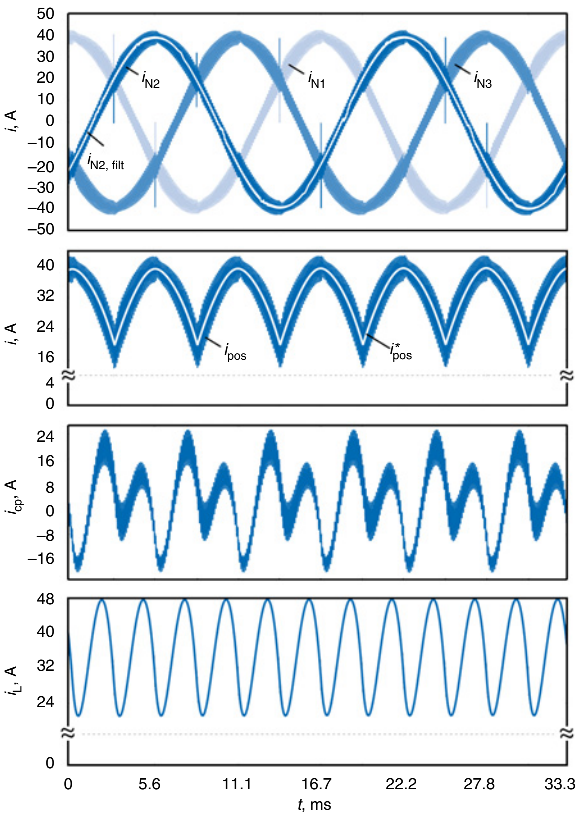

Fig. 3 *Simulated current waveforms of hybrid three-phase rectifier for 500 µH DC-side smoothing inductance (L_{DC}), 10 kHz switching frequency f_s and injection inductance values of 800 µH*

Considering both coil utilisation possibilities, three different options for a proper design of these chokes are emerging. For these implementation efforts, a standard 'double edge' pulse-width modulation (PWM) is assumed. (i) is the standard 2 choke implementation which assumes all PWM signals being synchronised. The inductance of both coils results in L_c (2) and (ii) resembles (i), however, PWM carrier signals of both injection legs are operated at 180° phase shift leading to a ≈ 12% reduction of the inductance value $L_{c,180^\circ}$ (2). The last design effort (iii) is utilising an additional choke L_{h3} in the third harmonic injection path which allows an additional inductance reduction for each choke ($L_{c,L_{h3}}$). Inductance values for the appropriate chokes compute to

$$L_c = \frac{V_c(1 - M/2)}{2 f_s \Delta I}, \quad L_{c,180^\circ} = \frac{V_c}{4 f_s \Delta I}, \quad L_{c,L_{h3}} = \frac{V_c(M+1)}{12 f_s \Delta I} \quad (2)$$

It has to be noted that only (iii) allows the implementation of a three-phase inductor. M is the modulation index and defined as $M = 3\hat{V}_N/(2V_{c(p/n)})$ which is given by 0.857. For a total DC voltage of $V_c = 600$ V, a switching frequency (f_s) of the cell of 10 kHz and a maximum current ripple (ΔI) of 25%I_{Npk} (≈10 A), the injection inductance value results in $L_c \approx 1700$ µH, $L_{c,180^\circ} = 1500$ µH or $L_{c,L_{h3}} \approx 900$ µH (depending on the respective design procedure).

Current stress calculations of all semiconductor components of the full-bridge stage ($S_{cp\pm}$ and $S_{cn\pm}$) have to be accomplished numerically as roots of i_{cp} and i_{cn} cannot be characterised in a closed analytical way. A design example is, therefore, given for a 208 V_{LL}/60 Hz/10 kW system. Average and RMS values of the switches are given below:

- AVG: $S_{cp+}/S_{cn-} = 1.6$ A; RMS: $S_{cp+}/S_{cn-} = 10$ A.
- AVG: $S_{cp-}/S_{cn+} = 1.6$ A; RMS: $S_{cp-}/S_{cn+} = 7$ A.

Due to an expected voltage stress of $V_{cp} + V_{cn} = 600$ V either CREEs C2M0080120D or ROHMs SCT2080KE appear to be perfectly applicable for the 10 kW system specifications.

Simulation results: The last section includes some simulation results of the proposed system considering specifications as previously derived and discussed. Fig. 3 depicts most important current waveforms of the 10 kW hybrid rectifier. The output filter current i_L is formed due to $6f_N$ output voltage components of the passive rectifier topology and hence shows the sixth harmonic current components dependent on the size of L_{DC}. These spectral components are compensated and suppressed by i_{cp} and result in $2\pi/3$ sinusoidal current waveshapes (i_{pos}). AC-side mains obviously result (due to proper filtering) in sinusoidal input currents ($i_{N2,\mathrm{filt}}$) with a total harmonic distortion ($\mathrm{THD_i}$) of 1.3% and power factor λ of 0.999.

Conclusion: In this Letter, a recently proposed novel DC-side current injection upgrade – realised as simple 'centre-tapped' full-bridge stage – for passive three-phase rectifier systems has been analysed. Low-harmonic input currents and unity power factor can be guaranteed for both high- and low-power applications. Considering line-to-line mains voltage levels of 200–220 V_{rms}, 900 V/1200 V SiC MOSFETs are perfectly applicable. The required inductor arrangement (L_{cp}, L_{cn}, L_{h3}) can advantageously be implemented as three-phase inductor for a volume optimised design.

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One or more of the Figures in this Letter are available in colour online.

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