Comparative Evaluation of Three-Phase Isolated Matrix-Type PFC Rectifier Concepts for High Efficiency 380VDC Supplies of Future Telco and Data Centers

P. Cortes,
D. Bortis,
R. Pittini,
J. W. Kolar

Comparative Evaluation of Three-Phase Isolated Matrix-Type PFC Rectifier Concepts for High Efficiency 380VDC Supplies of Future Telco and Data Centers

Patricio Cortes[1], Dominik Bortis[1], Riccardo Pittini[2] and Johann W. Kolar[1]

[1] Power Electronic Systems Laboratory, ETH Zurich

Physikstrasse 3, 8092 Zurich

Switzerland

Phone: +44 632 80 49

Email: cortes@lem.ee.ethz.ch

URL: http://www.pes.ee.ethz.ch

[2] Department of Electrical Engineering, Technical University of Denmark

Kgs. Lyngby, Denmark

Keywords

<<DC power supply>>, <<Matrix converter>>, <<Power factor correction>>, <<Power supply>>, <<Efficiency>>.

Abstract

Due to the high energy consumption in data and telco centers, the use of 380V or 400V DC facility-level distribution has been proposed as an alternative to the conventional AC distribution for a more efficient power delivery structure. The DC voltage is powered from the three-phase mains by a PFC rectifier and in many cases a mains transformer is used to provide galvanic isolation. In order to achieve a high efficiency in the DC voltage generation and to implement the required isolation, a single-stage concept, such as a matrix-type rectifier that enables PFC functionality and galvanic isolation in a single conversion, can be beneficial. In addition, due to the fact that with the matrix-type rectifier the galvanic isolation is performed with a high-frequency transformer, this results in a more compact rectifier system compared to conventional systems where the mains-frequency isolation transformer is located at the input of the PFC rectifier.

In this paper, an overview of isolated matrix-type PFC rectifier topologies is given and a new converter circuit is proposed, analyzed and comparatively evaluated against another promising PFC rectifier concept, the phase-modular IMY-rectifier.

1 Introduction

To improve the energy efficiency in telco and data centers, the use of a DC power distribution architecture (PDA) instead of an AC PDA has been proposed in the literature [1, 2]. The basic structures of a conventional AC PDA and a facility-level DC PDA are shown in **Fig. 1**. As can be noticed, the conventional AC PDA (cf. **Fig. 1(a)**) includes multiple conversion stages, which lead to a strongly reduced overall power distribution system efficiency. Typically, at the AC distribution system's input a double conversion Uninterruptible Power Supply (UPS) in combination with a bulky 50/60 Hz main transformer is utilized. The UPS rectifies the 400/480V AC into a DC voltage where an energy storage system, e.g. battery backup system, is connected. Then, the DC voltage is inverted back to 400/480V AC voltage that supplies the Power Distribution Unit (PDU). At the PDU, the voltage is stepped down to a voltage suitable to the Power Supply Units (PSU), typically between 90 and 264 V AC. In the PSU this AC voltage is then
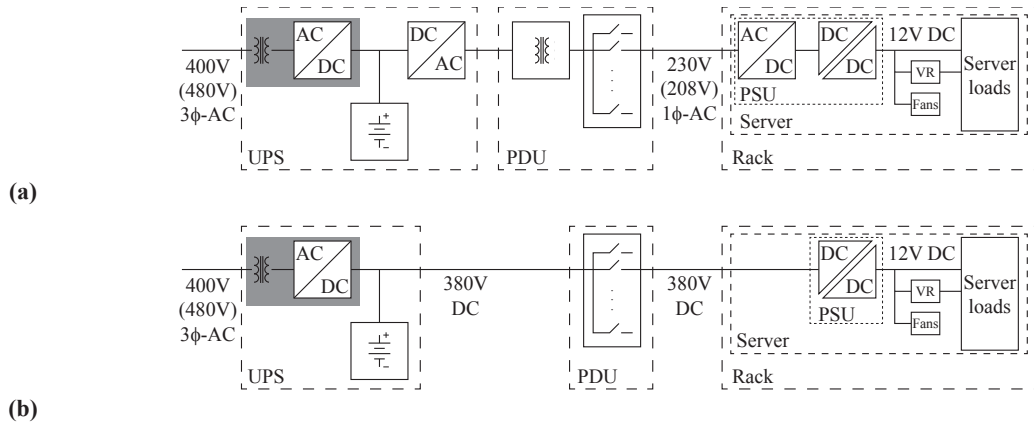
Fig. 1: Power distribution architectures (PDA) for data and telco centers, **(a)** conventional AC power distribution and **(b)** 380V DC facility-level power distribution.
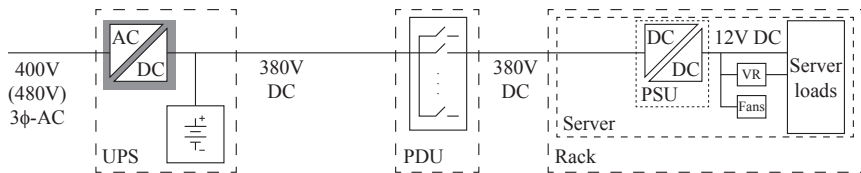

Fig. 2: 380V DC facility-level PDA with an isolated three-phase buck-type PFC rectifier that features PFC functionality and provides galvanic isolation with a high-frequency transformer.

again converted to a DC voltage which is finally – due to the large conversion ratio – stepped down by an isolated DC/DC converter to the 12V DC required by the different loads in the servers. Depending on the efficiency of the different components, the overall efficiency of such an AC PDA is between 50 % and 70 % [1].

In a facility-level DC PDA, however, several conversion steps can be avoided. As shown in **Fig. 1(b)**, the DC/AC conversion in the UPS, the transformer in the PDU and the AC/DC conversion in the PSU are eliminated, resulting in a higher efficiency of the power distribution system, e.g. 72.7 % efficiency [1] (assuming 95.3 % efficiency of the AC/DC converter).

In the last years, the selection of the optimal voltage level for the facility-level DC PDA has been discussed in the literature and also several organizations are working on the standardization of low voltage DC grids, where mainly the use of 380V DC [2, 3, 4] or 400V DC [1] is proposed for a more efficient DC power distribution architecture. However, a discussion about the optimal converter topology that supplies the facility-level DC power distribution is still missing in the literature.

Since the facility-level DC PDA is also powered from the three-phase 400V/480V mains, with the mentioned DC voltage selection of either 380V or 400V DC boost-type PFC rectifiers are no more suitable because the DC output voltage of boost-type PFC rectifiers has to be at least above the peak value of the mains line-to-line voltage; thus, with a wide input voltage range up to 480Vrms, the output voltage is typically selected to 700V to 800V DC. Consequently, a three-phase buck-type PFC topology has to be selected which allows to directly step down the varying input voltage to the proposed 380-400V DC. In addition, the overall system volume can be strongly reduced by omitting the bulky mains-frequency transformer if the galvanic isolation is realized with a subsequent DC/DC conversion stage which contains a high-frequency isolation transformer (cf. **Fig. 2**). Furthermore, in order to achieve a high overall AC/DC conversion efficiency, instead of this conventional two-stage conversion concept, a three-phase matrix-type buck rectifier topology which provides PFC functionality and galvanic isolation in a single conversion can be used; thus also no large DC-link capacitance for intermediate energy storage is required.

In this paper, a review of different three-phase matrix-type buck-type isolated PFC rectifier topologies is presented in **Section 2** and the most promising topology, regarding efficiency and realization effort, is
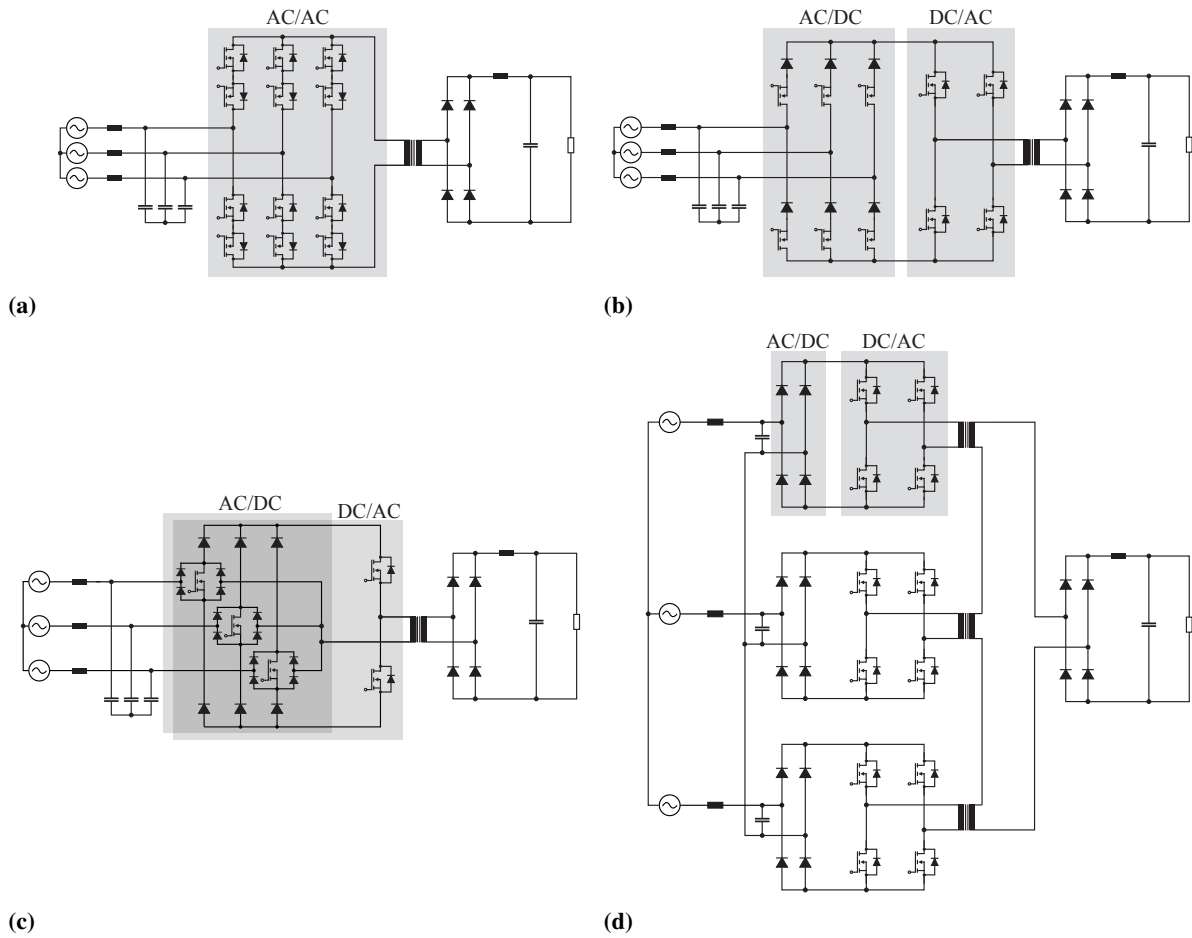
Fig. 3: Topologies of isolated matrix-type three-phase AC/DC converters, **(a)** direct matrix converter. **(b)** indirect matrix converter. **(c)** VIENNA rectifier III and **(d)** IMY-rectifier.

further analyzed in **Section 3**, and is compared in **Section 4** with a previously analyzed phase-modular matrix-type PFC rectifier system, the IMY-rectifier [5].

2 Isolated Matrix-Type PFC Rectifiers

Typically, the single-stage power conversion can be realized with a direct matrix-type PFC rectifier that directly converts the mains-frequency AC voltage into a high-frequency AC voltage which is supplied to a high-frequency isolation transformer and whose secondary voltage is then rectified to the desired DC output voltage as proposed in [6] (cf. **Fig. 3(a)**). As can be noticed, in this topology for the direct AC/AC conversion a large number of semiconductor devices is needed, thus, also the control and modulation scheme complexity are high.

In order to strongly reduce the system complexity and in most of the cases also the number of switches, the direct AC/AC conversion stage can be split into an AC/DC and a DC/AC conversion, which is then due to the still missing intermediate energy storage a so called indirect matrix-type PFC rectifier. As proposed in [7, 8], e.g. a conventional buck-type PFC rectifier in combination with a phase-shift DC/DC converter could be used (cf. **Fig. 3(b)**). In this case, however, the conventional buck-type PFC rectifier suffers from high conduction losses in the high-frequency diodes which are needed in series to the switches [9]. Nevertheless, since with the indirect matrix-type rectifier also other more efficient AC/DC converter topologies can be combined, it offers a high flexibility and is attractive for the realization of the active front end of the DC PDA. Therefore, in order to fully utilize the potential of indirect matrix-type isolated PFC rectifiers, in this paper it is proposed to substitute the conventional buck-type PFC rectifier by a simple diode rectifier with an integrated active filter as presented in [10, 11], which in combination with

the isolated DC/DC converter provides galvanic isolation and a highly efficient PFC functionality (cf. **Fig. 4**, [12]).

As an alternative, the indirect matrix-type converter in **Fig. 3(b)** could be modified in such a way that one bridge-leg of the DC/DC converter is again integrated into the input rectifier stage, thus results in the VIENNA rectifier III [13] which could be seen as hybrid combination of a direct and an indirect matrix-type rectifier (cf. **Fig. 3(c)**). However, even if the system complexity and the number of switches are further reduced – only five instead of ten switches are needed – the large number of diodes leads to high conduction losses. Consequently, this topology is not further considered in this paper.

Utilizing the indirect matrix-type rectifier concept, a different approach is to use phase-modular converters, e.g. the isolated matrix-type Y-rectifier (IMY-rectifier) as proposed in [5, 14], where the three-phase indirect matrix-type converter is split into three separated single-phase indirect matrix-type converters (cf. **Fig. 3(d)**). Besides the advantage of modularity, since to each of the single-phase converters only the single-phase voltage is applied, 600V instead of 1200V semiconductor devices can be used, which feature a lower on-state resistance and improved switching behavior. In addition, the converter can be controlled with a simple modulation scheme that enables soft-switching for each switching transition. Hence, due to the low system complexity and the expected high efficiency, the phase-modular IMY-rectifier is another suitable option to supply the DC PDA.

Therefore, in the next section the proposed three-phase Isolated Integrated Active Filter Matrix-type (I^2AFM) PFC rectifier is presented and will be evaluated in comparison to the phase-modular IMY-rectifier.

3 Isolated Integrated Active Filter Matrix-type PFC Rectifier

3.1 Operating Principle

As shown in **Fig. 4**, the rectifier stage of the proposed I^2AFM PFC rectifier consists of a simple three-phase diode bridge rectifier with an additional injection circuit, the integrated active filter (IAF), comprising a high-frequency bridge-leg with the switches S_1 and S_2, the inductance L and the low-frequency bidirectional switches S_a, S_b and S_c. As can be noticed, as long as the injection circuit is not enabled, that means S_1 and S_2 are not switched, the input stage of the I^2AFM rectifier is working as a simple three-phase diode bridge rectifier and a highly distorted input current is flowing through the two diodes connected to the highest and lowest input voltage (cf. **Fig. 5(c)** for $t < 40$ ms). However, in order to achieve sinusoidal input currents drawn from the mains, the switches S_1 and S_2 of the injection circuit can be controlled in such a way that always a third harmonic current is impressed into the phase with the smallest input absolute voltage, i.e. the input phase which would not conduct current at that time (cf. **Fig. 5(d)** for $t > 40$ ms). Since in the three-phase mains every 60° of the mains period the smallest absolute input voltage (v_a, v_b or v_c) alternates between the input phases a, b and c, the proper phase has to be selected by turning on one of the switches S_a, S_b or S_c (cf. **Fig. 5(b)** for $t > 40$ ms). As analytically described in [10, 11], if during each 60° interval the injected current is proportional to the smallest input voltage, i.e. a 60°-portion of a sine wave, and a constant output power is delivered by the DC/DC converter stage, with this modulation scheme all input currents will show a sinusoidal shape (cf. **Fig. 5(c)** for $t > 40$ ms). The major advantages of the IAF rectifier are the relatively low implementation effort with the low component count, the simple modulation scheme and the high expected efficiency, since on the one hand for the bridge rectifier slow switching rectifier diodes with a low on-state voltage drop can be used and on the other hand in the injection circuit always only the phase current with the lowest instantaneous value has to be processed. However, assuming a certain needed intermediate capacitance C_{dc} in order to keep the inductance in the commutation path of the injection circuit and the DC/DC converter low, the output voltage v_{dc} will not be constant but will vary with a sixfold mains-frequency (cf. **Fig. 5(e)**). In fact, the output voltage is always equal to the maximum phase-to-phase input voltage since it is now defined by the diode rectifier and thus the average output voltage can also vary with the possible wide input voltage range of the local mains. Therefore, in order to eliminate the sixfold mains-frequency and to avoid large output voltage variations, the highly promising IAF rectifier has to be combined with a subsequent DC/DC converter that provides an isolated and constant output voltage. In the DC/DC stage, both half-bridges are modulated with a 50 % duty cycle, whereas the output voltage is controlled by the phase shift between the two half-bridge voltages. As already mentioned, since the instantaneous input voltage is varying
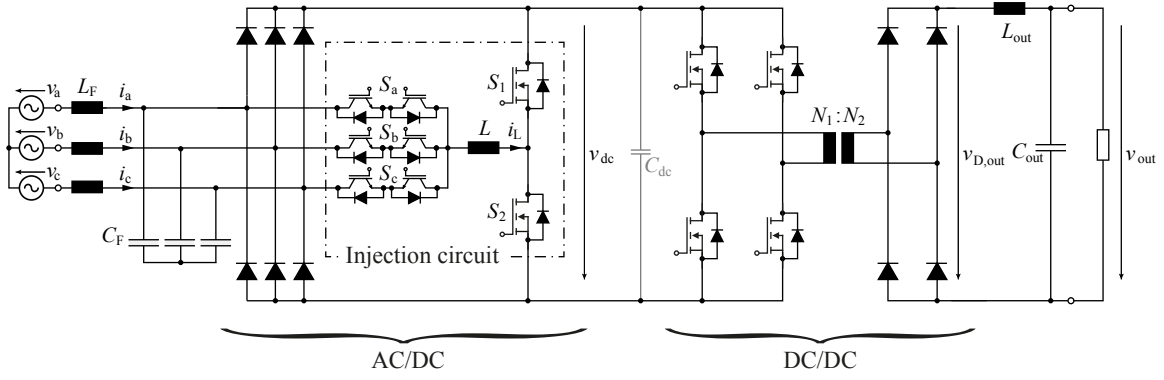
Fig. 4: Proposed Isolated Integrated Active Filter Matrix-type (I^2AFM) PFC rectifier.
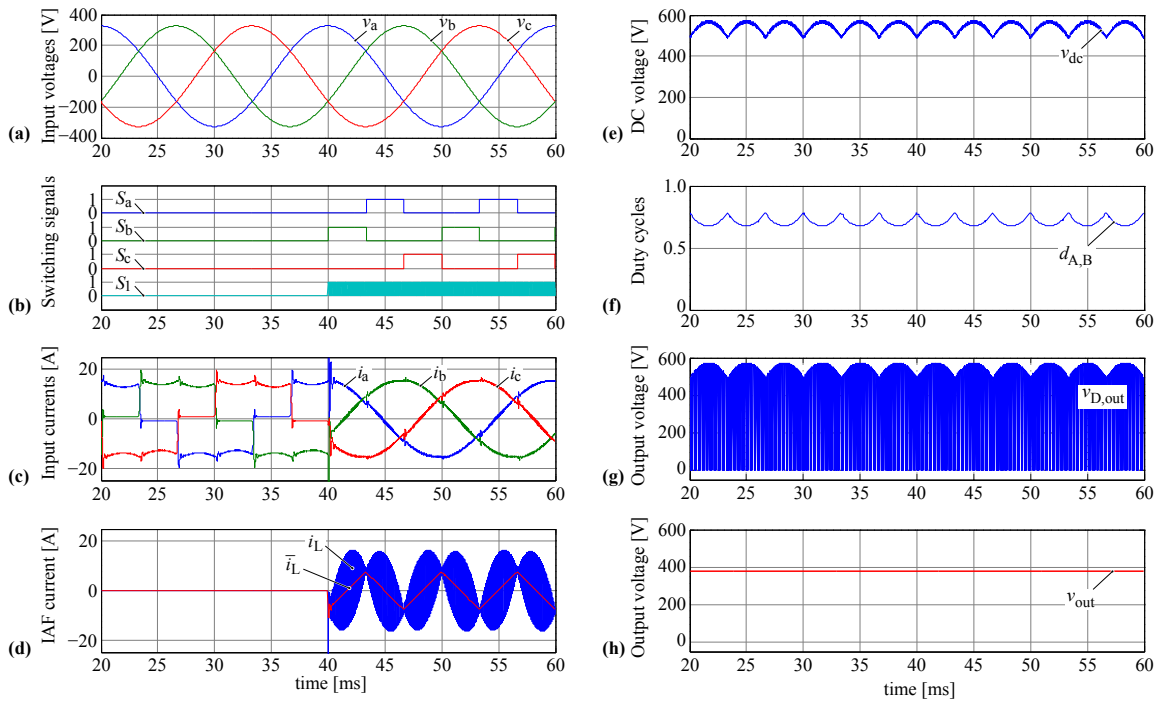

Fig. 5: Simulated waveforms of the I^2AFM PFC rectifier, where the IAF rectifier is turned on at time $t = 40$ ms, while the DC/DC stage is already in steady-state operation at $t = 0$ ms, **(a)** phase input voltages, **(b)** switching signals of the IAF rectifier, **(c)** phase input currents, **(d)** inductor current in the injection circuit, **(e)** intermediate DC-link voltage, **(f)** duty cycle of the DC/DC converter, i.e. the phase shift between the half-bridge voltages, **(g)** rectified output voltage of the transformer and **(h)** controlled output voltage.

over time, the phase shift between the two half-bridge, i.e. the duty cycle, has to be properly adapted in order to obtain a constant output voltage (cf. **Fig. 5(f)-(h)**). In addition, it is assumed that the leakage inductance of the isolation transformer is large enough and thus enables soft-switching for each switching transition. This almost eliminates all switching losses and only slightly increases the conduction losses in the switches, thus results in high overall system efficiency.

Table I: Current stresses in the semiconductor devices of the I^{2}AFM PFC rectifier. ($\hat{I}_{\text{in}}$ denotes the mains phase current amplitude and I_{dc} is the output current).

Component	Average current	RMS current
Input diodes	$\hat{I}_{\text{in}} \frac{\sqrt{3}}{2\pi}$	$\hat{I}_{\text{in}} \sqrt{\frac{1}{6} + \frac{\sqrt{3}}{8\pi}}$
Injection circuit switches $S_{\text{a}}, S_{\text{b}}, S_{\text{c}}$	$\frac{\hat{I}_{\text{in}}}{\pi} \left(1 - \frac{\sqrt{3}}{2}\right)$	$\hat{I}_{\text{in}} \sqrt{\frac{1}{12} - \frac{\sqrt{3}}{8\pi}}$
Half-bridge switches S_1, S_2	$\frac{3\hat{I}_{\text{in}}}{\pi} \left(\frac{\sqrt{3}}{2} \ln(\sqrt{3}) - \frac{\sqrt{3}-1}{2}\right)$	$\hat{I}_{\text{in}} \sqrt{\frac{3}{\pi} \left(\frac{\sqrt{3}}{2} - \frac{\pi}{6} + \frac{\sqrt{3}}{2} \ln\left(\frac{2}{\sqrt{3}}\right)\right)}$
Antiparallel diodes of switches S_1, S_2	$\frac{3\hat{I}_{\text{in}}}{\pi} \left(\frac{\sqrt{3}}{2} \ln\left(\frac{1}{\sqrt{3}}\right) + \frac{1}{2}\right)$	$\hat{I}_{\text{in}} \sqrt{\frac{3}{\pi} \left(\frac{3\sqrt{3}}{8} - \frac{\pi}{6} - \frac{\sqrt{3}}{2} \ln\left(\frac{2}{\sqrt{3}}\right)\right)}$
DC-DC converter switches	$\frac{N_2}{N_1} \frac{I_{\text{dc}}}{2}$	$\frac{N_2}{N_1} \frac{I_{\text{dc}}}{\sqrt{2}}$
DC-DC converter output diodes	$\frac{I_{\text{dc}}}{2}$	$\frac{I_{\text{dc}}}{\sqrt{2}}$

3.2 Converter Design

For the design and optimization of the proposed I^{2}AFM PFC rectifier, first the current stresses in the different components have to be calculated, which for the IAF PFC rectifier was already done in [11]. A summary of the current stresses in the semiconductor devices of the I^{2}AFM PFC rectifier is shown in **Table I**. There, a large output inductor of the DC/DC stage is assumed, whereby the switching frequency ripple of the output current can be neglected.

In order to enable a fair comparison of the proposed I^{2}AFM PFC rectifier and the IMY-rectifier, the design of the I^{2}AFM PFC rectifier is performed for the same operating conditions as described in [5] which are listed again in **Table II**.

Since in the I^{2}AFM PFC rectifier the voltage stress of all semiconductor devices is defined by the peak phase-to-phase input voltage of the three-phase mains, 1200V instead of 600V semiconductor devices have to be used. A major part of the losses in the IAF PFC rectifier result due to the conduction losses in the input bridge rectifier, which rectifies the low frequency input voltage. Therefore, silicon diodes with low forward voltage drop have to be selected, in order to keep the efficiency high. Based on the specification given in **Table II**, with the selected 1200V/45A diodes (DSP45-12A) the conduction losses in the input rectifier are 23.6 W.

For the bidirectional switches S_{a}, S_{b} and S_{c} of the injection circuit which also switch at low switching frequency – two times the mains frequency – the switching losses are negligible and therefore can be implemented with two standard IGBTs connected in anti-series that feature a low forward voltage drop. Alternatively, it would be also possible to use reverse blocking IGBTs in antiparallel connection, which would reduce the conduction losses from 6.6 W to 5 W. However, due to the limited availability of RB-IGBT, 1200V/40A standard IGBTs (IHW40T120) with integrated antiparallel diodes are used.

In contrast to the bidirectional switches S_{a}, S_{b} and S_{c}, for the switches S_1 and S_2 of the high-frequency bridge-leg, that controls the current over the IAF inductor L, the switching losses have to be considered. Due to the needed blocking voltage of 1200V silicon MOSFETs are not applicable, thus the selection of the proper switch technology is limited to either IGBTs which are optimized for fast switching applications (e.g. 1200V, 40A, IGW40N120H3) or Silicon Carbide (SiC) MOSFETs (1200V, 80 mΩ, C2M0080120D). Although the conduction losses in both cases are low (4.6 W with IGBTs and 1.6 W with SiC-MOSFETs),

Table II: Electrical specifications used for the comparative evaluation of the I^{2}AFM PFC rectifier and the IMY-rectifier.

Parameter	Value
Nominal power P_0	7.5 kW
Output voltage V_{out}	380 V
Input voltage V_{N}	400 V$_{\text{ph-ph,rms}}$
Switching frequency f_{sw}	48 kHz

Table III: Main components of the I^{2}AFM PFC rectifier prototype.

Component	Value/details
Input diodes	1200 V/45 A rectifier diodes (DSP45-12A)
Inj. circuit switches S_a, S_b, S_c	1200 V/40 A IGBTs (IHW40T120)
Half-bridge switches S_1, S_2	1200 V/31.6 A SiC MOSFETs (C2M0080120D)
DC/DC converter switches	1200 V/31.6 A SiC MOSFETs (C2M0080120D)
DC/DC converter output diodes	1200 V/54 A SiC diodes (C4D40120D)
IAF inductor L	380 μH, 1 pair E55 N87 cores, 3x1.4 mm air gap, 36 turns of 2 mm, 0.1 mm/175 strands litz wire
Isolation transformers	Stack of two E55 N87 cores, $N_1/N_2 = 16/16$, 40 μm/270 strands litz wire (4 in parallel)
Filter inductor L_{out}	2x497 μH, E55 N87 cores, 3x0.8 mm air gap, 34 turns of 2.5 mm solid copper wire

the switching losses in the IGBTs (36 W) are five times higher than for the SiC-MOSFETs (6.7 W) assuming a switching frequency of 48 kHz.

Consequently, the switches S_1 and S_2 of the injection circuit as well as the switches of the DC/DC converter's full-bridge are realized with SiC-MOSFETs, even if the full-bridge can be operated in soft-switching at nominal output power. However, namely at low load conditions, where the current in the leakage inductance is no more sufficient to charge/discharge the output capacitances of the switches, soft-switching is lost resulting in high switching losses. The conduction losses in the DC/DC converter's full-bridge are calculated to 44.9 W at nominal output power.

Due to the high switching frequency and the hard commutation of the output rectifier, which would lead to high reverse recovery losses if silicon diodes would be used, the output diode bridge is realized with 1200V SiC Schottky diodes (C4D40120D). Even if the reverse recovery losses can be neglected in this case, the conduction losses in the output rectifier of 83 W (together with the conduction losses of the full-bridge) are dominating the achievable efficiency of the DC/DC stage, since the forward voltage drop of SiC Schottky diodes compared to silicon diodes is relatively high.

In order to keep the input filter effort low and due to reasons of system controllability, the inductor L of the IAF rectifier's injection circuit is designed with respect to a maximum current ripple which has to be below 50 % of the peak input current. Based on this assumption, an inductor optimization considering different core types and wires (solid and litz wire) is performed, and the inductor design offering the best compromise between losses and volume is selected. The same optimization procedure of the magnetic components was also applied for the design of the output inductor L_{out}, however with a lower current ripple of 2.5A (25 %), as well as for the isolation transformer. The turns ratio of the isolation transformer was selected to $N_1/N_2 = 1$, which still allows a 15 % voltage margin for the output voltage control at minimum input voltage. Details concerning the design of the magnetic components and a list of the selected semiconductor devices are summarized in **Table III**.

The corresponding 3D CAD model of the designed laboratory prototype is visualized in **Fig. 6(b)**. In order to show the placement of the described power components, the top board containing the EMI filter, control board and output capacitors has been omitted. Based on this design, a total volume of 4.68 dm^3 and/or a power density of 1.6 kW/dm^3 is achieved.

For the sake of completeness, it has to be mentioned that the DC/DC stage of the laboratory prototype is advantageously realized with two parallel DC/DC converters (cf. **Fig. 6(a)**). Consequently, on the one hand the efficiency can be further increased, especially in part load below 50 % where e.g. one DC/DC converter can be turned off, and on the other hand the current ripple in the output capacitor can be reduced by interleaving the switching signals of two parallel DC/DC converters.
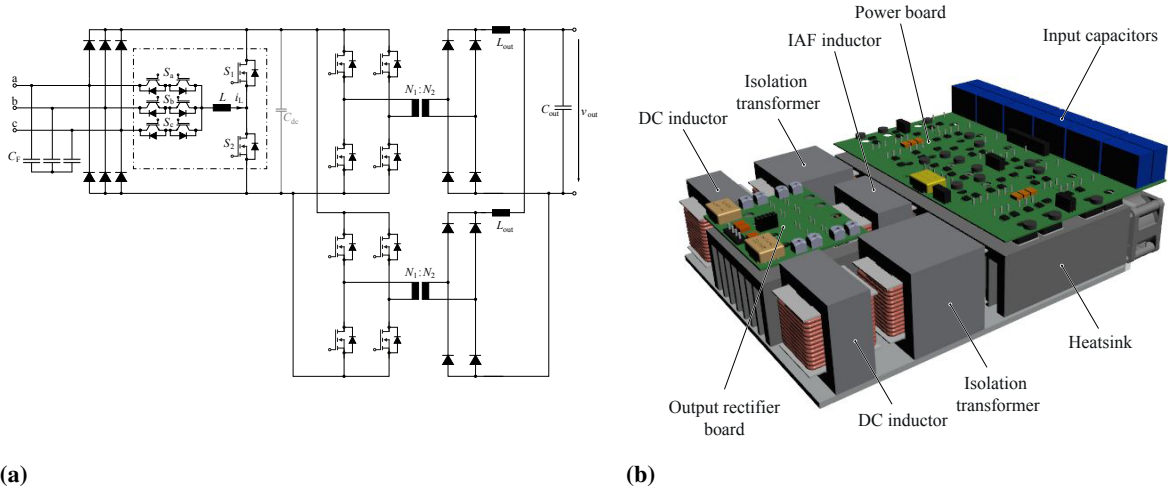
(a)   **(b)**

Fig. 6: I^{2}AFM PFC rectifier 7.5 kW laboratory prototype, **(a)** circuit diagram with two parallel interleaved DC/DC converters, **(b)** 3D CAD model of the converter without the top PCB.

4 Comparative Evaluation of Three-Phase Isolated Matrix-Type PFC Rectifiers

Based on the specifications given in **Table II**, now the performance of the proposed and designed I^{2}AFM PFC rectifier is compared to the also promising phase-modular IMY-rectifier presented in [5] (cf. **Fig. 3(d)**). Two alternative implementations for each PFC rectifier topology are considered for the comparative evaluation:

- I^{2}AFM PFC rectifier with a DC/DC stage consisting of only one DC/DC converter;
- I^{2}AFM PFC rectifier with a DC/DC stage consisting of two parallel DC/DC converters;
- IMY-rectifier where each switch of the full-bridge is implemented with only a single MOSFET of the CFD-CoolMOS series from Infineon (IPW65R041CFD);
- IMY-rectifier where each switch of the full-bridge is implemented with two parallel MOSFETs of the CFD-CoolMOS series (IPW65R041CFD).

For the efficiency calculations of the two considered implementations of the I^{2}AFM PFC rectifier, the analytical equations for the current ratings given in **Table I** and the devices listed in **Table III** are used. The efficiency of the phase-modular IMY-rectifier is calculated according to the design presented in [5]. In addition, for both PFC rectifier topologies it is considered that in the full-bridges soft-switching is only achieved above a certain minimum output power and thus in low load operation the switching losses have to be taken into account.

The calculated efficiencies of the different implementations as a function of the load power are shown in **Fig. 7(a)**. At nominal load, with the I^{2}AFM PFC rectifier and a DC/DC stage consisting of only one DC/DC converter an overall efficiency of 97 % can be achieved, which can be increased to 97.6 % if a second DC/DC converter is connected in parallel. The maximum efficiency of 97.7 % is achieved at 25 % of the nominal load, whereas 20.8 % (12.1W) of the losses are generated in the AC/DC stage and 79.2 % (45.9W) in the DC/DC stage. As already mentioned, in order to improve the low load behavior of the I^{2}AFM PFC rectifier, the second DC/DC stage is turned off when the load current is below a certain limit and therefore the efficiencies of both implementations, with either one or two DC/DC converters, are the same (cf. **Fig. 7(a)**).

In contrast, the achievable efficiency of the IMY-rectifier is considerably lower, which is 95.3 % if only one MOSFET is used per switch and 96 % if two parallel MOSFETs are used per switch [5] (cf. **Fig. 7(a)**). The main reasons for the difference in efficiency can be found in the conduction losses of the input diode rectifier, the full-bridge and the transformer, which in the IMY-rectifier are almost twice to three times higher than those of the I^{2}AFM PFC rectifier (cf. **Fig. 7(b)**). In all three cases this can principally be
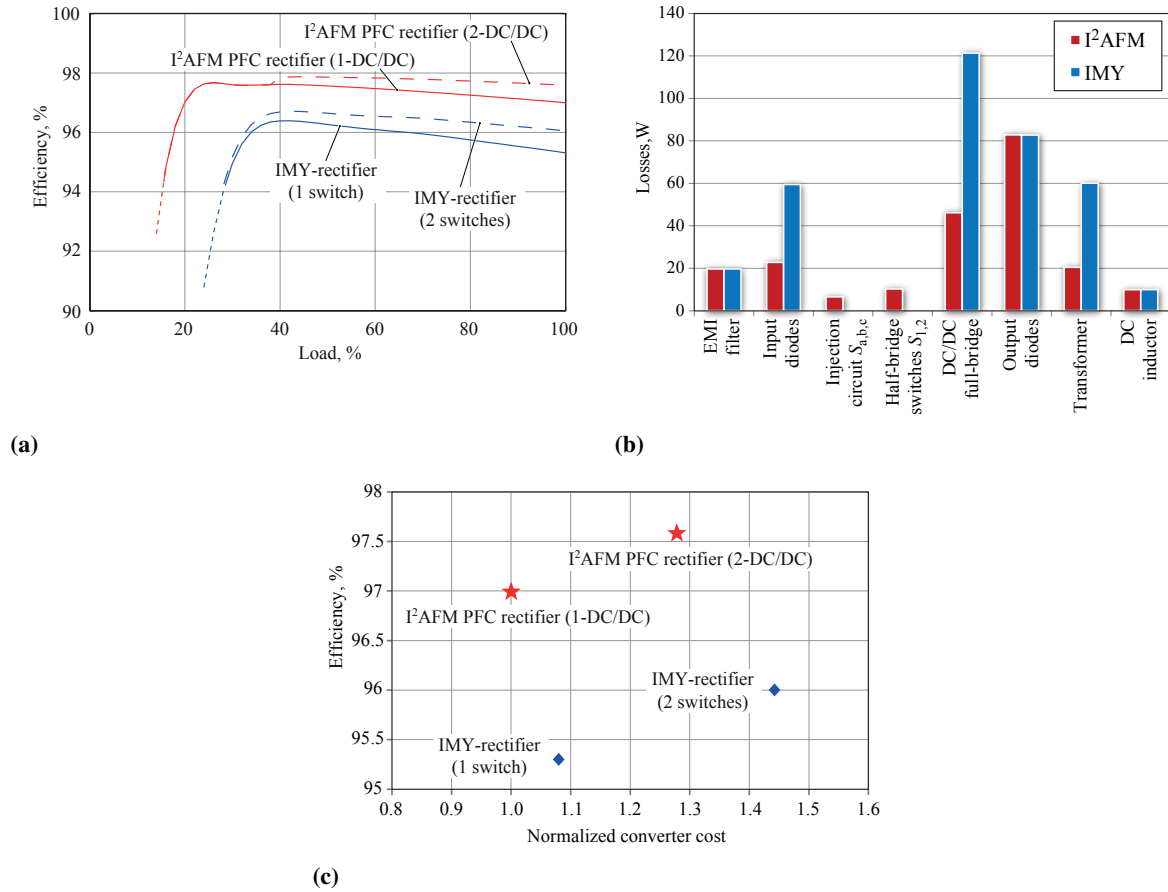
(a)

(b)

(c)

Fig. 7: Comparative evaluation of the I²AFM PFC rectifier and the IMY-rectifier, **(a)** achievable efficiency at different load conditions, **(b)** calculated loss distribution at nominal load of 7.5 kW and **(c)** resulting efficiencies at nominal load of 7.5 kW with respect to the normalized converter costs considering the power semiconductors and main passive components.

explained by the higher number of components which are needed in the IMY-rectifier compared to the I²AFM PFC rectifier; 12 instead of 6 input diodes, 12 instead of 4 switches in the full-bridge and 3 transformers instead of 1 transformer. In addition, each input diode of the IMY-rectifier is conducting the input current during one half-cycle of the mains voltage, while in the I²AFM PFC rectifier an input diode is only conducting during one third of the mains period. Hence, due to the same input current amplitude in both converter topologies, for the IMY-rectifier this results in higher average and RMS currents and consequently in higher conduction losses. Furthermore, even if in the IMY-rectifier 650V-CoolMOS devices with a superior low on-state resistance can be used, the three times larger number of switches results in more than twice the conduction losses in the full-bridge compared to the I²AFM PFC rectifier. Despite the fact that additional losses are generated in the injection circuit (cf. **Fig. 7(b)**), the IMY-rectifier can't compete in efficiency, since the losses in the injection circuit are moderate compared to the overall I²AFM PFC rectifier losses (cf. **Fig. 7(b)**).

Besides the achievable efficiency the comparative evaluation also considers another aspect, namely the resulting material costs of each PFC rectifier topology. In **Fig. 7(c)** a normalized cost comparison considering the costs of the power components is shown, where the prices for the semiconductor devices and passive components have been extracted from distributor's data, i.e. the price for 1000 pieces. It can be noticed that for both PFC rectifier topologies the costs are very similar (difference of only 8 %) if in the IMY-rectifier only one MOSFET per switch and in the I²AFM PFC rectifier only one DC/DC converter is used (**Fig. 7(c)**). Improving the efficiency of both rectifier topologies by approximately 0.6 % (45W), by either adding a second MOSFET per switch in the IMY-rectifier or a DC/DC converter in the I²AFM PFC rectifier, increases the corresponding costs by 33 % and 28 %, respectively. This relatively strong increase in costs clearly shows that the expensive semiconductor devices account for the largest share of the overall costs.

5 Conclusions

This paper gives an overview of isolated matrix-type PFC rectifier topologies suitable for facility-level DC PDA for more efficient telco and data centers. In the comparative evaluation of isolated three-phase PFC rectifier systems it is shown that matrix-type PFC rectifier topologies offer the advantage of performing PFC functionality and galvanic isolation in a conversion single-stage. On the one hand, this potentially enables higher system efficiency compared to two-stage concepts and on the other hand, the bulky mains transformer, which is typically used in existing power distribution systems, can be omitted. Furthermore, in this paper a new isolated matrix-type PFC rectifier topology is proposed, the I^2AFM PFC rectifier. The I^2AFM PFC rectifier features an indirect matrix converter structure which basically is a combination of an AC/DC stage and a subsequent DC/DC stage without intermediate energy storage elements. The rectification with PFC functionality is performed with a simple three-phase diode rectifier circuit with an additional injection circuit, the IAF-rectifier. The major advantages of the IAF-rectifier are the relatively low implementation effort with the low component count, the simple modulation scheme and its high efficiency.

The performance of the designed I^2AFM PFC rectifier is evaluated in comparison with the phase-modular IMY-rectifier, which is also a promising solution for the realization of the active front end of the DC PDA. It is shown that with the proposed I^2AFM PFC rectifier an almost 2 % higher efficiency can be achieved compared to the IMY-rectifier, even if the material costs are approximately the same. With a single DC/DC output stage of the I^2AFM system the achievable efficiency at nominal load is 97 %, and can be improved up to 97.6 % if a second DC/DC converter is used in parallel. Future work includes the realization of a 7.5 kW laboratory prototype to experimentally verify the presented converter performance.

References

[1] A. Pratt, P. Kumar, and T. Aldridge, "Evaluation of 400v dc distribution in telco and data centers to improve energy efficiency," in *Proc. of 29th International Telecommunications Energy Conference (INTELEC)*, 2007, pp. 32–39.

[2] E. Waffenschmidt and U. Boeke, "Low voltage dc grids," in *Proc. of 35th International Telecommunications Energy Conference (INTELEC)*, 2013, pp. 1–6.

[3] M. Noritake, T. Ushirokawa, K. Hirose, and M. Mino, "Verification of 380V dc distribution system availability based on demonstration tests," in *Proc. of 33rd International Telecommunications Energy Conference (INTELEC)*, 2011, pp. 1–6.

[4] M. Salato, A. Zolj, D. Becker, and B. J. Sonnenberg, "Power system architectures for 380V dc distribution in telecom datacenters," in *Proc. of 34th International Telecommunications Energy Conference (INTELEC)*, 2012, pp. 1–7.

[5] P. Cortes, L. Fässler, D. Bortis, M. Silva, and J. W. Kolar, "Detailed analysis and design of a three-phase phase-modular isolated matrix-type PFC rectifier," in *Proc. of International Power Electronics Conference - ECCE Asia (IPEC)*, 2014, pp. 3864–3871.

[6] V. Vlatkovic, D. Borojevic, X. Zhuang, and F. Lee, "Analysis and design of a zero-voltage switched, three-phase PWM rectifier with power factor correction," in *Proc. of 23rd Annual IEEE Power Electronics Specialists Conference (PESC)*, vol. 2, 1992, pp. 1352–1360.

[7] S. Manias and P. Ziogas, "A novel sinewave in ac to dc converter with high-frequency transformer isolation," *IEEE Transactions on Industrial Electronics*, vol. IE-32, no. 4, pp. 430–438, 1985.

[8] K. Wang, F. Lee, D. Boroyevich, and X. Yan, "A new quasi-single-stage isolated three-phase ZVZCS buck PWM rectifier," in *Proc. of 27th Annual IEEE Power Electronics Specialists Conference (PESC)*, 1996, pp. 449–455.

[9] A. Stupar, T. Friedli, J. Miniböck and J. W. Kolar, "Towards a 99% efficient three-phase buck-type PFC rectifier for 400-V dc distribution systems," *IEEE Transactions on Power Electronics*, Vol. 27, No. 4, pp. 1732–1744, April 2012.

[10] H. Yoo and S.-K. Sul, "A new circuit design and control to reduce input harmonic current for a three-phase ac machine drive system having a very small dc-link capacitor," in *Proc. of 25th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2010, pp. 611–618.

[11] T. Soeiro, T. Friedli, and J. W. Kolar, "Three-phase high power factor mains interface concepts for electric vehicle battery charging systems," in *Proc. of 27th Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2012, pp. 2603–2610.

[12] T. Soeiro, "High efficiency electrostatic precipitator systems with low effects on the mains," PhD. Dissertation, ETH Zurich, 2012.

[13] J. W. Kolar, U. Drofenik, H. Ertl, and F. Zach, "VIENNA Rectifier III - A novel three-phase single-stage buck-derived unity power factor ac-to-dc converter system," in *Proc. of IEEE Nordic Workshop on Power and Industrial Electronics (NORPIE)*, 1998, pp. 9–18.

[14] P. Cortes, J. Huber, M. Silva, and J. W. Kolar, "New modulation and control scheme for phase-modular isolated matrix-type three-phase ac/dc converter," in *Proc. of 39nd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, 2013, pp. 4897–4904.