12-Pulse Rectifier for More Electric Aircraft Applications

G. Gong, U. Drofenik and J.W. Kolar

ETH Zurich, Power Electronic Systems Laboratory
ETH Zentrum / ETL H23, Physikstr. 3, CH-8092 Zurich / SWITZERLAND
Tel.: +41-1-632 2833 Fax.: +41-1-632 1212
email: kolar@lem.ee.ethz.ch

Abstract. *- A high power density 10kW three-phase 12-pulse rectifier is analyzed for applications in future More Electric Aircrafts. The experimental results, which are in good accordance with the theory, show high efficiency and low input current harmonics for a wide operating range. Furthermore, two novel rectifier topologies, which are formed by combining the passive 12-pulse rectifier with a boost stage on the DC side are proposed. This allows to guarantee a constant output voltage and/or to overcome the problem of the dependency of output voltage on the mains voltage amplitude and output power level.*

I INTRODUCTION

The More Electric Aircraft concept, which is a new and basic concept of utilizing electric power to drive aircraft subsystems, is widely recognized as the future trend in the aerospace industry. Accordingly, there is a growing interest in the industry in technology to ensure that the subsystems are ultra-reliable, easy to maintain, low in cost and of high performance. As one essential part of the power distribution systems, AC/DC converters, which are connected to a variable frequency AC bus are employed for supplying power to all kinds of DC loads. Such systems are required to show low volume, high reliability, ability to carry over-current and low input current harmonics [1],[2],[3].

Passive converter systems with approximately sinusoidal input currents like the 12-pulse rectifier, as shown in **Fig.1**(a), are typically used in mid- and high-power applications [4]. Such passive systems do not require control electronics and are therefore characterized by a very low realization effort and high reliability. However, the required mains frequency magnetic components result in a low power density and high system weight.

Typically, in future aircraft power systems, the AC bus frequency ranges from 360Hz to 800Hz. Therefore, the size of the magnetic components of 12-pulse rectifiers can be significantly reduced as compared to a 50Hz mains operation. The 10kW prototype of a three-phase 12-pulse rectifier is shown in Fig.1(b). Surprisingly, the volume of this passive system is comparable to the volume of an active three-phase PWM rectifier systems [5] of the equal rated power.

In this paper experimental results derived from a 10kW prototype will be given and compared to numerical simulations. Furthermore, it will be shown how to actively control the DC output voltage of the 12-pulse converter by simply adding a turn-off power semiconductor and a power diode on the DC side resembling a boost stage. This approach results in a significant improvement of the functionality of the converter system. For further improvement a topology is proposed where a second active power switch enables interleaved operation of the output stage.

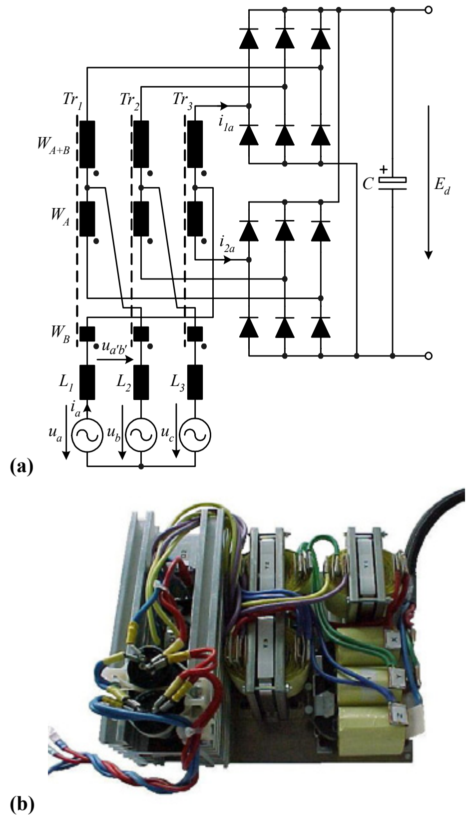


Fig.1: Topology of a passive three-phase12-pulse rectifier **(a)** and 10kW prototype of the system **(b)** with overall dimensions of 22 x 17 x 10 cm^3 and a weight of 4.4kg.

II PASSIVE 12-PULSE RECTIFIER

The prototype 10kW three-phase 12-pulse rectifier designed for an aircraft power system is introduced in this section. There, the specifications are given as:

Input phase voltage: $U_N = 96V_{rms} \ldots 132V_{rms}$

Input frequency:	f_N = 360Hz…800Hz
Nominal input phase voltage:	$U_{N,r}$ =115V_{rms}
Nominal input frequency:	$f_{N,r}$=400Hz
Nominal output power:	$P_{O,r}$=10kW
Max. admissible curr. harmonics:	$I_{N,(11)} \leq 0.10\, I_{N,(1)}$ $I_{N,(13)} \leq 0.08\, I_{N,(1)}$

Table 1 compiles the components employed in the 10kW prototype. The three input inductors L_1, L_2, L_3 are realized using a three-limb magnetic core.

TABLE 1
LIST OF COMPONENTS OF 12-PULSE RECTIFIER

Name	Denomination	Type
Input Inductors	L_1, L_2, L_3	Value: 188µH Magnetic Core: S3U 48b Material: Trafoperm N2/0.1mm
Line Interphase Transformer	Tr_1,Tr_2, Tr_3	Value: L_{WA+B} = 66mH, L_{WA} = 35.4mH, L_{WB} = 4.74mH Magnetic Core: 2 × SM 65 Material: Trafoperm N2/0.1mm
Diode Bridge		2 × IXYS VUE 35-06NO7
Output Capacitor	C	2 × 470µF/400 VDC

The no load output voltage E_d of the passive 12-pulse rectifier is

$$E_d = 1.52\hat{U}_a \tag{1}$$

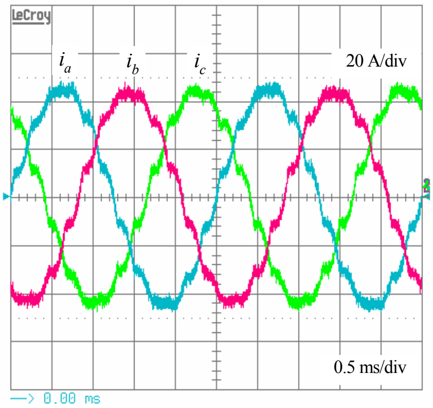
where $\hat{U}_a$ is the amplitude of the mains phase voltage [6]. The turns ratio of the transformer must fulfill

$$W_B / W_A = 0.366 \tag{2}$$

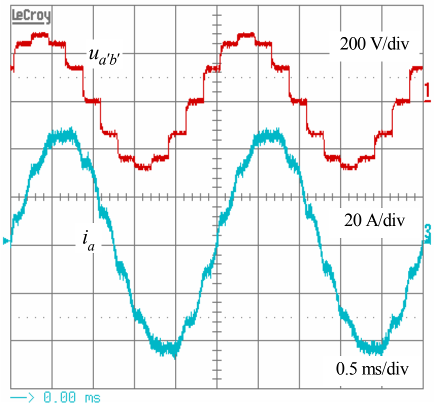
in order to achieve the necessary ±15° phase shift of the partial input currents i_{1a} and i_{2a}.

The measured rectifier input phase currents are shown in **Fig.2**(a) for the operating point U_N = 115V, f_N = 400Hz, P_O = 10kW, the time behavior of the line interphase transformer input voltage $u_{a'b'}$ (cf. Fig.1) and of phase current i_a are depicted in Fig.2(b). The waveform of voltage $u_{a'b'}$ clearly shows the 12-pulse shape which is characteristic for the passive rectifier system.

Due to the characteristics of passive multi-pulse rectifier systems the input current harmonics are occurring at multiples of the pulse number, i.e. a 12-pulse system will show current harmonics at ordinal numbers n= 11,13,23,25 etc. One of the requirements for the rectifier system is a limitation of the amplitudes of the low frequency input current harmonics, where the 11th and 13th harmonics must be lower than 10% and/or 8% of the input current fundamental.



(a)



(b)

Fig.2: Experimental results of 12-pulse rectifier at operating point U_N = 115V, f_N= 400Hz, P_o = 10kW; **(a)** input currents i_a, i_b and i_c, **(b)** voltage $u_{a'b'}$ and phase current i_a (cf. Fig.1).

The amplitude of the low frequency current harmonics is determined by the harmonics of the 12-pulse line interphase transformer input voltage (cf. Fig.2(b)) in combination with the input inductors. For fulfilling the requirements concerning current harmonics in the case at hand L=L_1=L_2=L_3=188µH (cf. Tab.1) has been selected.

The spectrum of the rectifier input current is shown in **Fig.3** for different operating points. On the left-hand side, the current harmonics resulting from measurement are depicted, which are in good agreement with the results of the numerical simulation shown on the right-hand side. The 5th and 7th harmonics being present in the measured spectrum are caused by the magnetic asymmetry of the three-limb core employed for realizing the input inductors.

Maximum current harmonics occur at maximum input voltage and minimum input frequency, i.e. for 132V_{rms}/360Hz. The amplitudes of the harmonics are by

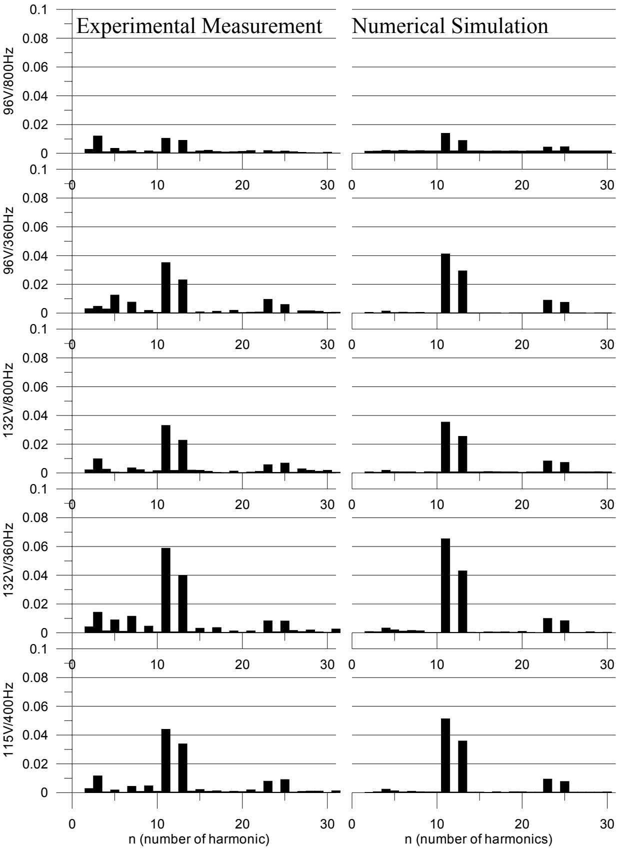


Fig.3: Comparison between experimental analysis and numerical simulation of the low-order harmonics (normalized to the fundamental) of the input current of the 12-pulse rectifier for different operating points: $96V_{rms}$/800Hz, $96V_{rms}$/360Hz, $132V_{rms}$/800Hz, $132V_{rms}$/360Hz, $115V_{rms}$/400Hz at 10kW output power.

more than 30% lower than required (cf. Fig.3). This is due to the stray inductance of the transformer which has been neglected for the calculation of the required input inductor value.

As one can see from **Fig.4**, **Fig.5** and **Fig.6**, the output voltage, system efficiency and power factor are relatively independent of the output power for most operating points. Only the operating point of $96V_{rms}$/800Hz shows a strong load-dependency of the system efficiency and power factor at higher output power levels. Obviously, with low input voltage the input currents are accordingly high in order to provide the required output power. This results in high copper losses of the magnetic components and high conduction losses of the power diodes. Additionally, a high input frequency results in high iron losses of the inductors and transformers, contributing to a relatively low system efficiency.

Especially at the operating point of $96V_{rms}$/800Hz a general problem of the passive systems can be seen: For low input voltage and, therefore, increased input current there is a relatively large voltage drop across the input inductors. At higher frequencies this voltage drop is further increased. Therefore, besides a reduction of the output voltage there occurs also a phase shift between mains voltage and mains current and/or a reduced power factor (cf. **Fig.6**). Due to the reduced power factor again a higher input current amplitude is needed for providing the output power what further increases the voltage drop.

Accordingly, there is a natural limit for the power the multi-pulse system can deliver

$$P_{O,\max} = \frac{3}{2}\frac{\hat{U}_N^2}{2\omega L} \quad . \qquad (3)$$

For an output power of 10kW at $96V_{rms}$/800Hz the system operation is close to this natural limit. Since the size of the inductors is determined by the input current harmonic limits, the only way would be to employ a 18-pulse rectifier system if operation at a lower input voltage and/or higher input frequency is required.

III 12-PULSE RECTIFIER WITH OUTPUT VOLTAGE CONTROL

An obvious disadvantage of 12-pulse rectifier, especially if compared to an active pulse width modulated (PMW) rectifier systems, is the missing controllability of the output voltage, i.e. the dependency of the output voltage on the mains voltage amplitude and on the load. In the following, two novel topologies which allow a control of the output

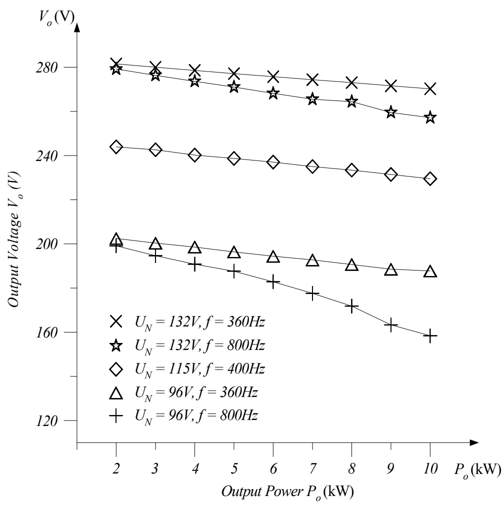


Fig.4: Measured output voltage in dependency on the output power for characteristic operating points.

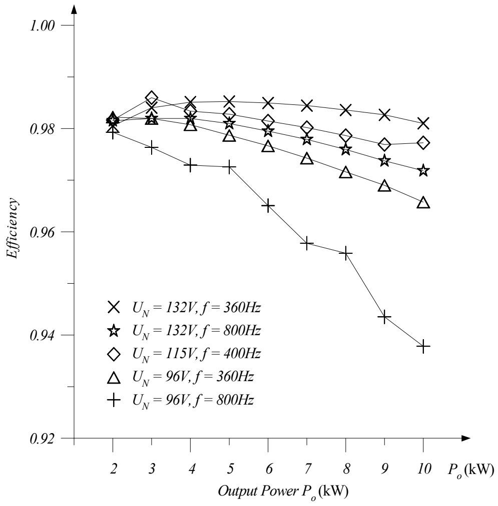


Fig.5: Measured efficiency in dependency on the output power for characteristic operating points.

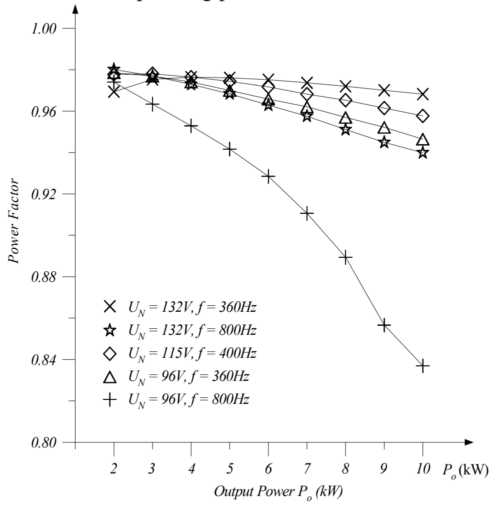


Fig.6: Measured power factor in dependency on the output power for characteristic operating points.

voltage by adding a minimum number of active components and a very simple control are proposed. Due to the simplicity of the approach the main advantages of the passive system, i.e. low complexity and high reliability, are still given.

A 12-pulse Rectifier Followed by a Single Switch Boost Stage

The topology of a 12-pulse rectifier followed by a single switch boost stage is shown in **Fig.7**.

The output voltage of the system can easily be derived as

$$U_o = \frac{E_d}{1 - D_1} \tag{4}$$

where, D_1 is the duty cycle ratio of the power transistor T_1. Combining (1) and (3), we obtain

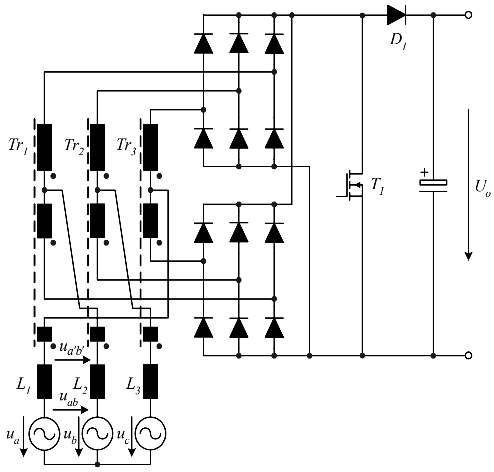
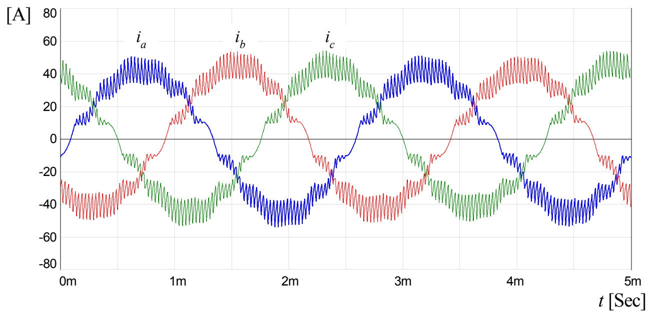
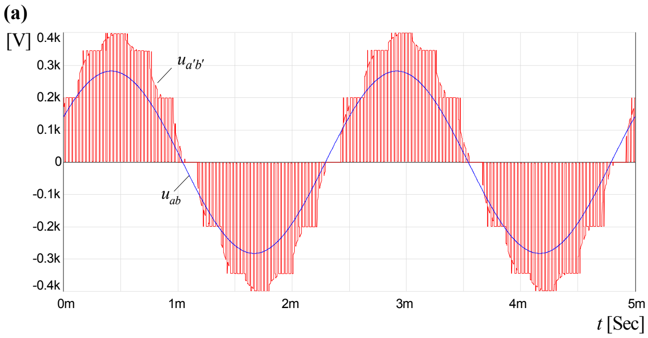


Fig.7: Proposed 12-pulse rectifier followed by a single switch boost stage which allows to control the system output voltage to a constant level independent of input voltage and load changes.



(a)



(b)

Fig.8: Simulation of proposed 12-pulse rectifier with controlled output voltage (cf. Fig.7); **(a)** time behavior of three-phase input currents i_a, i_b and i_c and of the line interphase transformer input voltage $u_{a'b'}$ and the mains line-to-line voltage u_{ab} (cf. **(b)**).

$$U_o = \frac{1.52\hat{U}_a}{1 - D_1}\,. \tag{5}$$

In **Fig.8**(a), the results of a numerical simulation of the system input phase currents are shown. The voltage $u_{a'b'}$ and line voltage u_{ab} are depicted in Fig.8(b). The simulation parameters are U_N = 115V_{rms}, f_N = 400Hz, P_{out} = 10kW, switching frequency f_P = 33kHz, duty cycle ratio D_I = 0.3. The 12-pulse shape of the line interphase transformer input voltage $u_{a'b'}$ is still visible, despite the chopping with switching frequency.

B 12-pulse Rectifier Followed by Interleaved Boost Stage

For reducing the switching frequency current ripple in the input inductors, a two-switch interleaved boost stage could be employed as shown in **Fig.9**. The power transistors T_1 and T_2 are operating in interleaved manner with equal duty cycle.

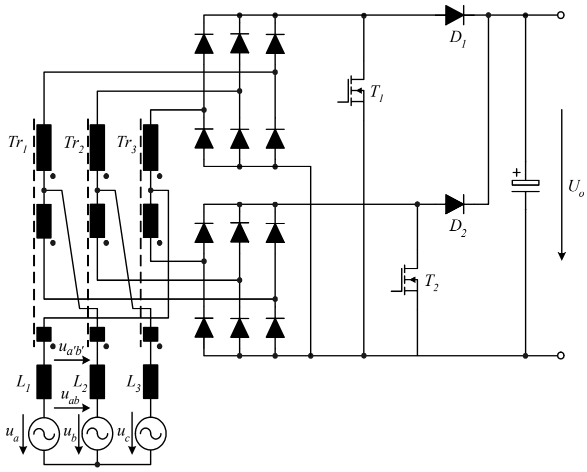


Fig.9: 12-pulse rectifier followed by interleaved boost stage. For guaranteeing a symmetric partitioning of the input current to the output stages a zero sequence current control has to be employed.

The output voltage of the system shown in Fig.9 can be deduced analogous to (4) as

$$U_o = \frac{1.52\hat{U}_a}{1-D_2} \tag{6}$$

where D_2 is the duty cycle ratio of power transistors T_1 and T_2.

In **Fig.10**(a), the simulated time behavior of the input currents of the system shown in Fig.9 is depicted. The line interphase transformer input voltage $u_{a'b'}$ and mains voltage u_{ab} are shown in Fig.10(b). The simulation parameters are again (as for Fig.8): U_N = 115V, f_N= 400Hz, P_O= 10kW, switching frequency f_P = 33KHz, duty ratio D_2= 0.3. The switching frequency current ripple is considerably smaller as compared to employing only a single boost transistor, as the switching frequency voltage drop across the input inductors is reduced and the equivalent switching frequency is doubled.

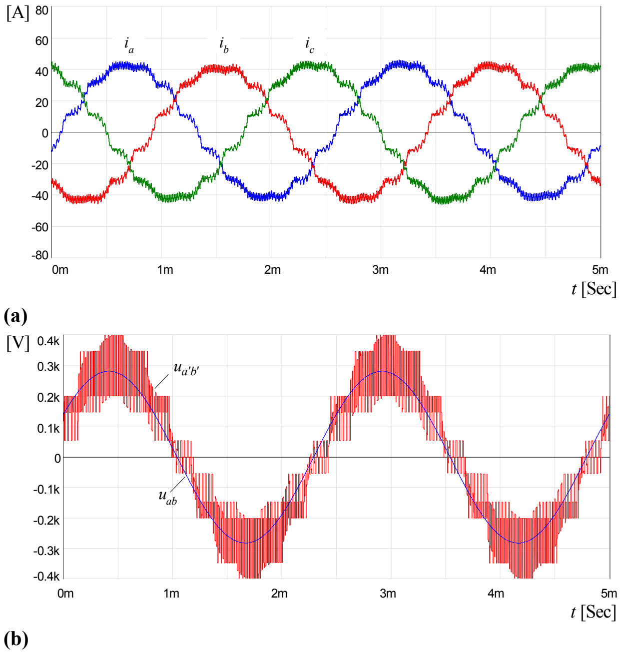


Fig.10: Simulation of the 12-pulse rectifier with controlled output voltage (cf. Fig.9); **(a)** time behavior of three-phase input currents i_a, i_b and i_c and of the line interphase transformer input voltage $u_{a'b'}$ and the mains line-to-line voltage u_{ab} (cf. **(b)**).

IV Conclusions

A high power density 10kW three-phase 12-pulse rectifier is analyzed for applications in More Electric Aircrafts. The experimental results, which are in good accordance with the theory, show a high overall efficiency and low input current harmonics for a wide operating range. A detailed design procedure for the system including the input side inductors and the transformers will be given in a future paper, especially with respect to the required limitation for the input current harmonics.

Furthermore, two novel rectifier topologies, which are formed by combining the passive 12-pulse rectifier with a boost stage connected in series on the DC side are proposed. The systems allow to guarantee a constant output voltage and/or to overcome the problem of the dependency of output voltage of the purely passive system on the mains voltage amplitude and output power level. There, the main advantages of passive multi-pulse systems as compared to an active PWM rectifier system, i.e. low complexity and high reliability, remain valid.

Therefore, in the course of further research the proposed hybrid 12-pulse rectifier systems will be analyzed in detail for airborne applications in comparison to an active PMW rectifier system based on the VIENNA rectifier concept.

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