A Robust 12kW Three-Phase Rectifier using a 18-Pulse Autotransformer and Isolated DC-DC Converters

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***Abstract* – A robust 12 kW rectifier with low THD in the line currents, based on an 18-pulse transformer arrangement and high-frequency isolation, is presented in this work. Three full-bridge converters are used to allow isolation and to balance the DC-link currents, without current sensing or current controller. The topology provides a regulated DC output with a very simple control strategy. Preliminary simulation and experimental results are presented in the digest.**

I. Introduction

Recent AC-DC converters used to supply telecommunications equipments are expected to draw a sine-wave current from the utility, with a power factor very close to unity.

Single-phase rectifiers meeting this requirement are well known and widely used. The standard solution uses a PWM boost DC-DC converter following the front-end full-wave diode rectifier. However, in medium power applications (6kW or higher), the single-phase solution is not convenient and three-phase AC-DC topologies are required.

In the same way that a great number of works have been developed for power factor correction in single-phase systems, the three phase techniques are growing constantly [1]. This growth also applies to converters with one or more associated switches, or by using specially connected transformers or mixed systems with transformers and static converters.

The simplest solution uses a three-phase diode rectifier, associated with passive filters to minimize the harmonic currents in the utility lines. Isolation can be obtained by use of a conventional low frequency Δ/Y transformer, resulting in bulky, heavy and expensive equipment. At the opposite extreme, we find the classic three-phase PWM, which requires a circuitry with complex control, modulation and commutation techniques.

Since isolation at the input is not required, the polyphase transformer arrangements [2-5] and the line inter-phase transformers (LIT) [6, 7] are very useful to improve the quality of the utility line current. These transformers present a reduced kVA capacity. The 18-pulse converter, using a Y or Δ-connected differential autotransformer, is very interesting since it allows natural high power factor correction (the lowest order harmonics are the 17^{th} and the 19^{th}). The autotransformer is designed to feed three six-pulse bridge rectifiers displaced in phase by 20^o and to rate about 20% of the output kVA. Usually, to provide parallel-connected output voltages, two Interphase Transformers (IPT), connected on the DC sides of the three bridge rectifiers, are required to absorb the instantaneous voltage differences between the bridges.

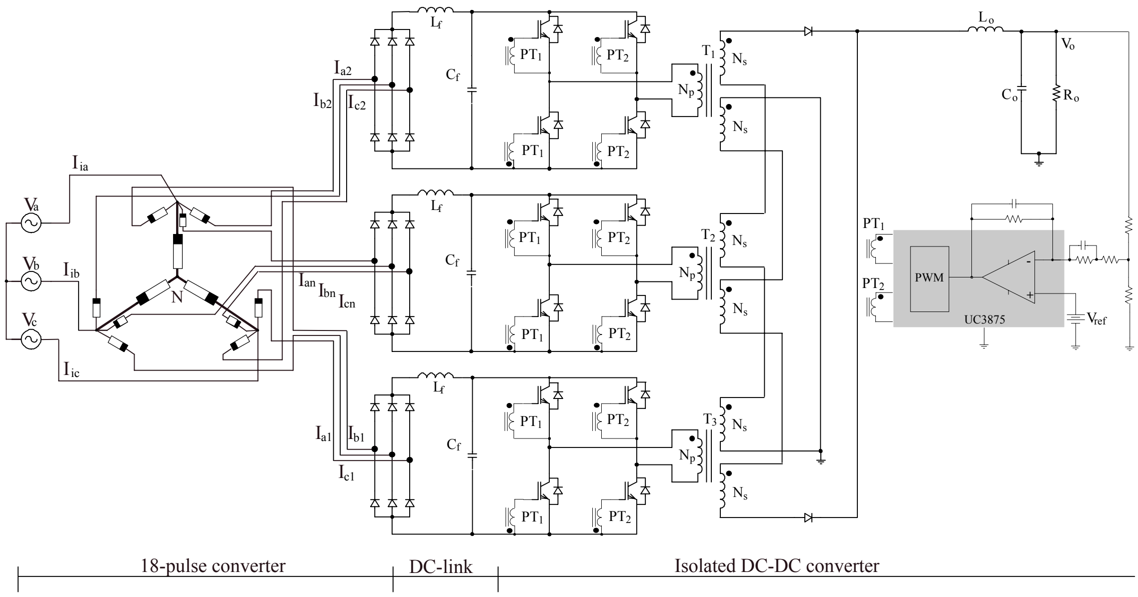

Fig. 1. Proposed low THD AC-DC converter with high-frequency isolation.

Whenever isolation and regulated DC output are required, like in telecommunications systems, the challenge is to find a high efficiency, high power density, low cost and robust three-phase converter [8].

This work proposes a 18-pulse isolated rectifier with regulated DC output of 60V/200A. This technique uses the same concept of the polyphase autotransformers in order to obtain a natural power factor correction. In addition to including the high-frequency isolation stage and to allowing adjustable output voltage at low-level, the current control loop is not necessary and the ZVS-PWM technique for active switches is applied in this topology. The proposed connection for the high-frequency transformers eliminates the interphase transformers. Therefore, the overall size of the converter and the command efforts are reduced.

II. Circuit Topology

The fundamental concept of the natural power-factor correction through non-isolated polyphase transformer is ensured by the 18-pulse Y-connected autotransformer, followed by three six-pulse diode rectifiers.

The proposed topology is shown in Fig. 1. This solution uses three Full-Bridge converters connected on the DC sides of each three-phase diode rectifier. A small-size high-frequency filter (L_f, C_f) is placed on each DC-link (between the full-bridge converters and the three-phase diode rectifiers).

Besides the high-frequency transformers allowing isolation between primary and secondary sides, the secondary windings are series connected to balance the DC-link currents. This simple and robust strategy eliminates all of the current sensing and current controllers, which are necessary to balance these currents. However, the full-bridge converters have to be synchronized. To reduce the commutation losses without auxiliary switches, the phase-shifted PWM technique is applied. The resonant components, snubber and clamping circuits are not shown in Fig. 1.

The regulated output voltage is easily obtained through conventional voltage controller. Only one integrated circuit (PS-PWM) [9], associated with some passive components and two pulse-transformer (PT_1 and PT_2), is used for regulation and driving all of the switches.

A. *Analysis of the Autotransformer*

1) Winding Voltages: The autotransformer is supplied by a three-phase balanced voltage system. Three diode rectifiers follow the secondary voltages, composed of three three-phase voltage systems, also balanced. One of these systems is placed in the same phase as the supply voltage and the others are placed at +20° and –20°, with regard to the supply system.

The three secondary voltage systems are obtained by combining the ratios between the primary and secondary windings. Fig. 2 shows the vector diagram and the auxiliary triangle used to obtain the three voltage systems.

The primary windings of the autotransformer are formed by N_a, N_b and N_c, which are Y-connected and linked to the line voltages V_a, V_b and V_c. In this connection, a virtual neutral point N is generated.

The secondary windings are designed, in such a way that, the turns-ratio and the connection between them and the primary winding generate three different three-phase systems with a 20° phase-shift from each other. These voltages feed the rectifiers.

All the windings of N_a, N_{an}, N_{a1} and N_{a2} are coupled together at the same limb core, the resulting voltages, V_a, V_{an}, V_{a1} and V_{a2}, are in phase. The same applies to phases "b" and "c", as shown in Fig. 2.

The magnitude of the voltages across the secondary windings V_{a1}, V_{a2}, V_{b1}, V_{b2}, V_{c1}, and V_{c2} are obtained by (1).

$$V_{b1} = V_a \cdot \frac{sin(20^o)}{sin(100^o)} = 0.3473.V_a \tag{1}$$

The winding turns-ratio (K_1) that ensures a phase displacement of 20° is given by (2):

$$K_1 = \frac{V_a}{V_{b1}} = 2.88 \tag{2}$$

This result shows that these secondary turns are 2.88 times lower than the primary turns.

The magnitude voltages between each pair of secondary terminals, (V_{R1}, V_{S1}, V_{T1}) and (V_{R2}, V_{S2}, V_{T2}), with respect to the virtual neutral point, are obtained in (3).

$$V_{R1} = V_a \cdot \frac{sin(60^o)}{sin(100^o)} = 0.8794.Va \tag{3}$$

The third secondary three-phase voltage system (V_{Rn}, V_{Sn} V_{Tn}) is in phase with the primary one. Its voltages however, must have the same magnitude as other secondary voltages. So, equation (4) must be fulfilled.

$$V_{Rn} = V_a - 0{,}8794.V_a = 0.1206.V_a \tag{4}$$

The winding turns-ratio that ensures 88% of the primary voltage (K_2), without phase displacement, is given by (5).

$$K_2 = \frac{V_a}{V_{Rn}} = 8.29 \tag{5}$$

This result shows that these secondary turns are 8.29 times lower than the primary turns.

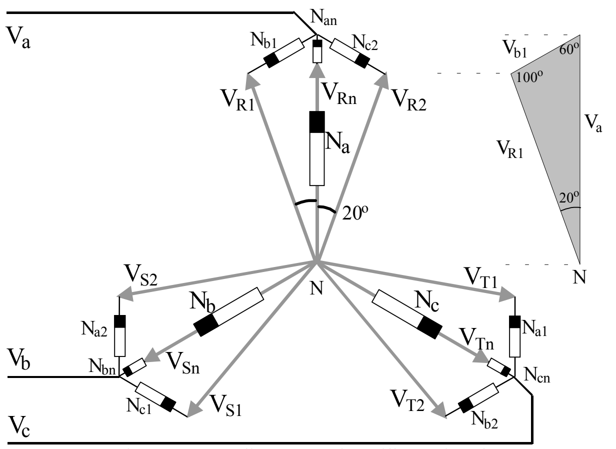

Fig. 2. Vector diagram and auxiliary triangle.

We can observe that the voltage magnitudes of each three-phase system are about 88% reduced in comparison with the input phase voltages.

2) Winding Currents: The technique to eliminate current harmonics in the multiple pulse converters requires current-mode operation to the load. The 18-pulse converter is obtained when each output voltage system is connected to a six-pulse diode rectifier. It is like three identical loads, with current source characteristics, are used.

The current waveform, through one secondary winding (N_{an}), in phase with input voltage V_a, is shown in Fig. 3. This waveform is adopted as an angular reference to represent the other winding currents.

The waveform of I_{an} can be decomposed in a *Fourier series* by conventional means. By the way, when a discontinuous function is considered, the series terms can be obtained by inspection. We can observe that this waveform presents alternate symmetry, the negative half cycle is an inverted reproduction of the positive half cycle. Thus, the even harmonics are zero and there are no cosine terms. The average value is also zero.

Note that winding N_{an} conducts current I/3 during 120° ($2\pi/3$), starting from 30° ($\pi/6$). Thus, the current expression results in (6):

$$I_{an}(t) = \frac{4}{\pi}.\frac{I}{3}.\sum_k \frac{1}{k}.cos\left(k.\frac{1}{6}\right).sin(k.\omega.t) \qquad (6)$$

Were, k=1, 3, 5, ...

The current waveforms through the other secondary windings of this three-phase system (I_{bn} and I_{cn}) are represented by the same equation for I_{an}. Therefore, the phases are displaced -120° and +120°.

In the other secondary three-phase system, current I_{b1} is expressed by (7).

$$I_{b1}(t) = \frac{4}{\pi}.\frac{I}{3}.\sum_k \frac{1}{k}.cos\left(k.\frac{1}{6}\right).sin\left[k.\left(\omega.t + 20^o\right)\right] \qquad (7)$$

The other currents of this three-phase system (I_{a1} and I_{c1}) are represented by the same equation for I_{b1}, only displaced -120° and +120°.

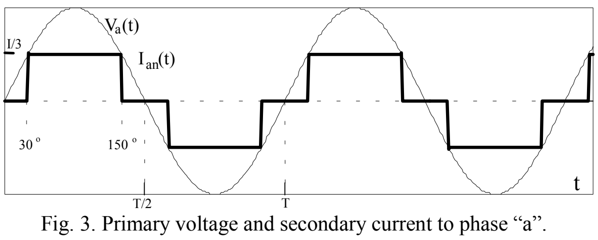

Fig. 3. Primary voltage and secondary current to phase “a”.

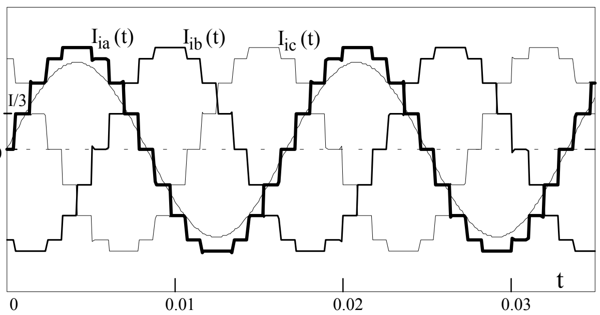

Fig. 4. Three-phase line currents and voltage of phase “a”.

For the last voltage system, current I_{c2} can be expressed by (8).

$$I_{c2}(t) = \frac{4}{\pi}.\frac{I}{3}.\sum_k \frac{1}{k}.cos\left(k.\frac{1}{6}\right).sin\left[k.\left(\omega.t - 20^o\right)\right] \qquad (8)$$

The other currents of this three-phase system (I_{a2} and I_{b2}) are represented by the same equation for I_{c2}, only displaced -120° and +120°.

The primary winding currents (I_a, I_b and I_c) can be obtained by (9), considering the currents of the three secondary windings coupled at the same limb core the turns-ratio (K_1 and K_2). As mentioned bellow, windings with the same index (a, b or c) are coupled at the same limb.

$$I_a(t) = \left(\frac{I_{a1}(t) + I_{a2}(t)}{K_1} - \frac{I_{an}(t)}{K_2}\right) \qquad (9)$$

3) Line currents: Line currents I_{ia}, I_{ib} and I_{ic} are obtained by adding all currents through windings at same node. Therefore, the follow equation for I_{ia} can be written. Fig. 4 shows the line currents (I_{ia}, I_{ib} and I_{ic}).

$$I_{ia}(t) = I_a(t) + I_{an}(t) + I_{b1}(t) + I_{c2}(t) \qquad (10)$$

B. *Isolated DC-DC converter*

The isolated converter topology of choice, should be a current-fed converter with a near-constant current at the output of each rectifier; in other words, the three DC-DC converters should absorb the balanced currents with low magnitude ripples. Thus, the class of isolated current-fed converters (boost) such as the push-pull and the full-bridge converters are the most attractive.

Balancing the currents can be achieved through current-mode control, monitoring the currents in the DC-link through current sensors. Besides, a voltage regulator that generates only one current reference for the three current regulators can control the output voltage [4].

In this work, the strategy to balance all DC-link currents doesn't use any current sensor or current controller. The topology itself balances the currents by means of its power circuit, described as follows:

1) The converter topology: The topology chosen for the isolated stage was the full-bridge voltage-fed converter with a LC filter at the input. This voltage-fed topology allows employing the soft switching technique through phase-shifted pulse-width modulation (PS-PWM). Therefore, there is no voltage stress across the switches and zero-voltage switching (ZVS) is guaranteed for a wide operation range [9]. The LC resonant components use the output capacitance of the switches and the leakage inductance of the primary windings.

The small volume LC filter, installed at the input of the DC-DC converter, is used to filter the current’s high frequency components (two times the switching frequency).

2) Balancing the currents: The three DC-DC converters present the following characteristics:

- They process the same power (1/3 of the total power).
- The rectified voltage systems (six pulses) are of the same magnitude, although displaced 20° from each other.

- The average currents through the DC-link are the same.

Current balancing can be reached through a series connection of the secondary windings of the three high frequency transformers and by synchronizing the command of the converters. Thus, the current waveforms of the secondary windings are the same and, due to the transformer turns-ratio, all of the currents through the primary windings are identical, as shown in Fig. 5.

Consequently, the instantaneous currents through the three converters are the same. Due to the instantaneous differences between the rectified voltages, the power processed by the DC-DC converters during a switching period is also different. Thus, the frequency ripples of the currents in the DC-links are three times the frequency ripples of the rectified voltages. This effect is a result of the composition of the three rectified voltages (6 pulses) with a displacement of 20°. Fig. 5 shows the strategy used to reach balanced currents through the DC-links.

3) The output rectifier: To reduce diode conduction losses, the center-tapped connection is chosen for the output rectifier. Thus, each transformer has two secondary windings, which are connected as shown in Fig. 1. The voltage to be rectified is composed of the sum of the secondary voltages.

Each secondary voltage, whose phase corresponds to its respective DC-link voltage, presents a six-pulse ripple. Then, the output voltage presents an 18-pulse ripple, composed of the three secondary voltages.

III. EXPERIMENTATION

A. Specifications and the most relevant components

- Three-phase input voltages: 220 / 380V.
- DC Output: 60V / 200A.
- Switching frequency: f_s = 30kHz.
- N_a, N_b, N_c = 330 turns with a 20 AWG wire.
- N_{an}, N_{bn}, N_{cn} = 40 turns with a 15 AWG wire.
- N_{a1}, N_{b1}, N_{c1} = 114 turns with a 15 AWG wire.
- N_{a2}, N_{b2}, N_{c2} = 114 turns with a 15 AWG wire.
- Autotransformer - area of the EI core = $27 cm^2$.
- Three-phase bridges = SKD 30/08 A1 (Semikron).
- L_f, C_f = 4 mH , 1.3 µF.
- IGBT modules = SK 25 GH 063 (Semikron).
- Rectifier diodes = HFA50PA60C (IR).
- N_p = 13 turns with a 16x23 AWG wire.
- N_s = 1 turn with a 150x23 AWG wire.
- High frequency transformer – EE-65/65 on ferrite core.
- PS-PWM = UC3875 (Texas Instruments).
- L_o = 2 x 7.5 µH – double EE-65/39 on ferrite core – 4 turns with a 100x20 AWG wire.
- C_o = 6 x 680µF / 100V – Electrolytic capacitors.

Fig. 6 shows a photo of the complete prototype of the experimented three-phase AC-DC converter.

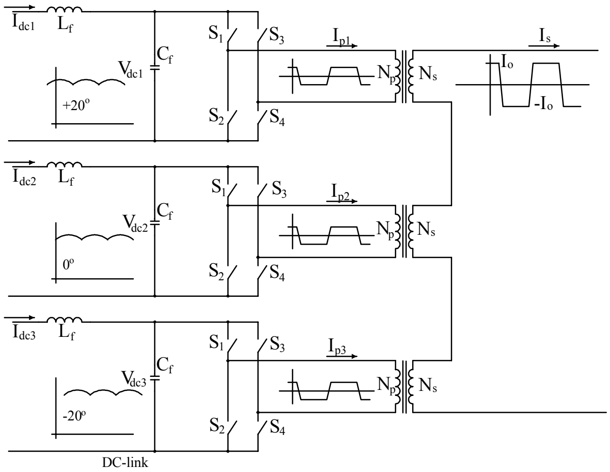

Fig. 5. Circuit to achieve balanced DC-link currents.

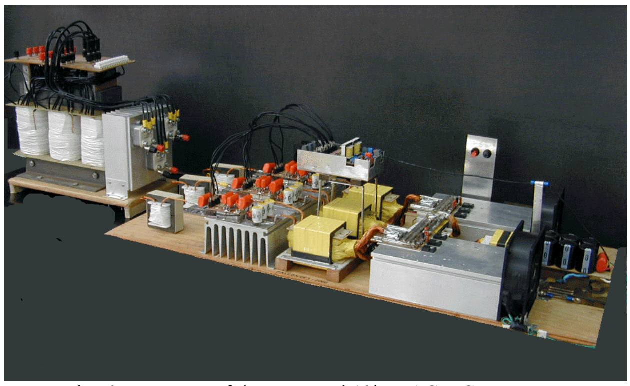

Fig. 6. Prototype of the proposed 12kW AC-DC converter.

B. Experimental results

Fig. 7 shows the waveforms of the DC-link voltage and current for operation **without** connecting the secondary windings in series. We can observe the high magnitude of the six-pulse ripple of the current. In this operation mode it is not possible to reduce the low harmonics in the line.

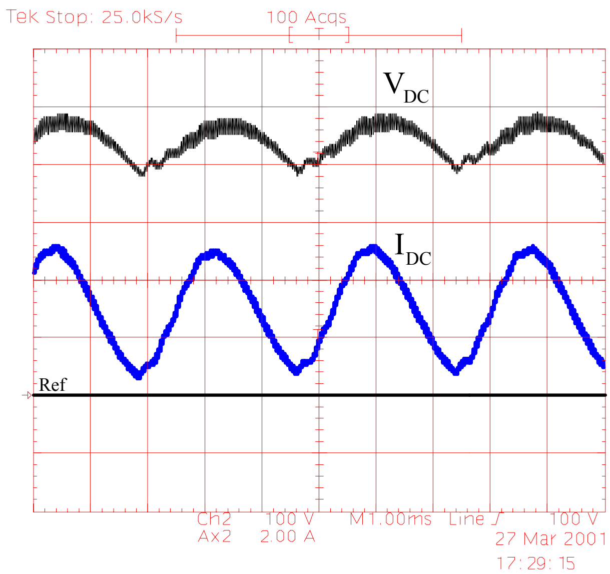

Fig. 7. DC-link voltage and current **without** series connection of the secondary windings (1ms/div, 100V/div, 2A/div).

The three balanced DC-link currents are shown in Fig. 8. In this case, the low-frequency ripples are minimized and the average currents of the DC-link are the same.

The voltage waveforms of the input of all diode rectifiers and the line voltage, for one phase, are shown in Fig. 9. Fig. 10 shows the waveforms of the rectified voltages. In both we can observe a displacement of 20^{o} and the balanced magnitude among them.

Fig. 11 shows the waveforms for input current and input voltage in the same phase and Fig. 12 shows all of the line currents (I_{ia}, I_{ib} and I_{ic}). We can observe the shape of input current between experimental result (Fig. 12) and mathematical results (Fig. 4) are the same. The measured input PF and the THD of the input current are equal to 0.99 and 8.6%, respectively.

Fig. 13 shows the efficiency for operation since low load to full load. It can observe the efficiency is higher than 90% for high load.

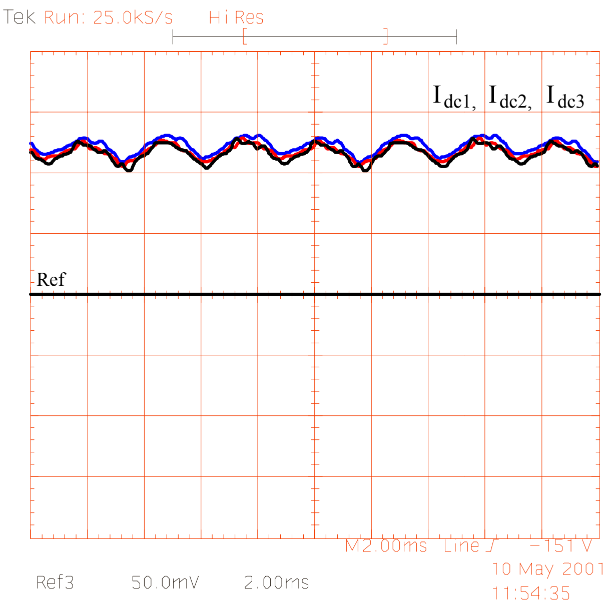

Fig. 8. Balanced DC-link currents (2ms/div, 5A/div).

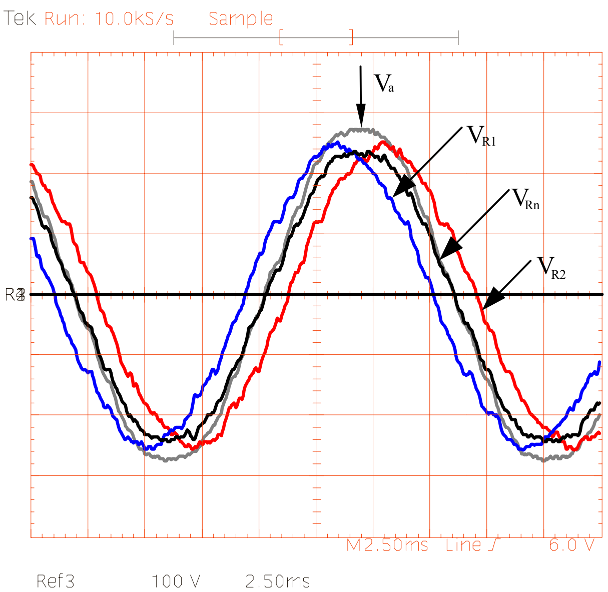

Fig. 9. Line voltage and input voltages of the diode rectifiers (2.5ms/div, 100V/div).

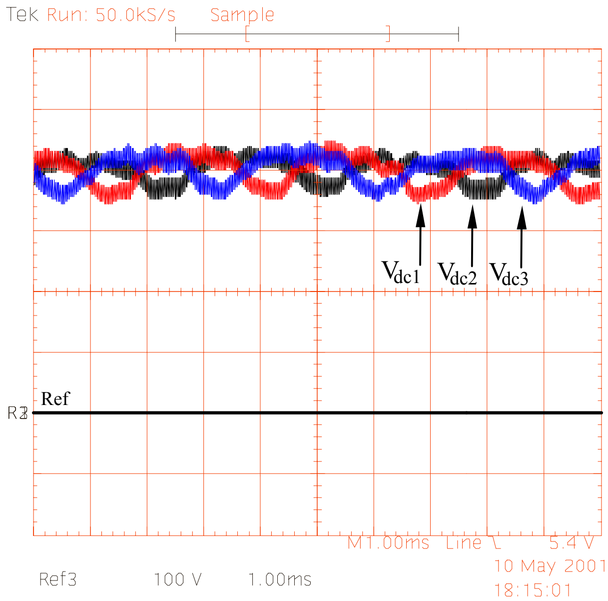

Fig. 10. Rectified voltages through the DC-links (1ms/div, 100V/div).

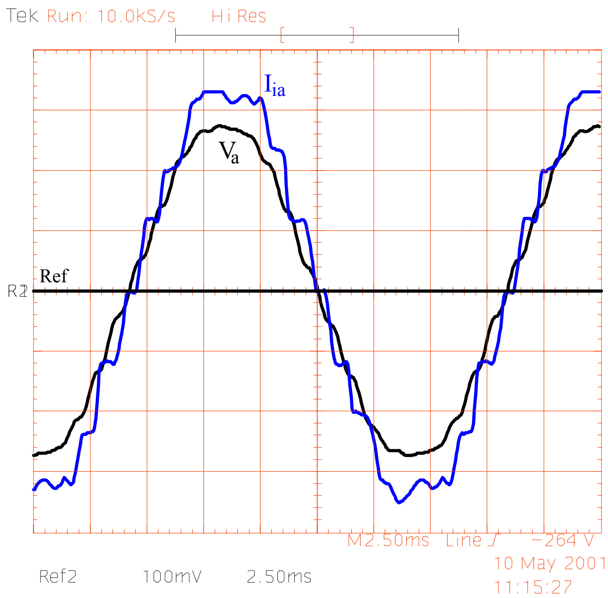

Fig. 11. Input current and input voltage in the same phase (2ms/div, 10A/div, 100V/div).

IV. Conclusions

In this work, a robust and isolated AC-DC converter with low THD is proposed. The 18-pulse converter is based on an Y-connected autotransformer and followed by three phase-shifted ZVS-PWM full-bridge converters. The secondary windings of the high-frequency transformers are series connected and all of the full-bridge converters are synchronized to achieve balanced DC-link currents. The balance and the low magnitude ripple of the DC-link currents are the fundamental requirement to provide reduced harmonic current in the mains. A 12kW laboratory prototype was implemented and some experimental results are presented. Other results will be presented in the final version of the paper.

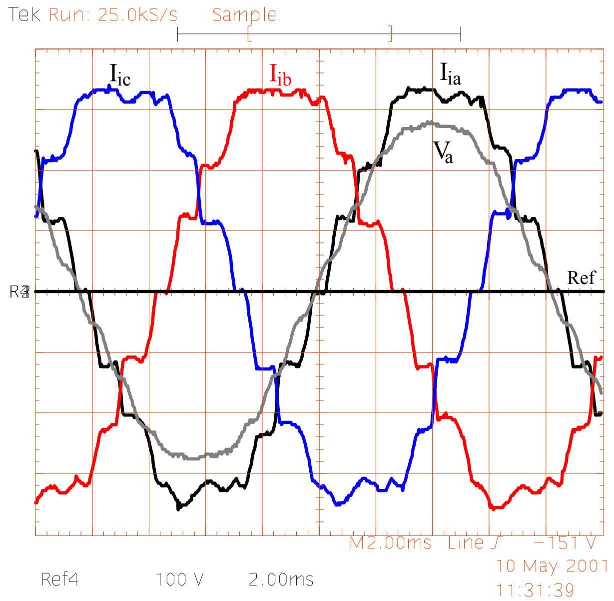

Fig. 12. Line currents (2ms/div, 10A/div, 100V/div).

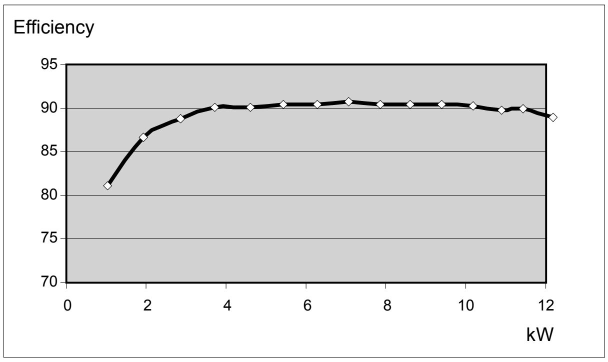

Fig. 13. Efficiency.

V. References

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