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BATTERY CHARGER BASED ON DOUBLE-BUCK AND BOOST CONVERTER

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Key words: electrical accumulators, battery charger, electric converters, voltage converters, buck converters, boost converters, nonlinear current controllers, experimental results

Abstract: The paper describes a double-buck and boost converter structure suitable for battery charger in electrical vehicle application. It is very convenient to use inverter elements for battery charging task. Different DC to DC converter structures can be organized from the inverter semiconductor elements. In the case of the induction motor electrical drive application, the required inductors could be established from the motor windings. Such combined converter should satisfy the unity power factor operation as well. By using the double-buck circuit the current high harmonic distortion will be either avoided or significantly reduced. The boost converter established from the inverter elements enables the energy transfer from the mains to the load during the whole mains voltage half period. Such combined converter does not need any additional semiconductor or inductor elements except the diode bridge.

Polnilnik baterij zasnovan na dvojnem pretvorniku navzdol in pretvorniku navzgor

Ključne besede: akumulatorji električni, polnilniki akumulatorjev, pretvorniki električni, pretvorniki napetosti, pretvorniki navzdol, pretvorniki navzgor, regulatorji toka nelinearni, rezultati eksperimentalni

Povzetek: V prispevku je predstavljena kombinacija vezij osnovnih DC/DC pretvornikov z namenom uporabe v polnilniku akumulatorskih baterij. Novo vezje je ocenjeno iz zahtev bremena (napetostna regulacija) in vpliva na obliko vhodnega toka (tokovna regulacija). Z ozirom na delne rezultate je podrobneje razčlenjeno sinhronizirano delovanje vzporedne vezave dveh pretvornikov navzdol in pretvornika navzgor. Na osnovi dinamične karakteristike sestavljenega pretvornika, ki je bila ocenjena z avtoregresivno metodo za identifikacijo sistemov, je bil določen regulator. Na sestavljenem pretvorniku so bile izvedene meritve vhodnih in izhodnih veličin. Rezultati so komentirani glede zahtev bremena in zahtev standarda IEC 1000-3-2.

1 Introduction

Power conversion system is sometimes constructed by paralleling converters in order to improve performance or reliability, or attain a high system rating. The parallel converters operation is a usual operation mode in the telephone-exchange power supply systems.

Some authors put their atention in the study of the current sharing techniques depending on the load requirements /1/, /2/, /3/. All of them considered the buck converter parallel operation as an autonomous system. The current reference values have been provided to the buck converters from the central control unit and the DC to DC converters do not operate under the synchronous mode /1/. The parallel operation of boost converter is an attractive operation mode as well. In /5/ authors discuss current ripple cancellation by simultaneous operation of two boost converters.

The inverters in electric vehicle consist of six transistors and diodes. It is simple to establish the battery charger circuit from this set of elements. It is possible to establish the different battery charger structures by using the inverter elements. Same converter circuits are going to be describe here. From the set of the converter circuits, the double buck and single boost have been chosen. By using this structure, it is possible to avoid the high current distortion when the single buck converter operates. This property could be reached if the double-buck structure is operated in synchronous mode. The voltage control and current inner loop control will be also presented.

The objectives for such operation mode is to reach the unity power factor operation with less current distortion than that of ordinary buck converter /4/. Such battery charger structure is also appropriate for the telephone-exchange power supply system.

2 Circuit proposals

In electrical vehicle applications and in telephone-exchange power supply systems, the battery charger circuits require an output voltage which is usualy less than the input voltage.

In Fig. 1(a) the inverter circuit is shown. This is a voltage source inverter and it is supplied from the battery (U_0). With dashed line the diode bridge is shown as well. The diode bridge will operate only when the battery charging function will be required. To transform the inverter circuit function into converters behaviour, suitable for battery charging tasks, some of the connections in inverter circuits should be disconected.

The first circuit of the stage is the simple buck circuit which is shown in Fig. 1(b). By using this configuration, the battery task function has been solved on an appropriate way, but regarding the mains this circuit have a poor power factor. As could be concluded from the input current waveform in Fig. 2(a), the power factor is poor because of two reasons:

- the input current is discontinuous;
- there is no energy transfer during the whole half period (only when $U_d > U_0$).

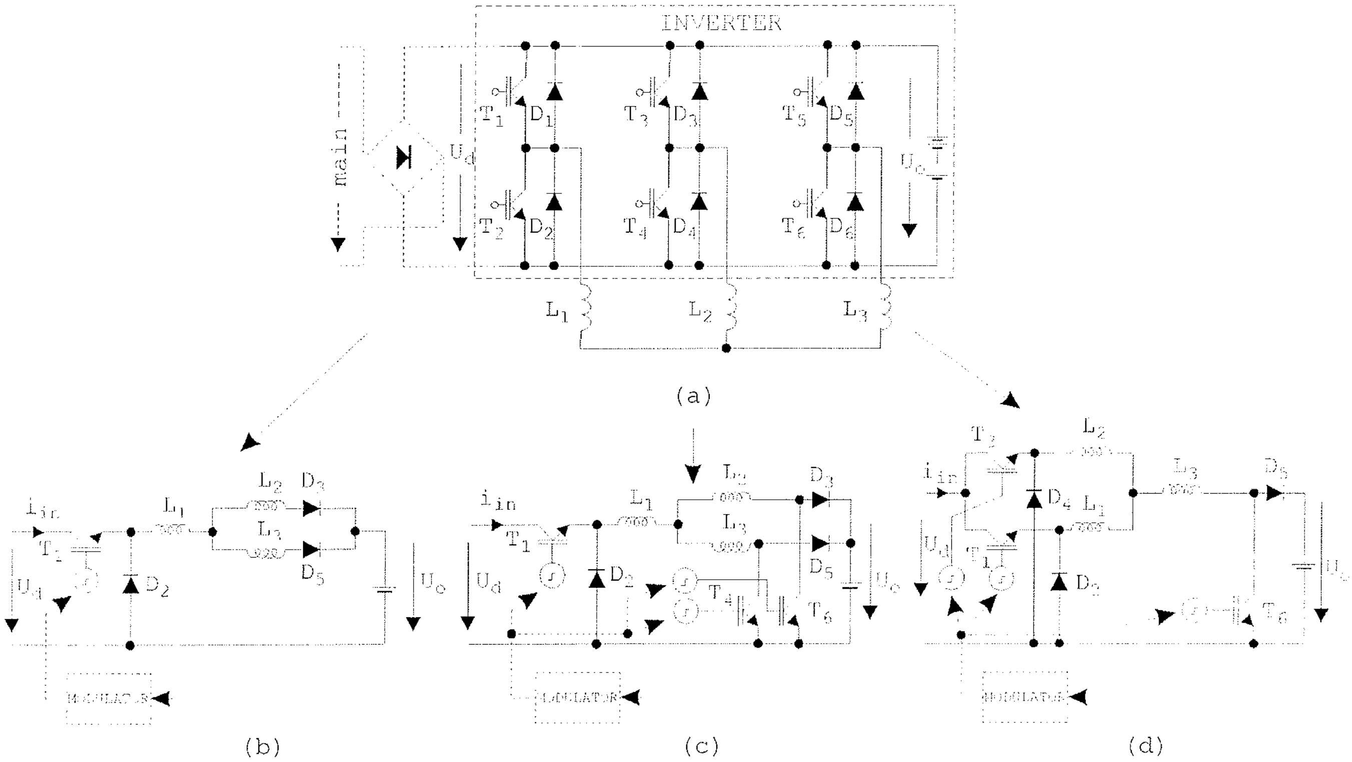

Fig. 1: Inverter to DC-DC converters transformation: (a) Electrical vehicle inverter, (b) Buck converter, (c) Boost and buck converter, (d) Double-buck and boost converter.

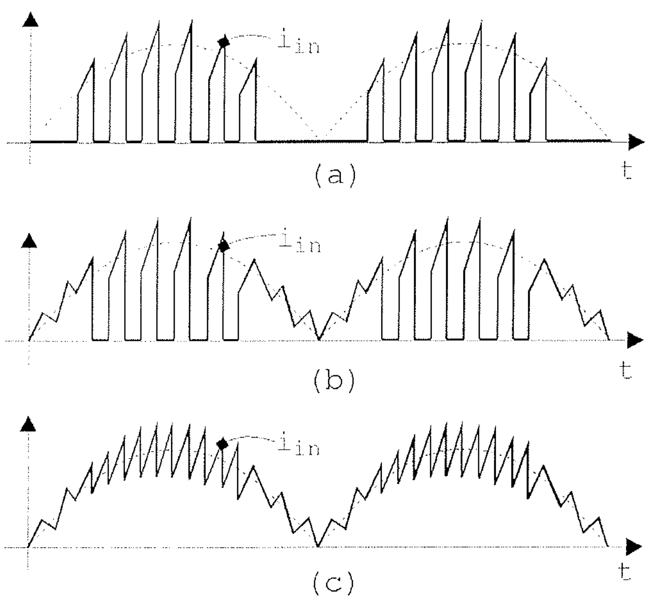

Fig. 2: Input current shapes: (a) Input current for single buck converter only; (b) Input current for single buck and boost converter; (c) Input current for double-buck and boost converter.

The circuit shown in Fig. 1(c) has an advantage regarding the converter shown in Fig. 1(b). This circuit enables the energy transfer from the mains, even if the instantaneous input voltage is lower than the DC output voltage. This advantage has been provided by two boost converters. These two converters could work in simultaneous mode or in synchronous mode as was proposed in /5/. Regarding the current waveform shown in Fig. 2(b), the power factor of this circuit is better than in the previous case but there is still discontinuous current when buck converter operates.

To avoid this disadvantage from the inverter circuit, the converter shown in Fig. 1(d) also proposed. This is a double-buck and boost converter circuit. By using the two buck converters, it is possible to avoid the discontinuous current, which appears in the previous proposed converters, as shown in Fig. 2(c). The boost converter provides the energy to the load when the instantaneous input voltage is lower than the output voltage. By using this structure, the previous mentioned disadvantages disappear. The circuit advantages can be summarized as follows:

- the input current is continuous;
- there is energy transfer during the whole half period.

For the further investigation the double-buck and boost converter has been chosen.

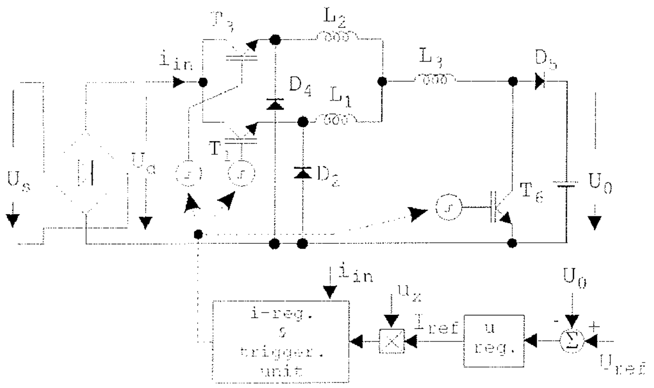

Fig. 3: The double-buck and boost converter complete control scheme.

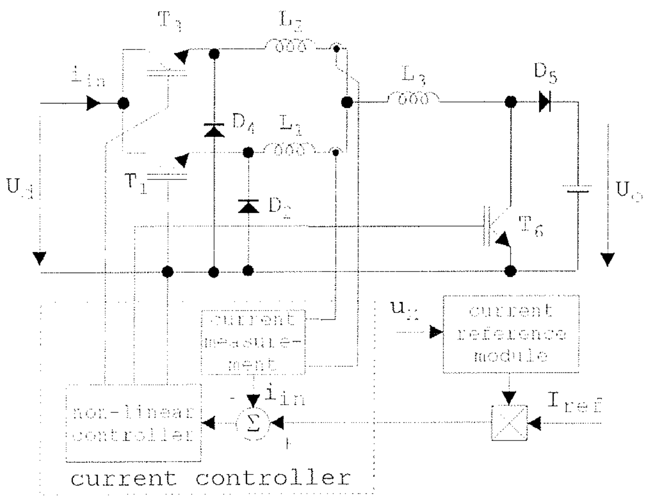

Fig. 4: The current control scheme.

3 Double-buck and boost converter control

For the double-buck and boost rectifier, the control requirements are defined regarding the load. There are two operating modes required by the bateries. The rectifier should operate as:

- a current source;
- a voltage source.

Regarding the battery condition, the converter will work as a current source or as a voltage source. The unity power factor requirements cause that the rectifier input current on the main side should follow the sinusoidal reference waveshape. This means, that when the rectifier works as a voltage source, a current loop control as an inner loop should be included in the control algorithm. In this case, the current reference will be produced by a voltage controller. The sinusoidal current

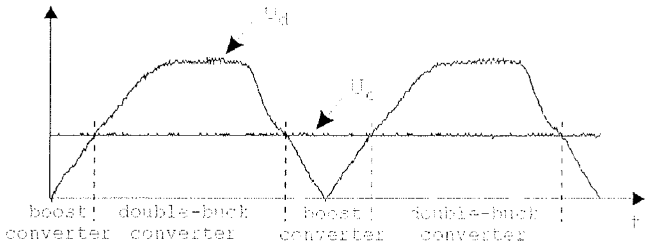

Fig. 5: Intervals where the converter changes its sturucture depending of input-output voltage conditions.

reference will be established by multiplication of the current reference produced by the voltage controller with the "sinusoidal" signal (u_x) of the input voltage normalized to a unity magnitude amplitude as follows:

$$u_x = \hat{U}_s \frac{1}{\hat{U}_s} \left|\sin(\omega t)\right|, \qquad (1)$$

where $\hat{U}_S$ represents the magnitude of the input voltage.

In Fig. 3 the complete control scheme is shown.

3.1 Current controller and triggering unit

The combined operation of two different converter structures requires a non-linear approach to control the system. In Fig. 4, a current control loop is shown. During the mains voltage half period the converter changes the structure as depicted in Fig. 5.

The boost converter operates only when the input voltage is lower than the DC output voltage ($U_d < U_0$) and the double-buck converter operates when the input voltage is higher than the DC output voltage ($U_d > U_0$). Each of those two modes requires a special atention regarding inner current references. Regardless what happens with the sinusoidal reference value (if it changes the magnitude), the input current average value in boost converter and the input current average value in the double-buck converter must follow the sinusoidal current reference.

3.1.1 The boost converter operation

Regarding Fig. 5 the boost mode of the converter operation is mandatory when the instantaneous input voltage is lower than output voltage value.The hysteresis-controlled principle of operation in the boost mode has been used. To avoid the discontinuous current mode operation from the current reference module, two current references are needed as shown in Fig. 6. From the timing sequences in Fig 6, the hysteresis controller is designed as shown Fig 7.

3.1.2 The double-buck converter operation

For double-buck converter operations, the intervals when the instantaneous input voltage is higher than the output voltage are obligatory. Otherwise there will be no energy transfer from source to load. In Fig. 8, the two buck converters synchronous operation is indicated.

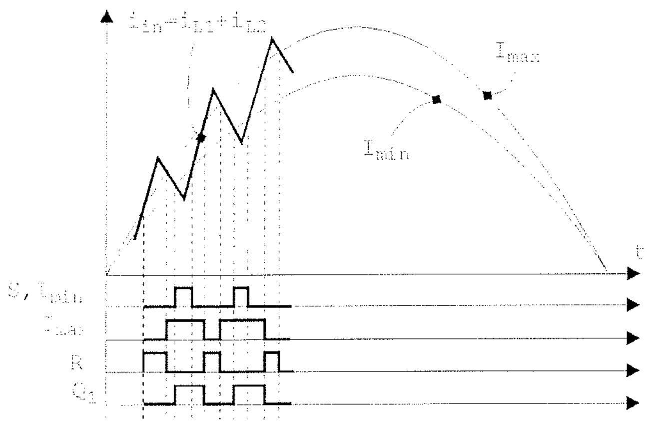

Fig. 6: The boost mode hysteresis control.

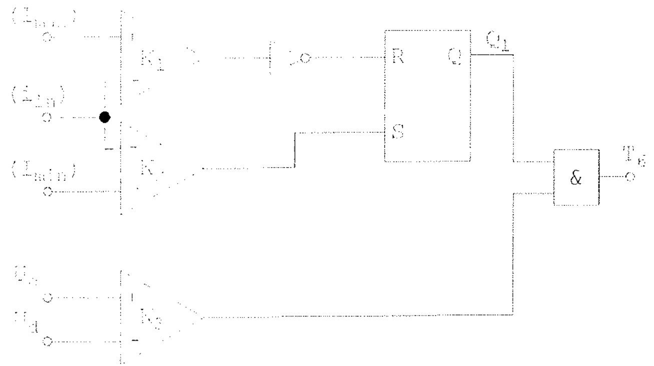

Fig. 7: The boost mode hysteresis controller.

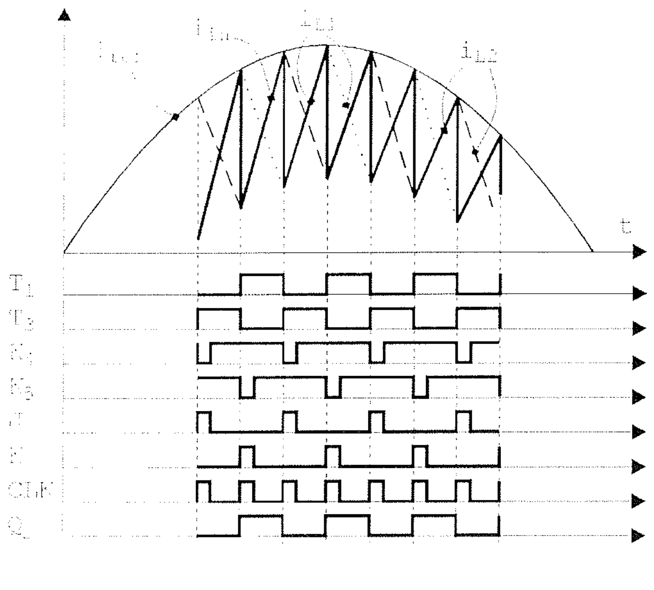

Fig. 8: The double-buck mode hysteresis control.

From Figs. 4 and 8, the double-buck converter operation can be described. When the current from the first converter, composed of transistor T_3 and inductance L_2 reaches the sinusoidal current reference value, then this transistor switches OFF and the transistor T_1 from the second converter switches ON. The current through T_3 is instantly zero and the current through inductance L_2 and diode D_4 is decreasing. At the same time, the current through transistor T_1 is increasing and when the current reaches the sinusoidal current reference, transistor T_1 switches OFF and the whole procedure is repeated. The above description can be summarized in the timing diagrams, of Fig. 8.

This time sequences help us to design the double-buck hysteresis controller (Fig. 9).

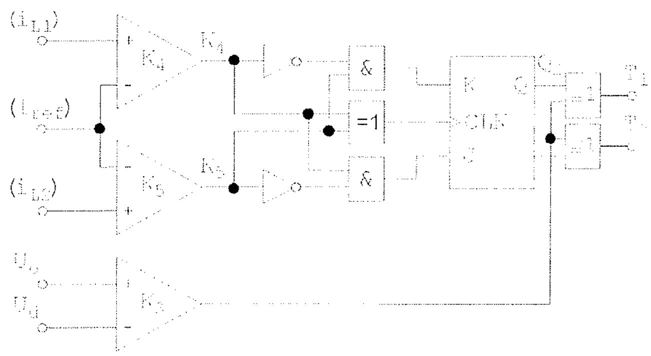

Fig. 9: The double-buck hysteresis controller.

As derived from the above description, when the converter is operated in double-buck mode, the input current i_{in} does not reach a zero value. This means that in the double-buck converter structure the continuous input current operation mode has been achieved. Actually there are some commutation problems when current goes from transistor T_1 to transistor T_3 but, appropriate snubber circuit design will make this problems negligeable.

3.1.3 The current reference module

As follows from the above description, the current controller needs three current reference values. Two of them are needed by the boost part of the converter and the third one is required by the double-buck converter part.

The current reference module provides to the current controllers the apropriate current references. At the output U_d the circuit provides the information to the comparator K_3 which will decide which converter will operate. Regarding the circuit in Figs. 7 and 9, the references $U(I_{max})$ and $U(I_{min})$ will be active when the boost structure has been chosen and the reference $U(I_{ref})$ will be active when the double-buck structure has been chosen.

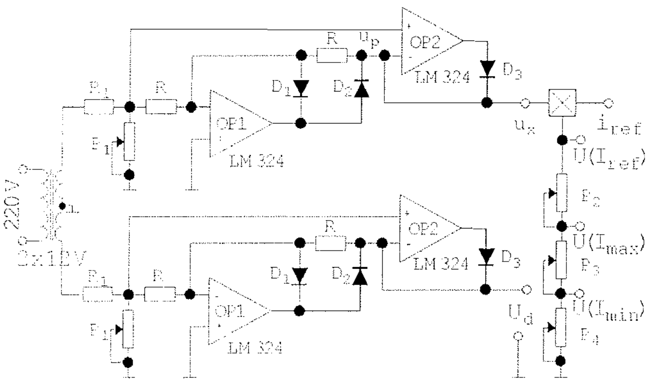

Fig. 10: The current reference module.

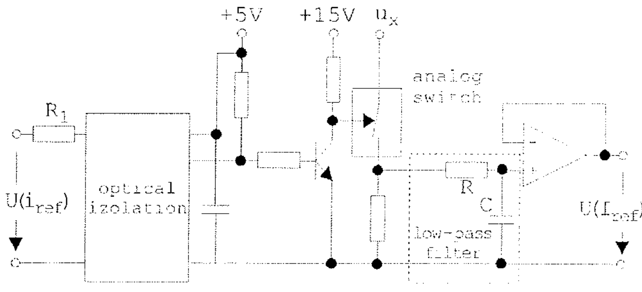

Fig. 11: The PWM multiplier.

3.1.4 The multiplier

As it has been shown in Fig. 10, for generating appropriate "sinusoidal" current references the multiplier function should be organized. At the voltage controller output, the PWM signal of i_{ref} is available in its voltage form $U(i_{ref})$. This signal should be multiplied by a voltage "wave-shape" signal u_x. The multiplier function can be realized by using the circuit shown in Fig. 11.

The circuit consist of an analog switch which is controlled by a PWM signal from the digital voltage controller, and a lowpas filter. The signal $u_x U(i_{ref}) = U(I_{ref})$ shown in Fig. 12 can be described by Fourier series, as follows:

$$U(I_{ref}) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos k\omega t + \sum_{k=1}^{\infty} b_k \sin k\omega t \qquad (2)$$

The coefficients a_0, a_k and b_k, can be evaluated in the usual way:

$$a_0 = \frac{2}{T}\int_0^T U(I_{ref})dt$$

$$a_k = \frac{2}{T}\int_0^T U(I_{ref})\cos k\omega_0 dt \qquad (3)$$

$$b_k = \frac{2}{T}\int_0^T U(I_{ref})\sin k\omega_0 t\, dt$$

where $\omega_0 = 1/T$.

The low-pass filter in Fig. 11 causes that the spectrum higher harmonics will be rejected because its cut-off frequency is much higher than the frequency of u_x which can be described as follows:

$$u_x = \hat{U}_x \sin \omega t\,, \qquad (4)$$

where $\omega = 2\pi f = 314.159$ rad/s. Because of that, only coefficients a_0 will be identified. Regardig the time diagrams in Fig. 12 for a_0 coefficients yields:

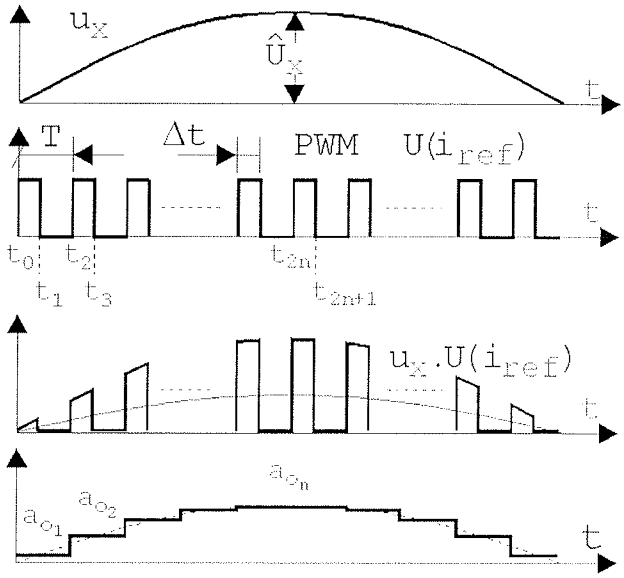

Fig. 12:The PWM multiplier timing diagrams.

$$a_{0_1} = \frac{2}{T}\int_{t_0}^{t_1} \hat{U}_x \sin \omega t\, dt$$

$$a_{0_2} = \frac{2}{T}\int_{t_2}^{t_3} \hat{U}_x \sin \omega t\, dt \qquad (5)$$

$$a_{0_n} = \frac{2}{T}\int_{t_{2n}}^{t_{2n+1}} \hat{U}_x \sin \omega t\, dt\,.$$

For coefficients a_{0n}, the next equation will be taken into consideration:

$$a_{0_n} = \frac{2}{T}\int_{t_{2n}}^{t_{2n+1}} \hat{U}_x \sin \omega t\, dt = \frac{2}{T}\int_{t_{2n}}^{t_{2n+\Delta t}} \hat{U}_x \sin \omega t\, dt\,. \qquad (6)$$

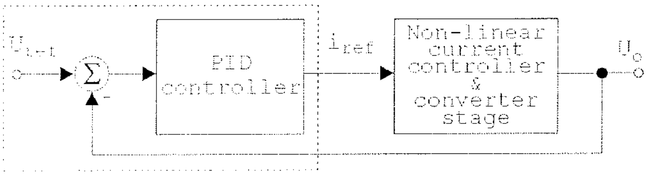

Fig. 13: The voltage control loop.

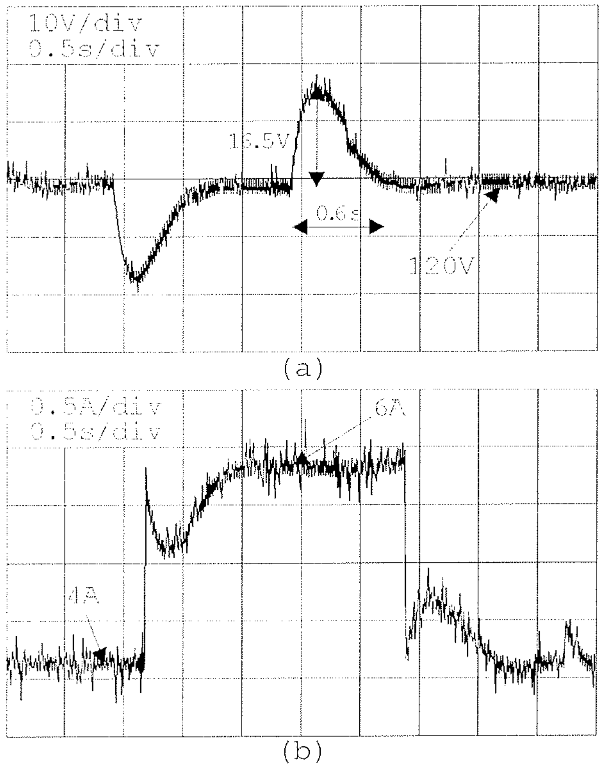

Fig. 14: Dynamic response to a resistive load change: (a) Voltage response; (b) Current response.

After soloving (6), it follows:

$$a_{0_n} = \frac{2\hat{U}_x}{\omega T} A \sin(\omega t_{2n} + \varphi), \tag{7}$$

where:

$$A = \sqrt{2}\sqrt{1-\cos(\omega \Delta t)}, \quad \tan\varphi = \frac{\cos(\omega t \Delta t) - 1}{\sin(\omega t \Delta t)}.$$

Because Δt is a small quantity tan φ approaches to zero and coefficient a_{0n} has a maximum value when sin (ω t_{2n}) is the unity. Then, (7) becomes:

$$a_{0_n} = \frac{2\hat{U}_x}{\omega T}\sqrt{2}\sqrt{1-\cos(\omega \Delta t)}. \tag{8}$$

After first order Taylor expansion of the expression under the square root, it follows:

$$a_{0_n} = \frac{2}{T}\hat{U}_x \Delta t. \tag{9}$$

The result is the product of signals u_x andΔt multiplied by factor 2/T. Signal Δt is proportional to i_{ref} ($\Delta t = K\, i_{ref}$).

3.2 The voltage control

The voltage control function has been realized by using digital signal processing. The risc microcontroller unit SH7032 has been used. The block diagram of the voltage control loop is shown in Fig. 13.

The non-linearity in the inner current loop causes that the clasical modeling methods as injected-absorbed current method or state space averaging method are not appropriate for modeling the double-buck and boost converter. Because of that, the auto-regressive identification method (AR-method) has been used /6/. The AR-method was based on the measured results. The output voltage to input reference current transfer function was estimated in the different operating points. For the controller design the worst case dynamic response has been taking into consideration. In Fig. 14(a) and (b) the dynamic response when the resistive load was changed from 30 Ω to 20 Ω and to 30 Ω afterwards is shown. The dynamic response to a step voltage reference change is shown in Fig. 15.

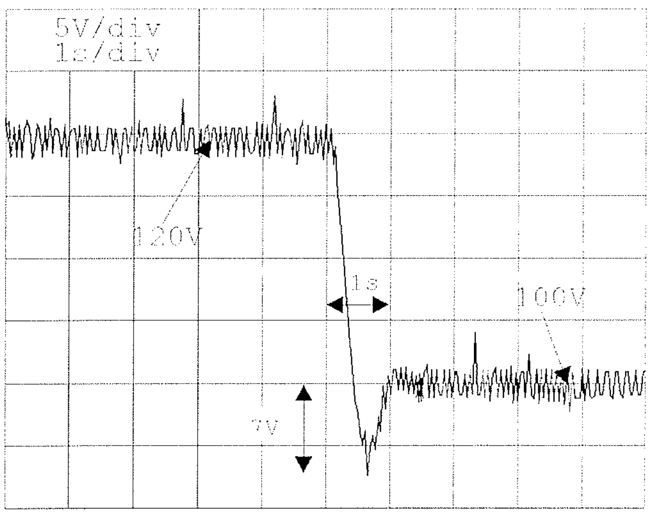

Fig. 15: Dynamic response to a step reference voltage change.

4 Unity power factor rectification - experimental results

The double buck and boost converter has been built with the aim of getting a good unity power factor of rectifier operation. Such control approach of this converter structure enables the converter operation with PF close to unity.

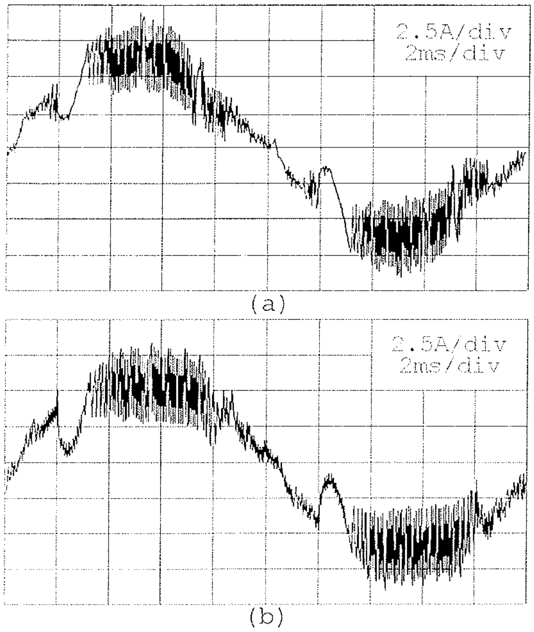

Fig. 16: The double-buck and boost rectifier input current: (a) Supplied by laboratory voltage source 220 V_{rms}; (b) Supplied by mains 220 V_{rms}.

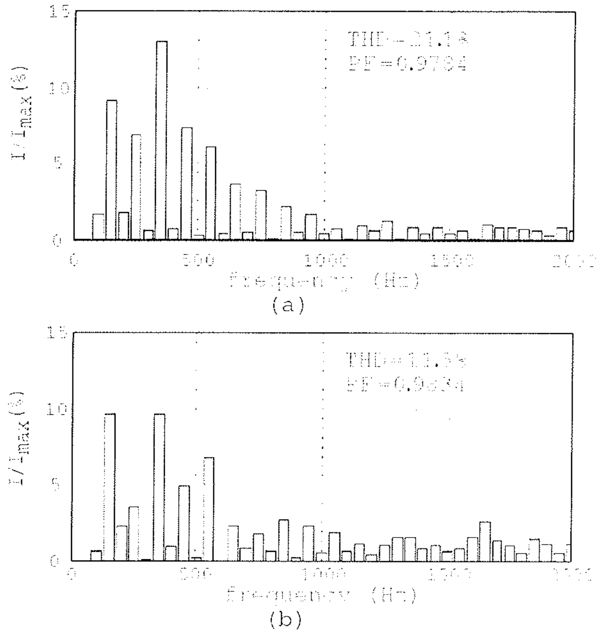

Fig. 17: The double-buck and boost rectifier input current spectrum: (a) Supplied by laboratory voltage source 220 V_{rms}; (b) Supplied by mains 220 V_{rms}.

In Figs. 16(a) and 16(b) the input current waveforms are shown when the double-buck and boost rectifier has been supplied by the laboratory voltage source and mains voltage source repectively. The current "drop" which appears, when the converter changes the operation mode from the boost to the buck mode, is consequence of the fact that, during the boost operation mode, the currents through inductances L_1 and L_2 are half of the current of inductor L_3 which, in term as the starting current of the buck converter.

The spectrum of the currents in both cases are shown in Figs. 17(a) and (b). The THD factors could be improved by the filter in the input line. The power factor meets the IEC standard requirements.

5 Conclusion

The experimental results show that it is possible to auto explote the double-buck and boost rectifier circuit to improve the unity power factor rectification. From the control point of view, this structure is a non-linear plant and the current controller solves this non-linearity problem. The experimental results have also demonstrated that this converter can operate in the required mode. Such converter is appropriate for telephone exchange power supply units where the current-sharing technique are required.

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