A New Approach to Synchronize a Bidirectional DC-to-DC Converter for Contactless Power Supplies

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Abstract

After a short introduction into the field of contactless energy transmission this paper describes a new method to synchronize a bidirectional DC-to-DC converter. For example a contactless inductive transmission of energy for robots is introduced. The employed bidirectional DC-to-DC converters are used to feed a rotatable transformer. To allow regenerative braking of the robot drives a bidirectional power flow is necessary. Therefore the DC-to-DC converter, consisting of two full bridge inverters, has to be clocked synchronously. With the new method only one transformer is needed for bidirectional power flow without any auxiliary components for signal transmission.

1 Introduction

In certain mechanical systems the transmission of electric energy to movable components is required. Currently in robots or tool machines the energy is transferred by slip rails, slip rings or movable cables. In [5] a new method of contactless inductive transmission of electric energy for robots is introduced. A rotatable transformer is part of a bidirectional DC-to-DC converter. Middle frequency converters (25 kHz) with bidirectional power flow must be synchronized at the AC-sides of the converter in frequency and phase. In some applications it is impossible or very inconvenient to install an additional signal transmission for synchronization. A new method to overcome these difficulties is subject of this article. The switching signals for the semiconductors of the non-stationary converter are derived only from the AC transmission voltage.

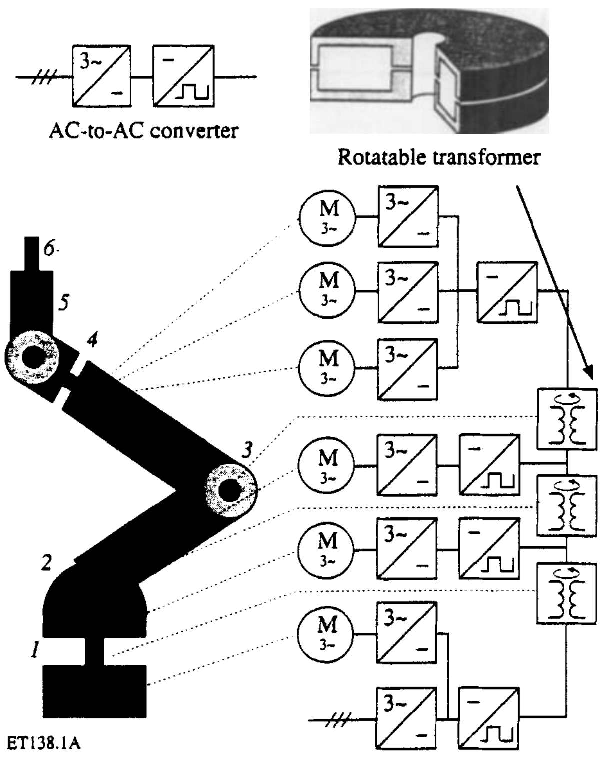

Fig. 1. Energy supply system for a buckling arm robot with six axes

2 Structure of the Converter

Fig. 1 shows the structure of a contactless energy transmission system for a buckling arm robot with six axes [6]. Several AC-to-AC converters (Fig. 1) are connected to machines which move the robot limbs on the one side of the pivot and connected together on the other side through the rotatable transformers. The AC-to-AC converters include a DC-link circuit. To allow energy transfer in each direction it is necessary that all AC-to-AC converters allow bidirectional power flow.

The operation mode can be achieved by employing bidirectional DC-to-DC converter [3, 2].

2.1 System Behaviour of the Bidirectional DC-to-DC Converter

The bidirectional DC-to-DC converter consists of two full bridge inverters connected by a rotatable transformer. To describe the operation of bidirectional DC-to-DC converter it is possible to simplify the

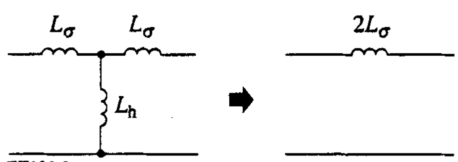

Fig. 2. Equivalent circuit of the rotatable transformer

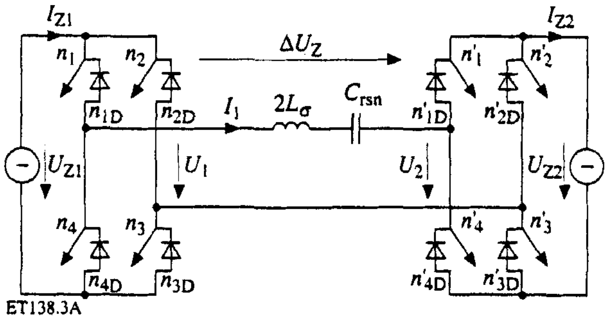

Fig. 3. Equivalent circuit of the bidirectional DC-to-DC converter

equivalent circuit of the rotatable transformer (**Fig. 2**) by leaving out the magnetizing inductance.

Investigations [7] have shown that the influence of the magnetizing inductance L_h of the transformer can be neglected, if the air gap is less than 0.1 mm.

In **Fig. 3** the equivalent circuit of the bidirectional DC-to-DC converter is shown. The capacitor C_{rsn} is included to form a series resonance circuit with the leakage inductance L_σ of the transformer [4]. The capacitance of C_{rsn} is given by:

$$C_{rsn} = 1/(2\omega^2 L_\sigma). \tag{1}$$

The pulse patterns of the switching elements ($n_1, \ldots, n_4, n'_1, \ldots, n'_4$) are shown in **Fig. 4c**. Tuning the $L_\sigma C_{rsn}$-resonance circuit to the switching frequency of the switches results in a sinusoidal transformer current I_1 (**Fig. 4b**) at a rectangular voltage ΔU_Z (**Fig. 4a**).

The main advantage of this mode of operation are the very low switching losses in the switching elements [8]. An efficiency of up to 97 % has been achieved [5–8].

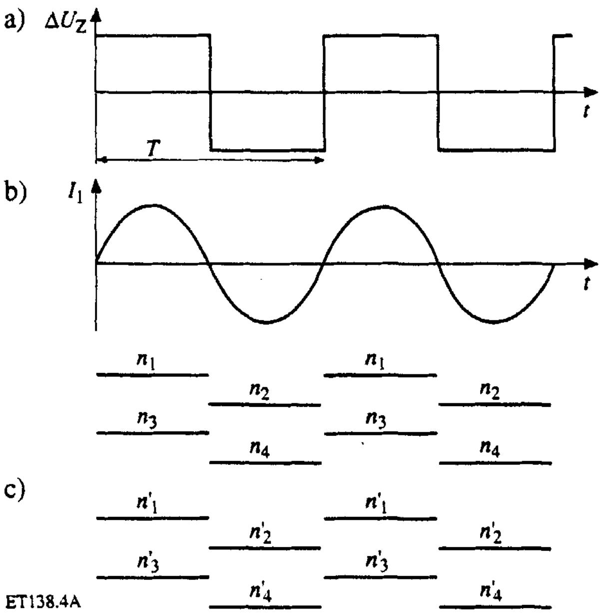

Fig. 4. Characteristic waveforms at resonant mode of
a) voltage ΔU_Z of the transformer
b) current I_1 of the transformer
c) pulse pattern of the switching elements

2.2 Synchronization

Previously it has been assumed that the switches of the converters are switched simultaneously. The bridge with index 1 is defined as the stationary part of the system (Fig. 3). This constant frequency bridge is controlled by a constant pulse pattern. Now it is assumed that the energy is transferred from the bridge with the index 2 (Fig. 3) to the fixed bridge 1. The DC link voltage U_{Z2} must therefore be greater than the DC link voltage U_{Z1}. The absolute value of the sum of the DC link voltages $|U_{Z1} + U_{Z2}|$ should be much greater than the absolute value of the difference $|U_{Z1} - U_{Z2}|$.

The basic idea of the synchronization is that the AC voltage at the AC-side of bridge 2 is used to detect the change of the AC voltage generated by bridge 1. Therefore it is necessary that the AC-side of bridge 2 is turned off shortly before bridge 1 changes the AC voltage. The turning off of bridge 2 is controlled by a clock which must be synchronized on the AC voltage of bridge 1.

The ideal waveforms of the voltages and the transformer current are shown in **Fig. 5**. The synchronization interval between t_1 and t_5 is shown enlarged.

The synchronization states of the bridges are shown in **Fig. 6**. The thick line indicates current flowing in the particular circuit section.

The starting point t_1 of the following considerations is shown in Fig. 5 and 6a. The transformer current I_1

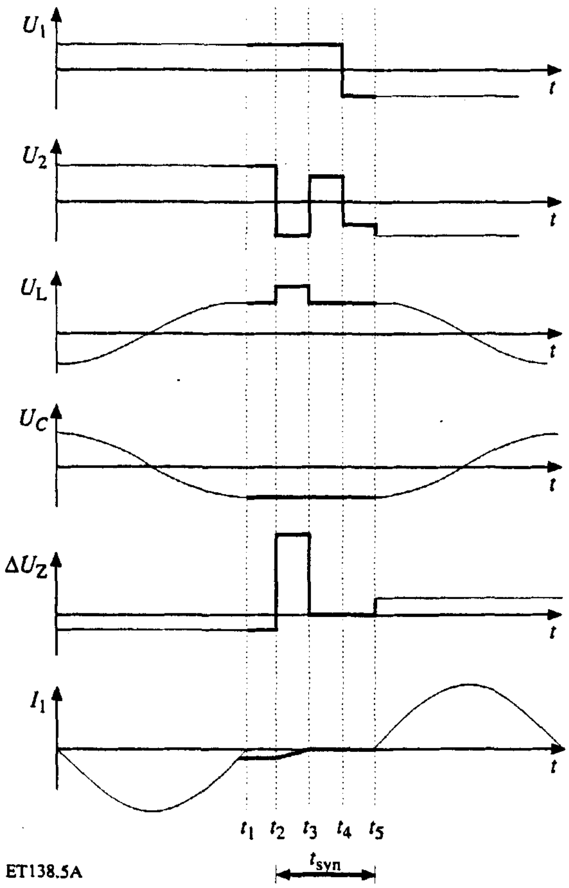

Fig. 5. Voltages and current waveforms during the synchronization (schematically)

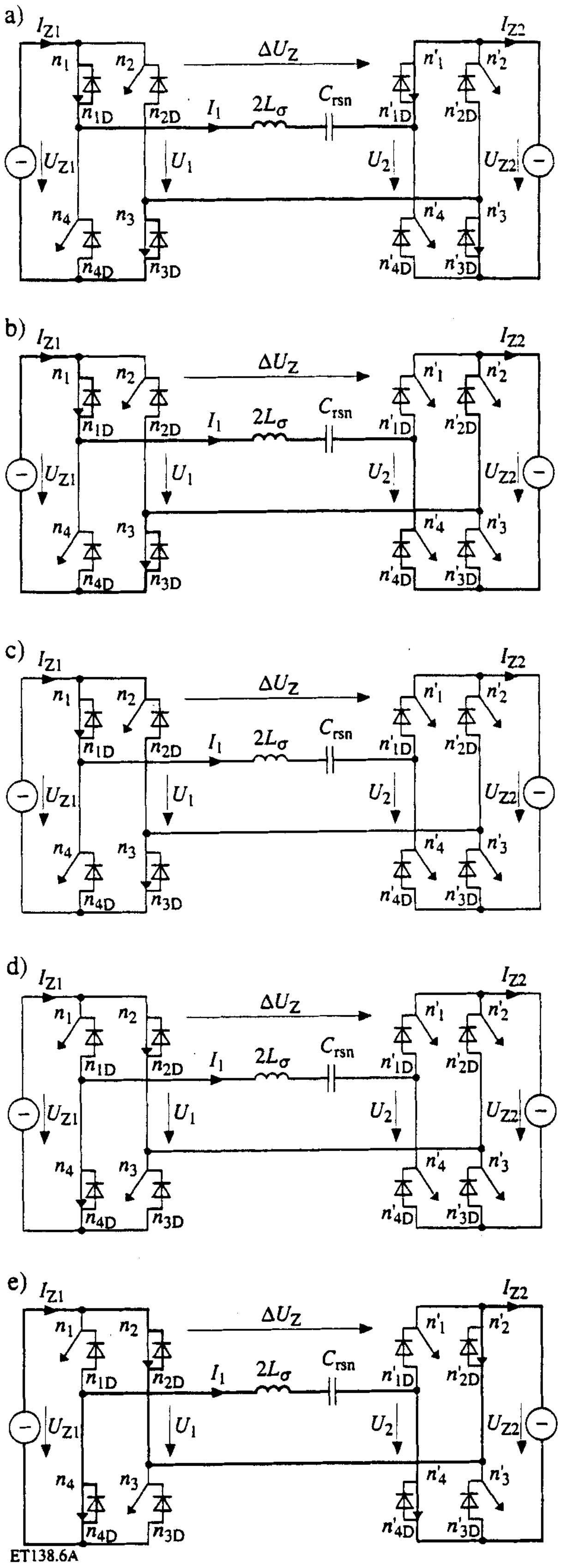

Fig. 6. Current paths and pulse patterns during the synchronization
a) Base point (before synchronization)
b) Initial switching (before synchronization)
c) Currentless period as safety margin
d) Detecting the switching of bridge 1
e) End of synchronization, power flow continues

flows through the switches n'_1 and n'_3 and the anti-parallel free-wheeling diodes n_{1D} and n_{3D}. The voltage ΔU_Z is negative, because the voltage U_{Z2} is greater than U_{Z1}. The voltages are given by:

$$\Delta U_Z = U_L + U_C,\; U_L(t_2) = \Delta U_Z - \hat{U}_C. \tag{2}$$

At t_2 the bridge 2 changes the output voltage (Fig. 6b). The switches n'_1 and n'_3 are turned off. Now the sum of the voltages U_{Z1} and U_{Z2} are connected across the leakage inductance L_σ, reduced by the voltage of the capacitor C_{rsn}, because the free-wheeling diodes n'_{2D} and n'_{4D} are conducting. For the period between t_2 and t_3 these equations are valid:

$$U_L = U_{Z1} + U_{Z2} - U_C,\; I_1 = I_{10} + \int_{t_2}^{t_3} \frac{U_L}{L_e}\,dt. \tag{3}$$

The current I_{10} is the transformer current I_1 at t_2, as the switches n'_1 and n'_3 are turned off. The value of the current will very fast be forced to zero.

Ideally, the transformer current I_1 at t_2 is very small compared to the maximum value. In this case the resonance period of the resonant circuit has to be reduced by the interval, which is needed for synchronization. If the frequency of the resonant circuit is set exactly equal to the frequency of the pulse patterns of bridge 1, the determination of the interval between $t_3 - t_2$ is possible by eqs. (4) to (6):

$$I_1(t_2) = \hat{I}_1 \sin\left(\omega_Z\left(\frac{T}{2} - t_{syn}\right)\right); \tag{4}$$

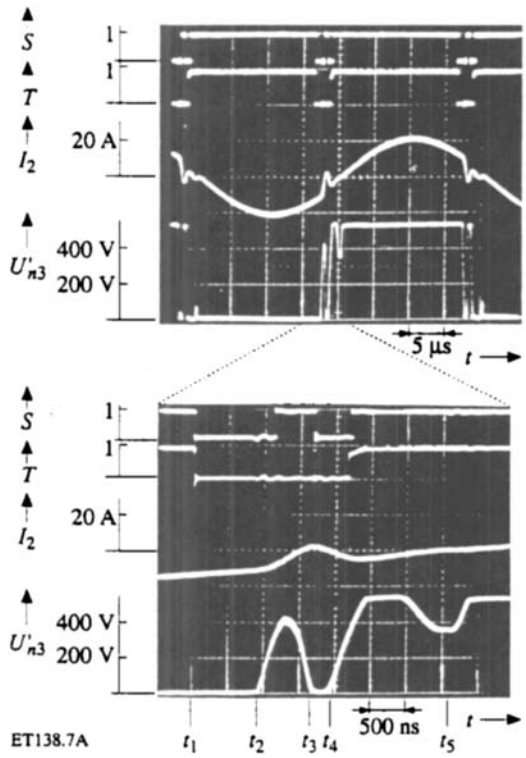

Fig. 7. Transformer current and voltage during the synchronization

	Nominal value
DC-link voltage U_{Z1}, U_{Z2}	650 V
DC-link capacitor C_{Z1}	1,75 mF
DC-link capacitor C_{Z2}	450 µF
Semiconductor: IGBT [1]	$I = 50$ A $U_{CE\,max} = 1000$ V
Transformer T-equivalent circuit values	$P_N = 11$ kW $L_h = 15$ mH $L_\sigma = 20$ µH
Resonance capacitor ($\omega/(2\pi) = 25$ kHz)	$C_{rsn} = 2$ µF

Tab. 1. Nominal values of the laboratory set-up

$$U_C(t_2) = -\hat{I}_1 \sqrt{\frac{L_\sigma}{C_{rsn}}} \cos\left(\omega_Z\left(\frac{T}{2} - t_{syn}\right)\right); \tag{5}$$

$$t_3 - t_2 = \frac{\Delta U_Z - U_C(t_2)}{L_\sigma}. \tag{6}$$

The time t_{syn} is the entire time needed for the synchronization and is indicated in Fig. 5. The time period between $t_2 - t_1$ is determined by the turn-off time of the semiconductors. The length of the interval $t_5 - t_4$ is determined by the turn-on time of the semiconductors. After the transformer current I_1 has become zero at t_3 (Fig. 5), the diodes of bridge 2 are blocking. At t_3 the following values exist:

$$U_{Z1} = U_1 = U_2, \quad \Delta U_Z = 0, \quad I_1 = 0. \tag{7}$$

The AC-side of the bridges are connected to the same voltage at t_3 (Fig. 6c). Then there is no current flowing in the transformer. Bridge 2 is not conducting, because the DC link voltage U_{Z2} is larger than the voltage U_2 at the AC-side.

At t_4 the voltage U_1 at the AC-side of bridge 1 is changing sign, caused by turn-off of switches n_1 and n_3 (Fig. 6d) and turning on the switches n_2 and n_4. By changing the voltage U_1 the sign of the voltage on the AC-side of bridge 2 changes:

$$-U_{Z1} = U_1 = U_2, \quad \Delta U_Z = 0, \quad I_1 = 0. \tag{8}$$

The transition of the voltage U_2 at t_4 (Fig. 5) can be detected by a comparator and can be used to generate a pulse pattern signal. However, this is the second transition of the voltage U_2 with the correct polarity. The first transition at t_2 (Fig. 5) is caused by turn-off of the switches in bridge 2.

After detecting the switching state of bridge 1 from the synchronization signal of bridge 2 at the time point t_5 (Fig. 5) the switches n_2' and n_4' are turned on (Fig. 6e) and the current I_1 is flowing again.

2.3 Measurements

The following measurements were obtained from a laboratory set-up with the specifications listed in **Tab. 1**.

The rotatable transformer is replaced by a normal PM 87/70 core transformer, because the needed pot core transformer was not yet available. The nominal values are shown in Tab. 1.

The lower picture in **Fig. 7** shows expanded the period of synchronization interval. In the upper oscillograph a complete switching period is shown. The enlarged interval in the lower picture shows the same sequence which is discussed in chapter 2.1.

At t_1 the synchronization starts and the signals T and S are switched to zero. The time interval $t_2 - t_1$ is due to the delay time of the driver stages and the IGBT. The voltage U_{n3} is zero until t_2, because the IGBT is still conducting (Fig. 6a). At t_2 the IGBT n_1' and n_3' are turned off. The current I_1 is forced to flow through the diodes n_{2D}' and n_{4D}' (Fig. 6b).

This commutation needs about 300 ns. The negative transition of the voltage U_{n3} causes an impulse in the detector signal S. This impulse cannot be used to synchronize the bridge 2 and it is not coupled with the clock signal T. At t_3 the transformer current I_1 is zero. The time between t_3 and t_4 (Fig. 6c) is a safety margin. This interval ensures the safe detection of the transition in the voltage U_{n3} at the time point t_4 independently from the amplitude of the current $\hat{I}_1$. The clock signal T and the detector signal S are set to a high level with the transition of the voltage U_2 at t_4. Herewith a successful synchronization is completed. At the point t_5 the IGBT of bridge 2 are conducting. The interval $t_5 - t_4$ is caused by the delay time of the driver stages and the switching-on time of the IGBT.

3 Conclusions

A new method to synchronize a bidirectional DC-to-DC converter is proposed. The main advantage of this method is that only one transformer is needed for bidirectional power flow without any auxiliary components for signal transmission. The bidirectional energy transmission to moving parts is used in machine tools and robots. For example the converter structure is introduced for a buckling arm robot with six axes.

The basic principle of the synchronization is introduced. The pulse patterns for the IGBT are generated by the synchronization. This is done only by analyzing the AC voltage of the movable converter. The good operation behaviour of the synchronization is demonstrated by a 20 kVA laboratory set-up. The used IGBT are switched with a frequency of 25 kHz.

4 List of Symbols

C	capacitance
I	current (RMS)
$\hat{I}$	current, peak
L	inductance
n	switch
P	power
T	period
t	time
U	voltage (RMS)
$\hat{U}$	voltage, peak
Δ	differential
ω	angular frequency

– **Indices**

C	capacitance
D	diode
h	main
L	inductance
n	switch
rsn	resonant
syn	synchronization
Z	intermediate circuit
s	leakage
0	initial value

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This paper is dedicated to Professor Dr.-Ing. *H.-Ch. Skudelny* on the occasion of his 60th birthday.

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