Design and Experimental Evaluation of the Loss-Free Braking Resistor Concept for Applications in Integrated Converter Machine Systems

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Abstract – **If the braking resistor of a conventional dissipative braking system (braking chopper) of a three-phase AC drive is replaced by a thyristor bridge (Loss-Free Braking Resistor) controlled in the full inverter operation, the braking energy of the drive can be fed back into the mains. This means that the current flowing into the mains via always two phases from the DC link is controlled by the power transistor of the braking chopper. In this paper this regenerative braking system as proposed in [1] is discussed based on a 10kW laboratory model.**

I. INTRODUCTION

Variable speed drives are being realized in the lower power region (up to about 20kW) more and more by standard induction machines with integrated frequency converters. By combining of motor and converter to a construction unit the following advantages are given (on top of the basic technical and economic advantages of electronically adjustable variable speed drives – as compared to constant speed drives with gears, belt drives or pole changing for speed adjustment):

- long cables to the motor, which would have to be shielded in many cases due to the pulsating output voltage form of the converter can be avoided; also, an output filter can be omitted which would be possibly necessary for avoiding reflections and/or voltage overshoots across the motor windings;
- converter and motor form an overall unit concerning EMI which has been optimized already by the manufacturer; its complexity is of no concern to the user;
- switching cabinets being necessary for separate arrangement of the converter can be omitted (minimization of the assembly effort); a simple installation of the drive is given because the mains connections can be realized in the same manner as for a motor with constant speed and the incorporation into an automation system is equal as for a conventional variable speed drive.

In order to keep the space requirement by the direct mounting of the converter to the motor (e.g., inclusion of the converter in an enlarged motor terminal box) as low as possible, and in order to obtain a system whose outer dimensions deviate as little as possible from the outer dimensions of a standard motor (and/or to guarantee an applicability in a region as wide as possible) particular high requirements have to be met concerning the power density during development of the converter part.

Therefore, e.g., the electrolytic capacitors to be provided in the DC link of conventional pulse width modulated converter systems which require typically a relatively high volume are being replaced by foil capacitors having a high current carrying capability and/or the DC link capacitance of the converter is substantially reduced. (The life time of electrolytic capacitors shows a pronounced dependency on the core temperature and/or of the losses caused by the equivalent series resistance (ESR); this results in a minimal volume and/or a minimal capacitance value for a given current carrying capability.) The effect of the output voltage ripple of the rectifier stage feeding the DC link on the motor voltage is eliminated there by direct control of the motor phase currents. However, a (short-time) regenerative braking operation of the drive via charging of the DC link capacitor cannot be realized any longer because due to the low capacitance value not allowable high values of the DC link voltage are obtained in a very short time. Therefore, the drive is limited mainly to motoring operation (e.g., as drive for pumps and fans) and/or only a DC current injection braking mode of the motor is possible. There, however, the electrically supplied braking power and the energy of the rotating masses is dissipated in the rotor circuit of the induction machine. This leads to an increased thermal stress on the motor for frequent speed changes.

If now a regenerative braking operation is required (as, e.g., for lifting devices – feed back of potential energy of the load into the DC link for lowering the load), an additional resistor-chopper braking unit has to be integrated into the terminal box. Thereby, however, the power density of the converter is reduced and the already high thermal stress on the converter electronic (typical operating temperature 80°C) is further increased. Therefore, one has to ask the question for alternate braking circuits which are simple concerning the circuit topology.

In [1] a braking circuit (designated *Loss-Free Braking Resistor*) has been proposed which is connected in anti-parallel to the

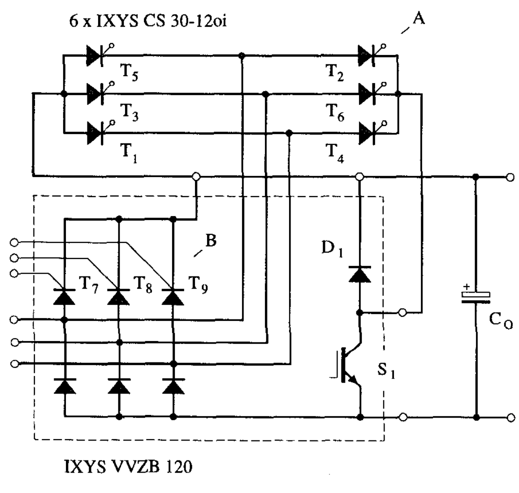

Fig. 1. Basic structure of a bidirectional input stage of a voltage DC link PWM converter drive system for application of a *Loss-Free Braking Resistor* (thyristor bridge A) for feed back of braking energy from the DC link (DC link capacitor C_O) into the mains.

0-7803-4503-7/98/$10.00 1998 IEEE

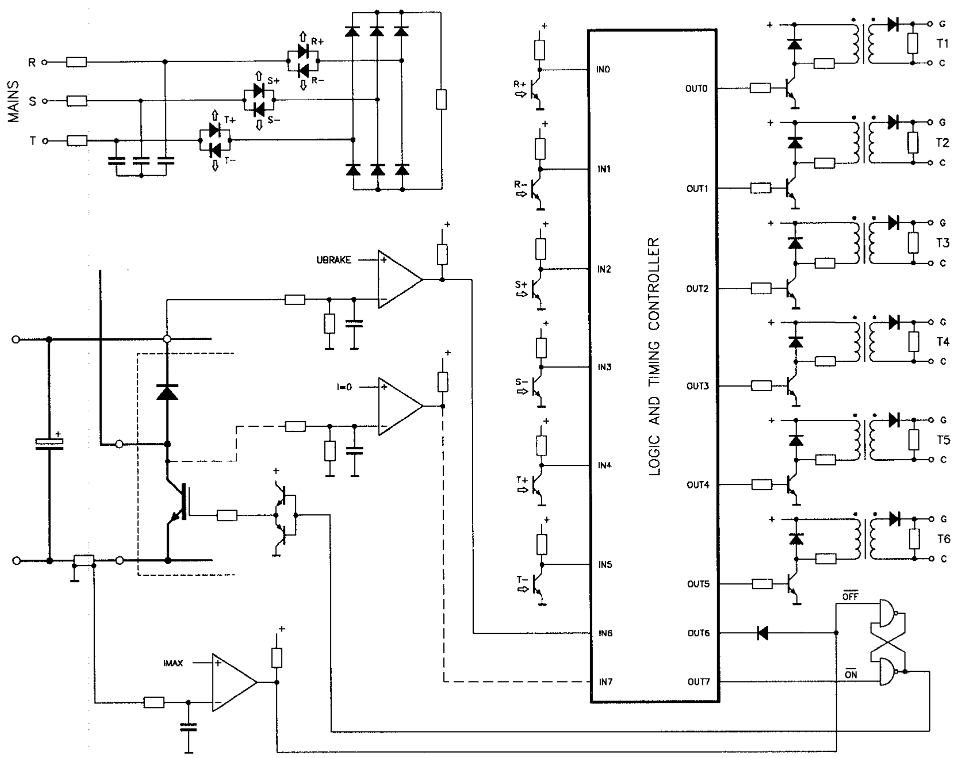

Fig. 2. Schematic of the control and firing circuit. The synchronization of the gating signals to the mains voltages is achieved by detecting the natural commutation instants applying a small signal three-phase diode bridge with input current sensing optocouplers. This also performs galvanic isolation of the detection circuit. The gating pulses of the thyristors and the control signal of the power transistor are generated by an inexpensive digital control circuit. The braking operation is initiated if the DC link voltage exceeds a preset maximum value and is inhibited in case of occurrence of an overcurrent. The reliability of the system can be improved by guaranteeing that the demagnetization of the mains side inductances has been completed before turn on the power transistor (shown dashed). There, a sufficient recovery time for the thyristors has to be considered.

input rectifier bridge of a converter (cf. Fig.1) and which makes possible a feed back of the braking energy into the three-phase mains. The system can basically be realized without passive power devices (filter elements). Therefore, it seems to be especially suitable for an application for integrated converter machine systems.

In this paper results of a first experimental verification of the concept (which has been described in [1] only in theory, cf. Fig.15 (a)) using a 10kW laboratory model are compiled.

II. POWER CIRCUIT

The experimental analysis is based on a power module IXYS VVZB 120 (cf. Fig.1, half-controlled thyristor bridge B, power transistor S_1 and free-wheeling diode D_1) in connection with discrete thyristors IXYS CS 30-12oi (T_i, $i=1...6$, A). The power module has originally been prepared for conventional dissipative braking operation (pulsed braking resistor). By realization of the feeding circuit as half-controlled circuit the charging of the DC link capacitors can be performed in a controlled manner for applying the mains voltage [2]. Thereby, an overshoot of the DC link voltage over the rated value can be avoided. The thyristors are turned on fully for motoring operation and are kept off for braking operation. Therefore, for feeding power back into the mains only thyristor bridge A, power transistor S_1 and free-wheeling diode D_1 have to be considered.

Operation of the Loss-Free Braking Resistor in the European low-voltage mains (400V rms line-to-line voltage) typically requires a DC link voltage in the range of 580–600V depending on the braking power and the inner mains impedance. Details are given in Fig.9 of [1]. With reference to a continuous current carrying capability of the IGBT of the power module for a case temperature of 80°C and a junction temperature of 125°C a maximum braking power of about 25kW would be achievable. Aiming for high reliability and considering the high thermal stress of the power electronic devices being integrated into a motor terminal box and the influence of an asymmetry of the mains voltage system we, however, select $P = 10\,\mathrm{kW}$ as nominal braking power.

As already described in [1], the short circuit impedance being effective on the AC side of the system advantageously should be 0.02p.u. In the case at hand this can be achieved by connecting explicit inductances $L_N \approx 1\,\mathrm{mH}$ in series on the mains side. As already mentioned in [1] L_N also would have to be provided for a pure rectifier operation for limiting the current stress on the DC link capacitor and/or guaranteeing high service life and for limiting the effects on the mains.

For limiting the rate of rise of the blocking voltage of the thyristors occurring at the end of the conduction interval of the free-wheeling diode D_1 following the on-interval of the power transistor S_1 to admissible values (<1 kV/μs) RC-snubbers (10Ω, 22nF) are provided across each valve T_i, $i=1...6$.

As a closer analysis shows, the total losses of all power semiconductors of the circuit amounts to about 1% of the throughput power in the nominal operating point. Considering furthermore the losses in the AC side inductances results in a remarkable high efficiency of the braking unit of about $\eta = 0.985$.

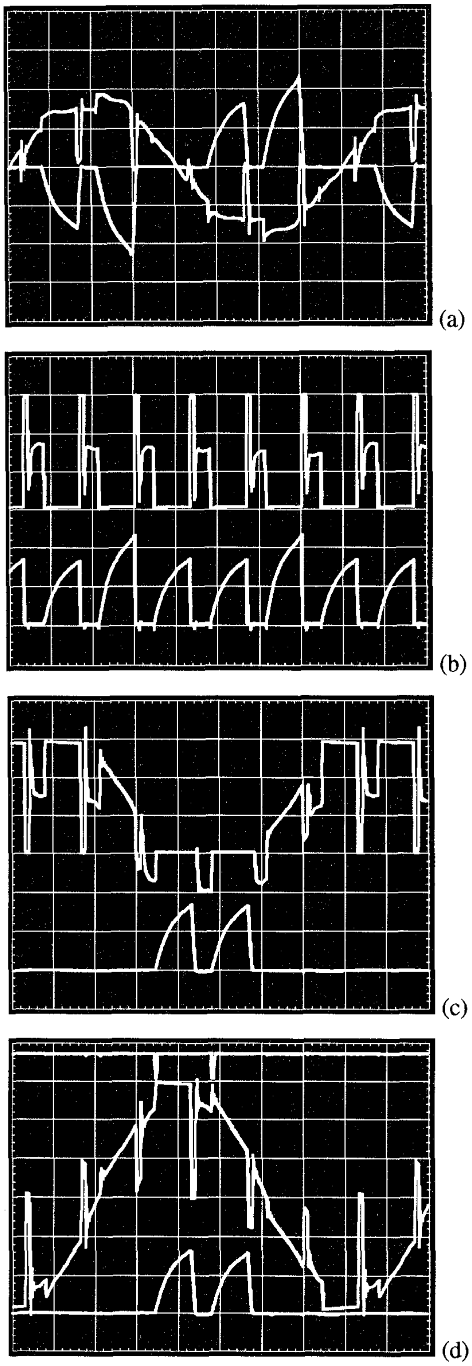

Fig. 3. Results of the experimental analysis of the system. (a): Phase voltage at the input of the thyristor bridge and corresponding phase current. (b): Transistor voltage and transistor current. (c): Thyristor blocking voltage and corresponding thyristor current. (d): Thyristor firing signal (shown inverted, 20V/div) and corresponding thyristor current, and line-to-line voltage at the AC terminals of the thyristor bridge. Operating parameters: Mains line-to-line voltage: 400Vrms (nominal value); for showing the influence of an asymmetry of the mains voltage system one phase voltage has been increased by about 4% by connecting the secondary of an isolated adjustable transformer in series; mains frequency: 50Hz; DC link voltage 590V impressed by an isolated DC voltage source; mains side inductances: 1mH per phase (rated inductance: 0.02p.u. for 10kW nominal braking power); on-interval of the power transistor: 40°el.; power fed back into the mains: 9.5kW. Scales: 200V/div, 20A/div, 2.5ms/div.

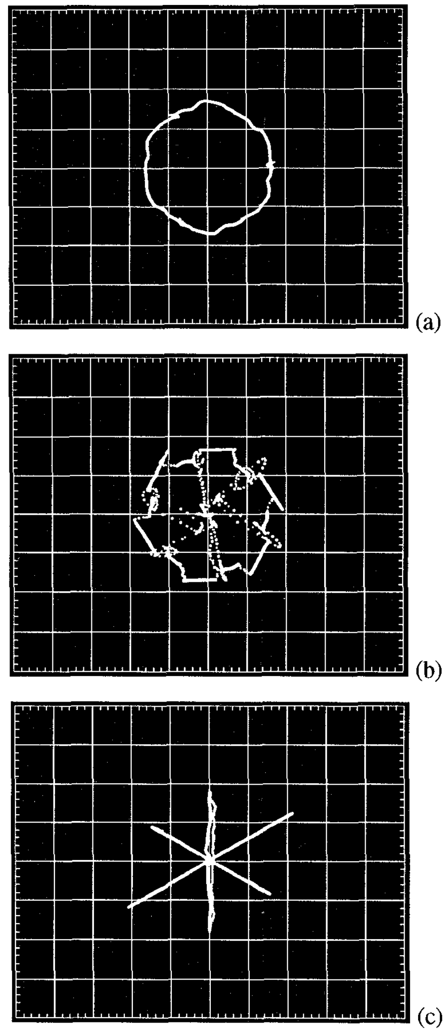

Fig. 4. Trajectories of the space vectors of the voltage at the AC terminals of the thyristor bridge ((a): no-load condition, (b): braking operation) and the mains current (c) corresponding to Fig. 3. Scales: 200V/div, 20A/div. For purely sinusoidal mains voltages (a) should show a circular shape. The deviation to this ideal case is caused by single-phase rectifier systems with capacitive smoothing resulting in flat tops of the phase voltages and/or low frequency (5th and 7th harmonic) distortion. (c) is in close correspondence to Fig.6 (b) in [1] and also reflects clearly the asymmetry of the mains voltage system.

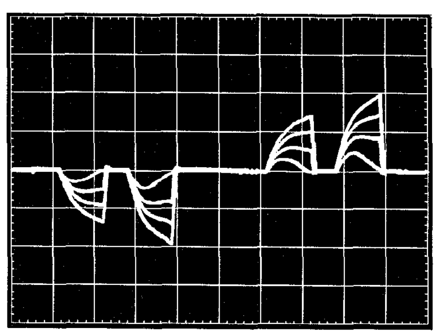

Fig. 5. Shape of a mains phase current for different values of the DC link voltage (590V/580V/570V/550V) and/or different braking power levels (9.3kW/7.2kW/5.4kW/1.6kW). Remaining operating parameters of the system according to Fig.3. Scales:20A/div, 2ms/div.

III. CONTROL UNIT

The primary difficulty with controlling the system is the derivation of gating signals of the power semiconductors in synchronism to the mains voltage system based on a heavily corrupted voltage appearing at the AC terminals of the thyristor bridge. Furthermore, the control unit has to prevent the occurrence of overcurrents in case of commutation failures or mains failures and should show a low realization effort.

The basic idea of the circuit shown in Fig. 2 is to use optocouplers for detecting the natural commutation instants appearing in time intervals where the demagnetization of the mains side inductances has been completed and/or the voltage at the input of the thyristor bridge shows an undistorted shape. In each natural commutation instant two valves are fired according to Fig.3 in [1] and also the power transistor is turned on. The turn-on interval is limited to 40°el. in order to guarantee a minimum time for thyristor recovering. False triggering of the detection circuit by notches of the line-to-line voltage is inhibited by a blanking time being started in the turn-on instant of the power transistor amounting to about 55°el.

IV. EXPERIMENTAL RESULTS

The results of the experimental analysis (cf. Figs.3, 4 and 5) very clearly show the functional principle of the system which already has been described in [1] in detail.

Controlled by the power transistor S_1, in the region of the maxima of the line-to-line mains voltages braking energy pulses are fed into the mains (there, the DC link voltage shows a value slightly higher than the amplitude of the mains line-to-line voltage). Thereby, we have a distribution of the conduction intervals within a mains period as known from diode bridges with capacitive smoothing (however, with inverse direction of the phase currents, cf. Fig.3 (a)). The turn-on and demagnetization intervals of the system also can be clearly identified in the shape of the trajectory of the space vector of the thyristor bridge AC terminal voltage (see straight segments in Fig.4 (b)).

The braking operation is robust with respect to low frequency distortion and asymmetries of the mains voltages. The occurrence of different peak values of the phase currents could be avoided by directly controlling the turn-off current of the power transistor. For a given braking power level this would reduce current stress on the power semiconductor devices.

V. CONCLUSIONS

In this paper the theoretical considerations of the Loss-Free Braking-Resistor Concept given in [1] have been experimentally verified using a 10 kW laboratory model. The system turned out to be very robust, reliable, compact and highly efficient. This motivates further research which will be focused on the influence of the capacitance of the DC link capacitor on the mains current shape, and/or the achievable braking power for low DC link capacitance and the stresses on the power components.

VI. ACKNOWLEDGMENT

The authors would like to thank Dipl.-Ing. M. Arnold of IXYS Semiconductor GmbH, Lampertheim, Germany for supporting the experimental work in the field of three-phase converter systems of the Dept. of Electrical Machines and Drives and of the Power Electronics Section at the Technical University Vienna. Furthermore, also the assistance of cand.ing. G. Ritzberger in realizing the laboratory model is highly appreciated.

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