AC/AC Power Conversion Based on Matrix Converter Topology with Unidirectional Switches

Siyoung Kim, Seung-Ki Sul, *Fellow, IEEE*, and Thomas A. Lipo, *Fellow, IEEE*

***Abstract*—In this paper, a new type of ac/ac converter is proposed. The proposed converter is capable of direct ac/ac power conversion and, except for a few small snubber elements, it does not require the use of any input inductors or a dc-link capacitor. In contrast to the matrix converter, which requires bidirectional switches, the proposed converter consists of only unidirectional switches such as insulated gate bipolar transistors. The converter has a unity input displacement power factor, and its input line current waveform is similar to that of a diode rectifier with a dc-link inductor. The proposed converter has been validated experimentally using an induction motor driven with field-oriented control.**

***Index Terms*—AC/AC conveter, matrix conveter, unidirectional switch.**

I. Introduction

An AC/AC POWER converter widely used in a high-performance drive system is shown in Fig. 1. It is capable of bidirectional power flow and unity input power factor operation, and it allows a wide rage of output voltage. As shown in Fig. 1, it is divided into a pulsewidth modulation (PWM) boost converter and a PWM inverter with dc voltage link. As an energy storage component, it requires a large tank capacitor in the dc link and a heavy inductor at the input terminal. The dc-link capacitor can be a critical component, especially in high-power or high-voltage applications, since it is large and expensive, and it has a limited lifetime. The source-side inductors are also a burden to the system. Their size is usually 20%–40% of the system size if a switching frequency of several kilohertz is assumed. High cost, large size, heavy weight, and energy loss are drawbacks of conventional ac/ac converters.

Many efforts to reduce such components have been reported [1]–[4]. In [1] and [2], the dc-link capacitor was minimized using the input/output power balancing control. In [1], the bulky electrolytic capacitor was replaced by a small polypropylene capacitor. However, the heavy source-side inductor was still necessary, and system operation was too dependent on the reliable operation of the power balance control. Unfortunately, reliable operation of the power balance control can be difficult to achieve under real-world conditions. In [3], two different converter topologies were proposed. The first topology requires bidirectional switches. Bidirectional switches are not available in a single package and, thus, must be made out of multiple unidirectional switches. Because of this unique construction requirement, bidirectional switches are not yet cost effective or reliable. The second topology uses conventional unidirectional switches, but it does not eliminate the large input inductor. Furthermore, because the study focused only on steady-state operation, the converter's dynamic operation is still largely unknown. In [4], an ac/ac converter without dc-link capacitor was reported, but it, too, requires bidirectional switches implemented with two antiparallel thyristors and, thus, the modulation of the source-side converter has limitation.

The objective of using no reactive components can be achieved by using a matrix converter. Matrix converters were first investigated in [5] and have received considerable attention [6]–[9]. As shown in Fig. 2, the matrix converter does not need reactive components. The available output phase voltage of matrix converters is up to $\sqrt{3}/2$ of the input phase voltage with full control of magnitude and phase [8], [9]. If some harmonic distortion is allowed, the ratio between average input voltage and average output voltage can be unity. The implications of additional harmonics, however, should be considered when selecting the matrix converter topology. Regardless of its merits, no reactive components and unity power factor operation, the matrix converter is not yet a cost-effective solution because of its bidirectional switches. Moreover, protection against external faults is complex and not yet reliable.

The proposed converter is a hybrid of the matrix converter and the conventional converter. Like a conventional converter, it uses only unidirectional switches and consists of two converter stages. However, it does not need a dc-link capacitor or input inductor for energy storage.

II. Principles of Operation

A diagram of the hybrid converter can be seen in Fig. 3. The depicted converter can be viewed as a cascade connection of two converters. The first converter stage is an ac/dc current-source rectifier, and the second converter stage is a dc/ac voltage-source inverter. This configuration allows the bidirectional switches of the matrix converter topology to be replaced with unidirectional ones. Insulated gate bipolar transistors (IGBT's) are used as the unidirectional switches. The rectifier bridge IGBT's are

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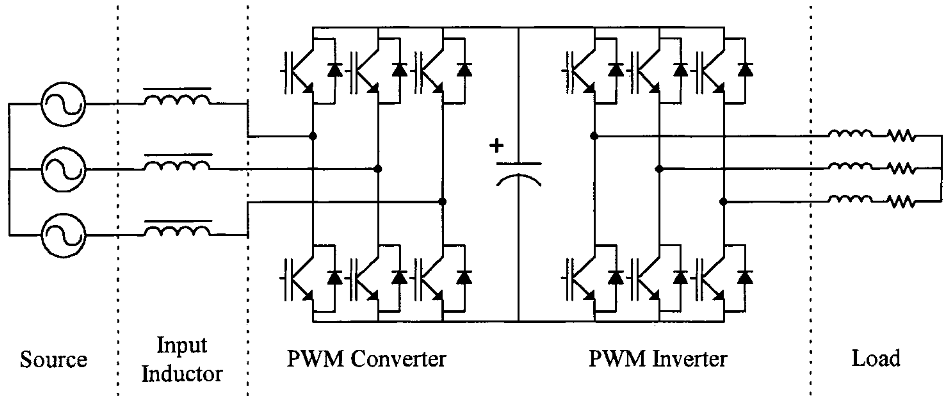

Fig. 1. Conventional ac/ac converter.

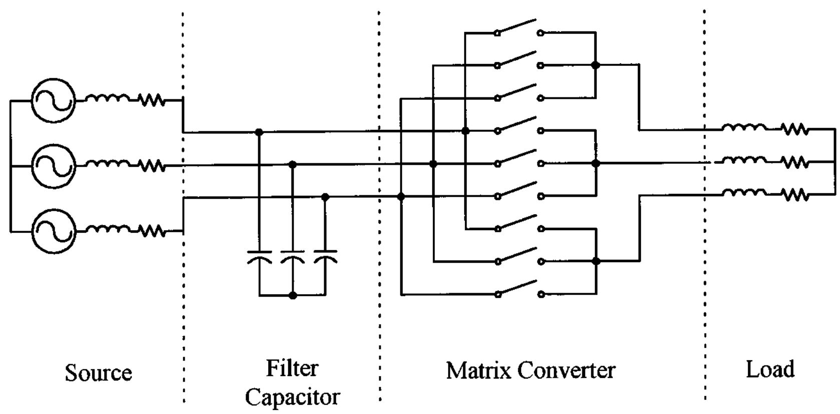

Fig. 2. Matrix converter.

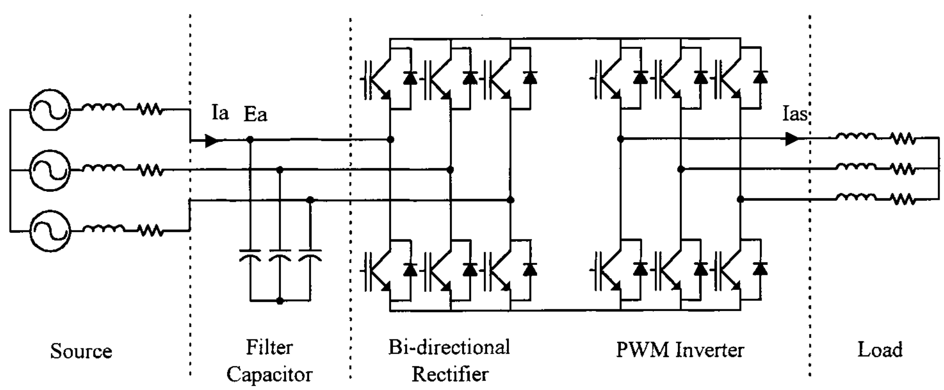

Fig. 3. Proposed ac/ac converter.

turned on for a 120° interval per cycle, as shown in Fig. 4. The switching frequency of the IGBT's is basically the same as the source frequency. The rectifier bridge's output, which is the dc-link voltage, is a rippled voltage waveform that traces the top of the absolute value of the line-to-line input voltages. The ac output voltage of the inverter bridge is synthesized based on the dc-link voltage by the space-vector PWM (SVPWM) [10], [11]. Due to the high-frequency switching and the advanced modulation method, the varying dc-link voltage is compensated for and, therefore, does not affect the output voltage.

The dc-link voltage can be viewed as both a voltage source and current source. The stiff current characteristic is provided by the inductive components of the load, and the stiff voltage characteristic is provided by the input source itself. However, the source has its impedance, so the input filter capacitors are added to compensate for the impedance. The rectifier bridge is capable of bidirectional current flow and the power can transferred from the source to load or from load to the source freely.

The source-side bridge has a switching frequency of one-hundredth of that of the inverter bridge, so it thus generates no switching losses. Moreover, because there is no dc-link capacitor, there is no need of initial charging circuits for the capacitor, which is a considerable burden to the conventional ac/dc/ac power conversion system. In regard to the protection of the con-

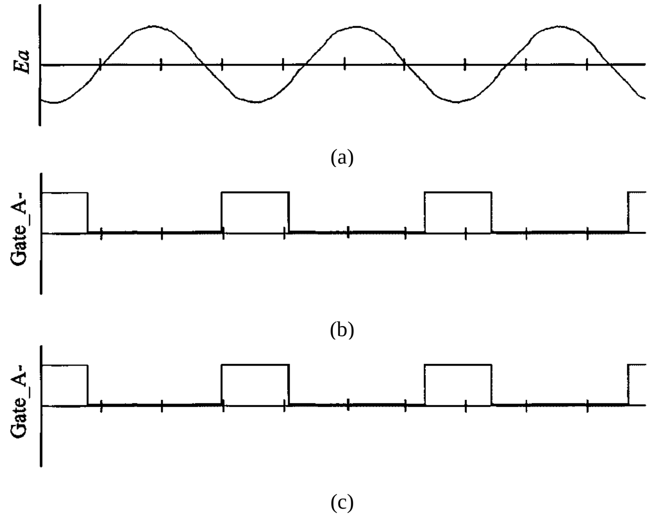

Fig. 4. Switching of the rectifier bridge. (a) Phase voltage of the source. (b) Gating signal of the upper leg. (c) Gating signal of the lower leg.

verter from external load faults, it can be easily protected by stopping operation of the inverter bridge and maintaining operation of the rectifier bridge. By doing this, the energy stored in the load inductance can be transferred to the source-side filter capacitors without any overvoltage. This is an advantage over the matrix converter.

III. Simulation

Using the circuit in Fig. 3, computer simulations were carried out for the *R-L* load specified in Table I. The line current waveform at the input filter capacitor is shown in Fig. 5(b), where the waveform is almost six-step. From Fig. 5(a) and (b), it can be seen that the displacement power factor is unity, but the total power factor is not unity. The waveform is much better than that of the conventional diode rectifier with dc-link capacitor, but worse than that of the PWM boost converter. The efficiency of the proposed converter is higher than any other ac/ac or ac/dc/ac power converter because of its reduced use of reactive components and low switching frequency of the rectifier bridge.

Without low-order harmonics, the maximum available output voltage can be up to $\sqrt{3}/2(=0.866)$ of input phase voltage with full control of magnitude and phase of output voltage. If low-order harmonics are included, the output voltage magnitude can match that of the input voltage.

IV. Implementation Issues

A. Switching of the Rectifier Bridge

The rectifier bridge IGBT's should be switched on and off in a manner synchronized to the source voltage. In order to guarantee the path of the regenerative current of the inverter bridge, an upper switch and a lower switch should always be on. Without this path, the circuit is open, and a severe high voltage can be created in the dc-link. If more than two switches among upper ones or lower ones are turned on, the source is short circuited through the rectifier bridge. These two restrictions make the switching of the rectifier bridge considerably difficult.

TABLE I
Simulation Condition

Input voltage	220V(line-to-line, RMS)
Input frequency	60Hz
Line inductance, Ls	60μH
Line resistance, Rs	0.09Ω
Filter capacitor	33μF/phase (Δ connection)
Load resistance	1Ω
Load inductance	1mH
Commanded output freq.	80Hz
Commanded output voltage	122 V(line-to-line, RMS)
Switching freq.of inverter	5kHz

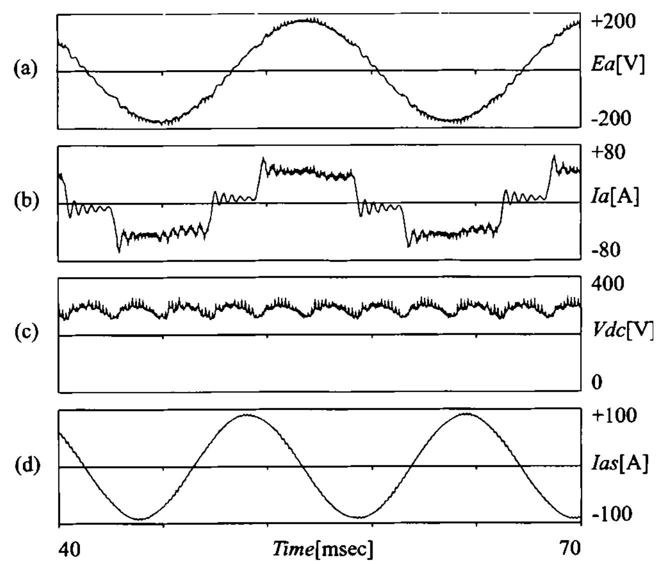

Fig. 5. Simulation results. (a) Input phase voltage. (b) Input line current. (c) DC-link voltage. (d) Output currents.

For the open-circuit problem, the switching of the rectifier bridge is forced to occur only in the zero vector period of the inverter bridge, when the load current is not transferred to the rectifier bridge. For the short-circuit problem, the forward voltage drop of an IGBT and its diode give a margin of several volts for the switching of rectifier bridge. The margin is equivalent to several microseconds in the case of the 220-V/60-Hz source. It means that, if the rectifier bridge completes its switching within that time, there is no short circuit. Fortunately, this period of time is enough time for the controller. With these two measures, the open and short-circuit problems can be effectively managed.

B. Inductance Between the Filter Capacitor and the DC Link

If not for the stray inductance of the IGBT's and the effective series inductance of the input filter capacitors, the input filter capacitor could act as an ideal voltage source. These inductances, however, cause large voltage spikes at the dc link when switching of the inverter bridge occurs, as seen in Fig. 6. Fig. 6(c) shows that these spikes are actually resonant peaks with peak voltages up to 300 V for the 160-V dc-link voltage. The resonant frequency is several megahertz. The input source voltage is 110 V (rms). Because of the danger of damaging the switches used in the experiment, the source voltage was reduced

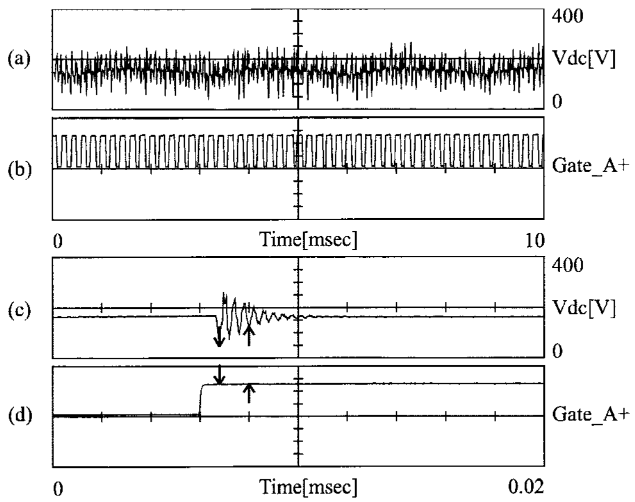

Fig. 6. Spikes in the dc link without the snubber capacitor (experimental waveforms). (a) DC-link voltage. (b) Gating signal. (c) DC-link voltage. (d) Gating signal. [(c) and (d) are time-magnified version of (a) and (b). It is 1.2 μs between the down arrow and the up arrow in (c) and (d)].

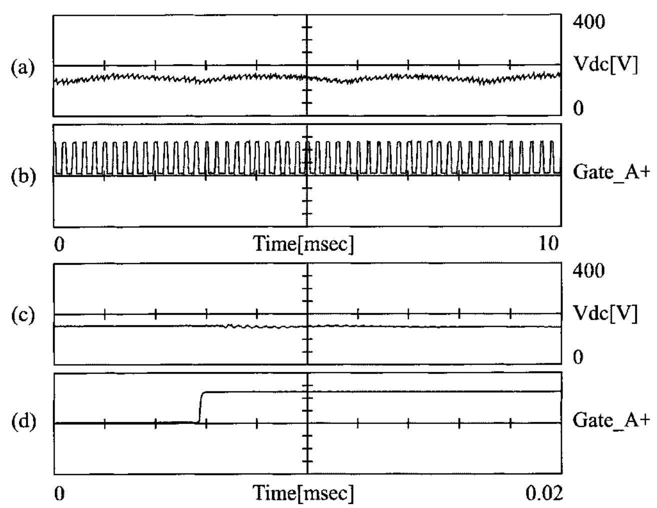

Fig. 7. Suppression of the spikes with the snubber capacitor (experimental waveforms). (a) DC-link voltage. (b) Gating signal. (c) DC-link voltage. (d) Gating signal. [(c) and (d) are time-magnified version of (a) and (b)].

from 220 to 110 V. Even though the resonance is damped out rapidly by the loss in the continuous exposure to the voltage, spikes could be disastrous to the switches. The input filter capacitors could not provide effective suppression of the spikes because of capacitors internal inductances. For this reason, a small snubber capacitor was added in the dc link. This new capacitor effectively suppressed the spikes, as shown in Fig. 7. A 4-μF snubber capacitor was used for the 20-kVA converter in the experiment. Because there is a voltage source on either side of the rectifier bridge, one created by the filter capacitor and the other by the snubber capacitor, there is a possibility of collision between them. However, collision does not occur because the switching of the rectifier bridge is done only at the time when they are the same voltages.

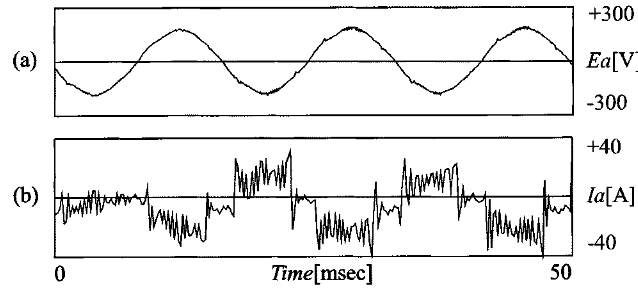

Fig. 8. Resonance at the input terminal (experimental waveforms). (a) Phase voltage of the source. (b) Line current at the input terminal.

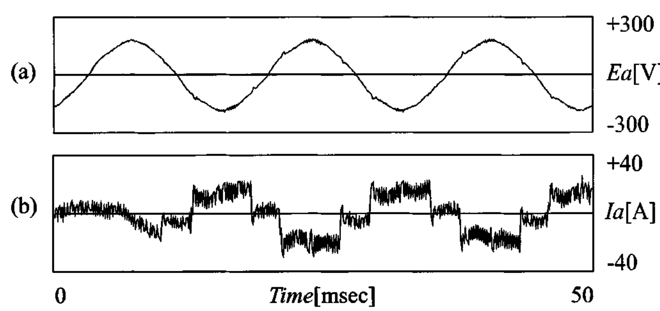

Fig. 9. Resonance suppression at the input terminal (experimental waveforms). (a) phase voltage of the source. (b) Line current at the input terminal.

TABLE II
CHARACTERISTICS OF THE SNUBBER INDUCTOR

IMPEDANCE \ FREQ.	60HZ	1KHZ	10KHZ
RESISTANCE [Ω]	0.0	0.044	0.35
INDUCTANCE[μH]	35.0	32.5	16.7

C. Resonance at the Input Terminal

Since the source has line inductance, there can be a resonance between the line inductance and the input filter capacitor. The six-step current could easily excite the resonance because the quality factor is very high. This kind of resonance is inevitable when the converter uses input filter capacitors. There are several ways to suppress the resonance. The simplest method of supression is inserting an extra inductance and resistance in series with the source. With the additional inductance and resistance, the resonance frequency and quality factor can be controlled to a desired value. Another method is to use the power converter to provide active damping [9]. The active damping method is very effective and no loss, but it can be applied only in case that the resonance frequency is one order of magnitude less than the switching frequency of the converter. In the proposed converter, the resonance frequency depends on the line inductance and the frequency is in the range of 2–10 kHz under the condition of the experiment. Hence, for the proposed converter the active damping method cannot be applied.

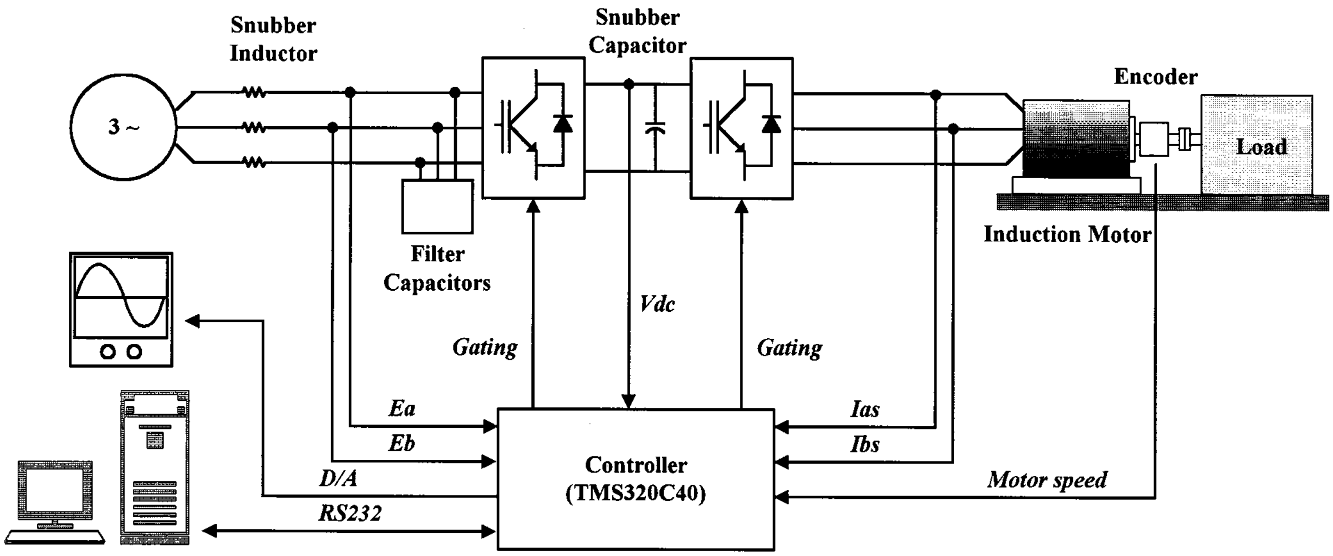

Fig. 10. Experiment configuration.

TABLE III
EXPERIMENTAL CONDITION. (a) CONVERTER. (b) MOTOR

Rated power	20 kVA
Source voltage	220V (line to line, RMS)
Line inductance	About 30 μH
IGBT module	600V, 150A (Six in a pack)
Switching freq. Of inverter	5kHz
(Sampling freq.)	(10kHz)
Snubber capacitor	4μF, 600V
Dynamic damper	0.35 Ω,16.7μH (at 10 kHz)
Filter capacitor	25μF/phase (Δ connection)

(a)

Number of Poles	4
Rated Power	7.5 kW
Stator resistance, Rs	0.15 Ω
Rotor resistance, Rr	0.17 Ω
Stator inductance, Ls	0.035 H
Rotor inductance, Lr	0.035 H
Air-gap inductance, Lm	0.0338 H
Inertia, Jm	0.11 kg.m^2
Rotor flux reference	0.42 Web
Speed sensor	Optical Encoder, 1024ppr

(b)

To suppress the resonance, a small iron-core snubber inductor was inserted between the source and the filter capacitor. This inductor effectively acts as a damping resistor. Because of the nonlinear characteristic of the core, the snubber inductor effectively filters out the resonance frequency range and passes the source frequency. The source current without any snubbing inductance is shown in Fig. 8, where the filter capacitor is 25 μF per phase in delta connection. The resonant frequency is 4.8 kHz and magnitude of resonant peak is about 40% of the fundamental component of the input line currents. The waveform of the source current with the snubber inductor is shown in Fig. 9, where it can be seen that the resonance is effectively suppressed. The snubber inductor characteristics are shown in Table II. In this case, the energy loss of the snubber inductor is less than a few watts.

V. EXPERIMENTAL RESULT

In order to better understand possible implementation problems, a prototype converter was built and tested with an induction motor drive system. The converter and motor parameters are listed in Table III. The hardware block diagram is shown in Fig. 10, where all control is carried out by a digital signal processor, and field-oriented control was applied.

Overall operation of the converter is shown in Fig. 11. The motor speed is varied from –1500 to +1500 r/min. At that time, the motor torque is about 42 N/m. The left side of the plots shows the generating mode of motor, that is, power flows from the motor to the source, and the right side shows the motoring mode. At the beginning of regeneration, the power generated at the motor is 6.6 kW. The dc-link voltage has a ripple of 360 Hz, and the peak is about 305 V. The line current in the generating mode is smaller than that of the motoring mode because part of the generated energy is consumed by system loss, as shown in Fig. 11(e).

Fig. 12 shows the reversal of power flow. The torque is changed at the predetermined motor speed, ±1500 r/min. The rapid torque reversal causes the phase of the input line current to be changed by 180°, as shown in Fig. 12(f). At this point, the speed is –1500 r/min, and the operation mode is changed from motoring to generating. Even though the power flow has been rapidly reversed, there are no erratic behaviors.

Fig. 13 shows the operation in case of motor faults. By cutting off the gating of the inverter bridge and maintaining the gating of the rectifier bridge, the converter can be easily protected. Because the energy stored in the motor leakage inductance can be transferred to the input filter capacitor through the diodes of the inverter bridge and the IGBT's of the rectifier, there is no overvoltage problem at the dc- link. The motor currents and the input line current decay to zero. The input lines have some phase-leading currents caused by the filter capacitors.

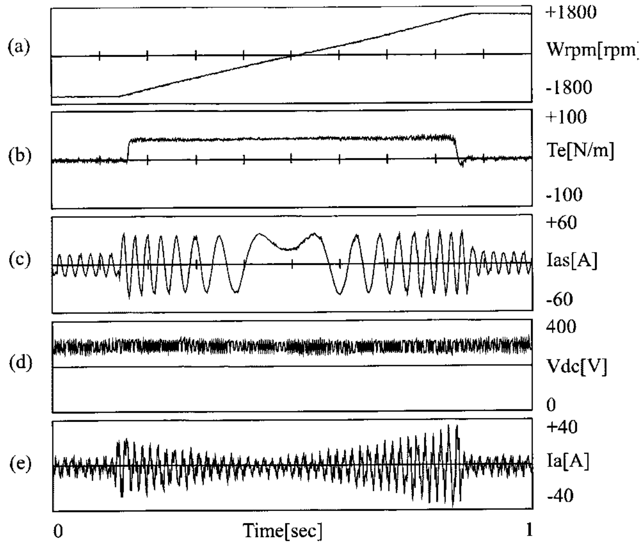

Fig. 11. Motoring and regenerating operation. (a) Motor velocity. (b) Motor torque. (c) Motor current. (d) DC- link voltage. (e) Input line current.

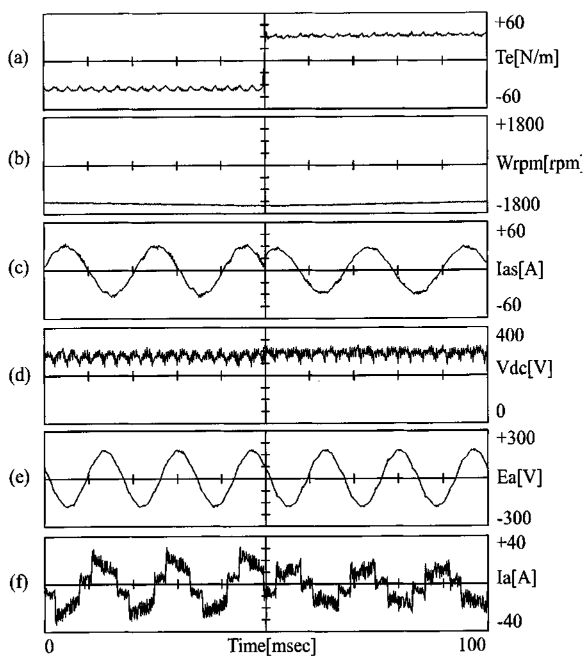

Fig. 12. Reversal of the power flow. (a) Motor torque. (b) Motor velocity. (c) Motor current. (d) DC-link voltage. (e) Filter capacitor phase voltage. (f) Iinput line current.

Fig. 14 shows the converter operation when a voltage sag occurs. The sag causes the dc-link voltage to drop, which, in turn, creates a torque fluctuation, as shown in Fig. 14(d). The motor speed is about 800 r/min. Due to the inertia of the motor, the motor speed hardly changes. The converter runs through it and resumes normal operation. Because of the limited power capacity of the power supply, which produced the sag, the flux reference and the torque reference of the motor were reduced for the experiment.

VI. Conclusions

In this paper, a new ac/ac power converter has been proposed. The proposed converter consists of only unidirectional

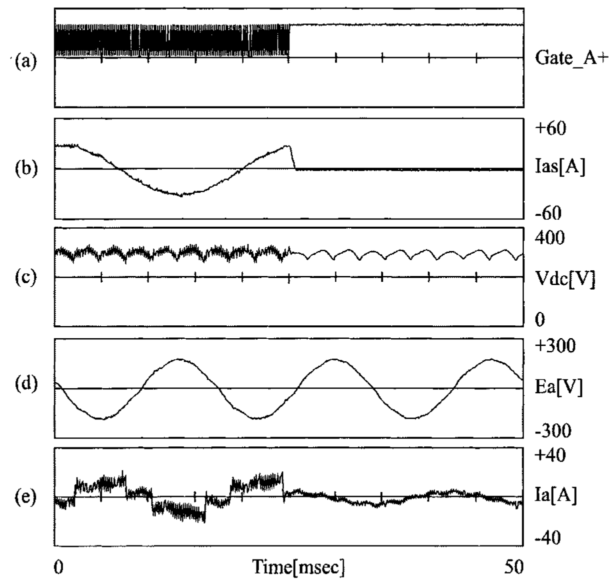

Fig. 13. Stop of inverter gating. (a) Gating signal of inverter bridge. (b) Motor current. (c) DC-link voltage. (d) Filter capacitor phase voltage. (e) Input line currents.

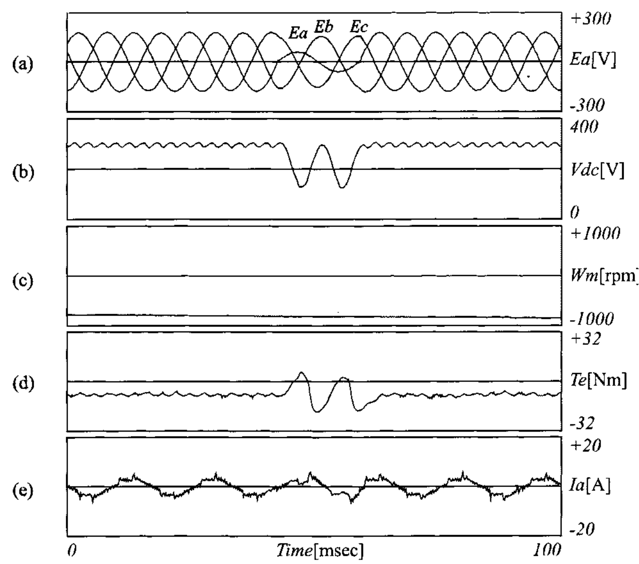

Fig. 14. Converter operation on a voltage sag. (a) Phase voltage at the filter capacitor. (b) DC-link voltage. (c) motor speed. (d) Motor output torque. (e) Line current of the source.

switches. It does not use bulky dc-link capacitors or heavy input inductors. So, the weight and size of the converter are dramatically reduced. In spite of reduced reactive components, satisfactory performance in an ac drive system has been demonstrated. Characteristics of the converter were investigated, and the feasibility was confirmed with computer simulation and experiment. Some issues encountered in the real implementation, such as switching of the rectifier bridge, resonance at the input terminal, and voltage spikes at the dc link, were also addressed.

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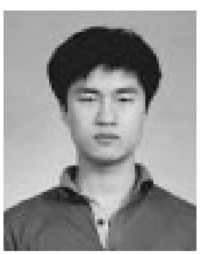

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