Research Report

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

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***Abstract* - In this paper a new circuit for ac to ac power conversion is presented. The circuit is derived from the matrix converter topology, which has the capability of direct ac to ac power conversion without any dc link reactive component and input inductance except a small snubber. And it consists of only unidirectional switches such as IGBTs with antiparallel diodes contrast to the matrix converter which consists of bi-directional switches. The input displacement power factor of the proposed one is unity and the overall power factor is near unity. The waveform of the input line currents is much alike with the diode rectifier with a large dc-link reactor. The validity of the proposed circuit and its operation is confirmed by the experiment which uses a dynamic load–field oriented induction motor drive system.**

I. INTRODUCTION

The ac-ac matrix converter topology was first investigated in 1976[1] and then recently more using a generalized high frequency switching strategy[2]. The main advantage of matrix converter shown in Fig. 1 is the possibility of reduction of reactive components. The drawback of the limited output voltage range of the matrix converter is almost solved by the space vector algorithm and its modulation strategy is clearly developed in several literature[3,4]. With this modulation strategy, the available output phase voltage is $\sqrt{3}/2$ of input phase voltage with the full control of magnitude and phase without low order harmonics. And in the sense of average voltage the ratio between input and output voltage can be unity at the cost of some harmonics. But, regardless of these developments and its merits such as minimum filter requirement, low switching loss, and unity power factor operation, still, bi-directional switches are not available and the matrix converter is not yet a cost effective solution. Moreover, the protection of the circuit against external faults is complex and not reliable yet.

The converters as in Fig. 2, which has the bi-directional power flow capability and unity power factor operation at source side without bi-directional switches, are widely used for high performance machine drive systems. The PWM inverter with front end PWM boost rectifier in Fig. 2,

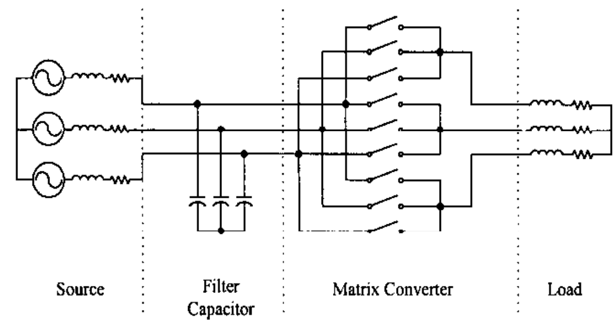


Fig. 1. Matrix Converter

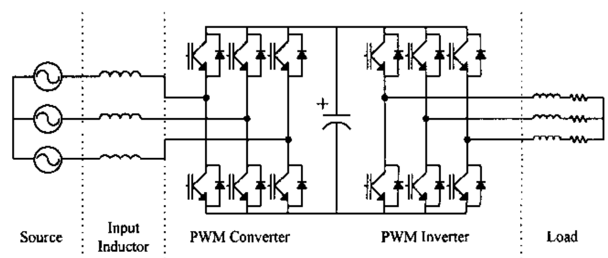


Fig. 2. Conventional ac-ac Converter

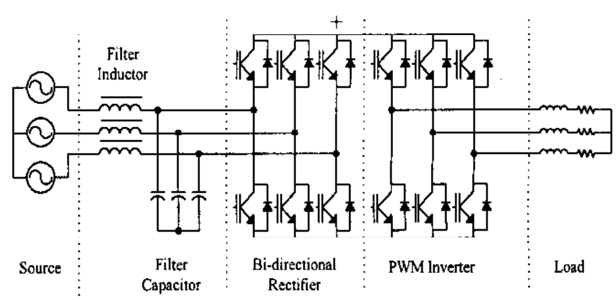


Fig. 3. Ziogas' second structure

requires a bulky electrolytic capacitor in the dc link and a large and heavy reactor at the source side. The reliability of the electrolytic capacitor is always a concern in heavy duty industrial applications. Also the size of the source side reactor is in 5–10 % range of rated power of the system assuming several kHz switching frequency and less than 5 %

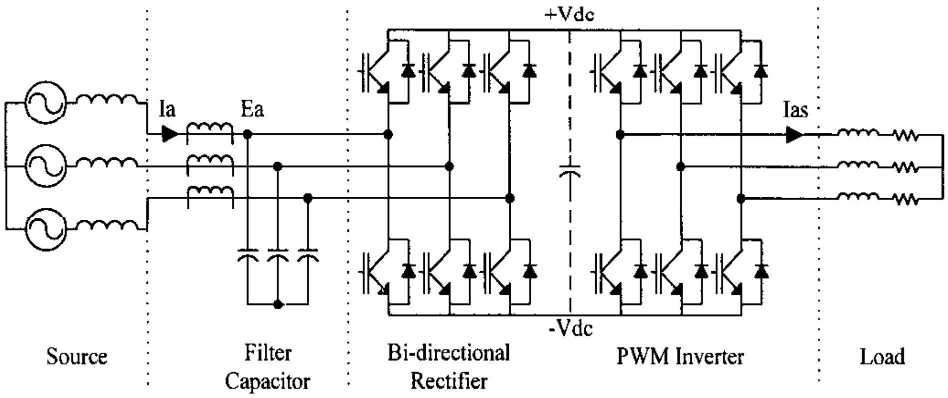


Fig. 4. Proposed ac-ac Converter

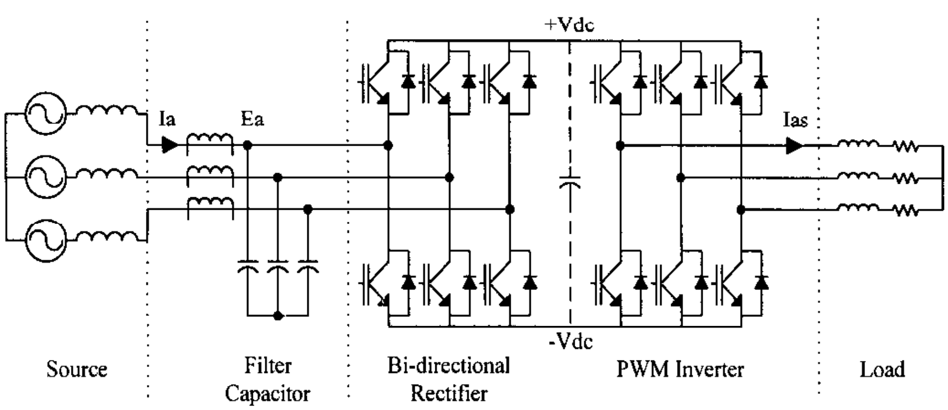
ripple current in the source. The cost, size, weight and losses of the reactor are main drawbacks of the PWM boost rectifier.

The efforts to reduce such components have been made and reported [5-7]. In [5], the dc link capacitor size has been minimized using the source and load side power balancing control. Hence, the bulky electrolytic capacitor was replaced by a small polypropylene capacitor, but still need a heavy source side reactor. In [6] Ziogas and et. al. proposed two structures, of which the first one uses bi-directional switches and the second one uses conventional uni-directional switches. The second one, which is similar to the proposal of this paper, eliminated the dc-link capacitor but the study was focused on steady state operation. And the issues of the control of the source side converter and regeneration operation were not addressed properly. A novel circuit without dc link components, which use bi-directional switches implemented with two antiparallel thyristors, has been reported in [7]. Because of the thyristors, the modulation of the source side converter has limitations in switching operation. And the experimental results were not reported .

In this paper a circuit which has the bi-directional power flow capability with much less reactive components compared to previous studies[4-7] is proposed. The matrix converter can be decomposed as a cascade connection of two reduced reactive components and low switching frequency of the source side converter.

II . Configuration and Operation Principle

The circuit diagram of the proposed converter is shown in Fig. 4, where two three phase PWM bridge circuit is connected in series. The source side bridge (rectifier bridge) acts as a current source rectifier, and load side bridge (inverter bridge) as a PWM voltage source inverter. The dc link can be considered as a voltage source and current source simultaneously. The stiff current characteristics is provided by inductive components of the load and stiff voltage characteristics by the input filter capacitor. The input rectifier has the capability of bi-directional current flow and the active power can be transferred from source to load or from load to source freely. The IGBT switches of the rectifier turn on and off simultaneously with their own antiparallel diode and the switching frequency is basically the same as the input line frequency. The output of the rectifier bridge, which is the dc link voltage, is the largest one among the line to line source voltage. The ac output voltage of inverter bridge is synthesized based on the dc link voltage by the space vector PWM [8]. The circuit has 12 IGBTs, but the half of them–the ones in the source side bridge– generate



III. SIMULATION

The simulation was carried out for a R-L load with parameters given in Table 1. The line current waveform after input capacitor filtering with distribution line inductance is shown in Fig. 5, where the waveform is almost 6 steps. The displacement power factor of the line currents is unity, but the total power factor is not the case. The maximum available output voltage can be up to $\sqrt{3}/2$ of input phase voltage with full control of magnitude and phase of output voltage without low order harmonics. With reasonable harmonics, the peak of the output phase voltage can be as large as input phase voltage. With ideal input source which has no internal impedance, the output current waveform with R-L load is shown in Fig. 6, where the magnitude of output phase voltage is same with that of input phase voltage. The harmonic frequency spectrum of the load current, shown in Fig 6, reveals a reasonably good characteristics even with same input and output voltage ratio.

IV. SOME IMPLEMENTION ISSUES

The IGBTs and antiparallel diodes of the input rectifier should be switched on and off in a synchronized manner with source voltage. Two switches among six which output the largest line-to-line voltage to the dc link should be turned on. And, at least two switches, upper one and lower one, should be turned on to guarantee the path of the regenerative current of inverter bridge. Without the path an open circuit problem occurs and causes a severe high voltage to the dc link and the switches. If more than two switches are turned on, there should be a short circuit to the source voltage through the rectifier bridge. This contradictory situation makes the switching of rectifier bridge non-trivial. For the open circuit problem, the switching of input bridge is controlled to occur only in the zero vector period of the inverter bridge, where the load current is not transferred to the rectifier bridge. With this restriction, the problem of open circuit in the rectifier bridge can be eliminated. For the short circuit problem, the forward voltage drop of the switches and diodes give a margine of several volts for the switching of rectifier bridge. The margin is equivalent to one hundred and several tens of microseconds in case of 220[V] and 60[Hz] source voltage. It means that the rectifier bridge should make an switching within that time, and it is an enough time for the controller. With above two measures the open and short circuit problems can be effectively managed.

Another issue is voltage spikes caused by stray inductance of the switches themselves and connection line between two bridges. Without any extra capacitor the peak of spikes in the dc link are up to 150[V] in case of 160[V] source voltage and the resonant frequency is several mega hertz range as shown in Fig. 7. In the figure input source voltage are reduced to 110[V(rms)] because there is a limit in the voltage blocking capability of the switches used in the experiment. Even though the resonance is damped rapidly by the stray loss, the continuous spikes could be disastrous to the

TABLE 1.
PARAMETERS OF SIMULATION

Input voltage	220V(line to line, rms)
Input frequency	60Hz
Line inductance, Ls	80μH
Input resistance, Rs	0.07Ω
Filter capacitor	33μF/phase (Δ connection)
Load resistance	1Ω
Load inductance	1mH
Output frequency	80Hz
Switching freq. of inverter	5kHz

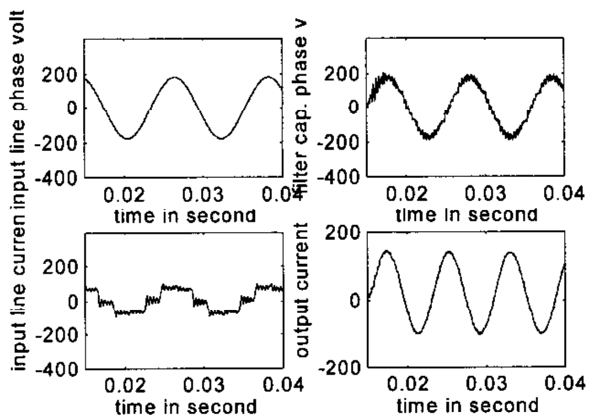


Fig. 5. Simulation results (From the left top clockwise, input phase voltage, input filter capacitor voltage, output phase current, input line currents)

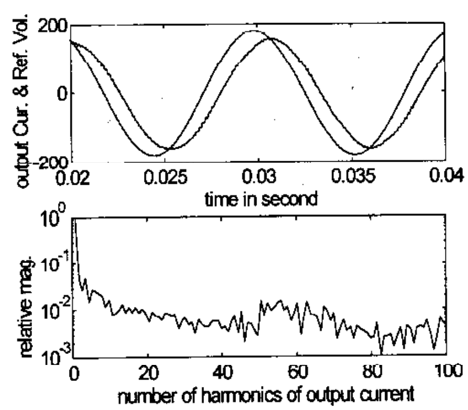


Fig. 6. Output command voltage and output load current and its frequency spectrum

switches. The filter capacitor in the source side can not provide effective suppression to the spikes because of the stray inductance of rectifier bridge. For this reason a small snubber capacitor is placed in the dc link and it effectively suppresses the spikes as shown in Fig. 8. The snubber capacitor is 4[μF] in the experiment. Because there are two voltage sources at the both side of the rectifier bridge, there is a possibility of collision between them. But, the voltage difference between the snubber capacitor and input filter capacitor does not exist because the switching of rectifier bridge occur only at the time they are same voltage.

Since there is a distribution inductance or leakage inductance in the source, the proposed circuit has the possibility of resonance between the input line inductance and the input filter capacitor. The resonance can be easily excited by six step source current and by a high quality factor of the filter capacitor and input line inductance. This kind of resonance is inevitable in any case of power converter with input filter capacitors. There are several ways to suppress the resonance. Most simple one is inserting a 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 providing an active damping by use of power converter itself [9]. The active damping method is very effective and lossless in some cases, but it can be applied only in case that the resonance frequency is one order less than the switching frequency of the converter. In the proposed circuit, the resonance frequency depends on the line inductance and the frequency is in the range of 2–10[kHz] under the assumption of practical distribution line inductance. Hence, with the hard switched PWM of the proposed circuit the active damping method can not be applied. The source current without any measure is shown in Fig. 9(a), where the filter capacitor is 25 [μF] per phase in delta connection. The resonance frequency is 4.8 [kHz] and magnitude of resonance peak is about 40 % of the fundamental component of the input line currents. The resonance can be effectively suppressed with a small snubber inductor which is connected in series to the source. The snubber inductor reveals higher losses in a higher frequency range because of the characteristics of its core–an conventional iron core. The waveform of source current waveform with the snubber inductor at the same operation condition is shown in Fig. 9(b), where the resonance is damped out conspicuously. The total loss of snubber inductor is less than some watts because of its nonlinear loss characteristics.

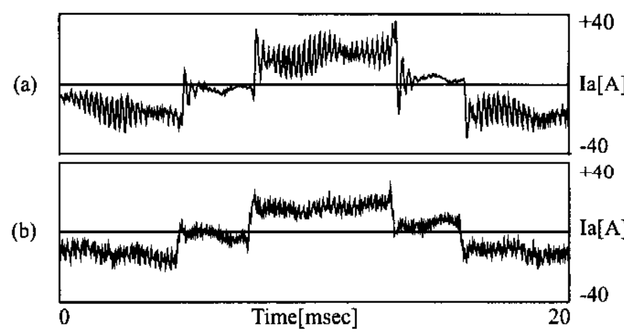


Fig. 9. Resonance suppression using snubber inductors

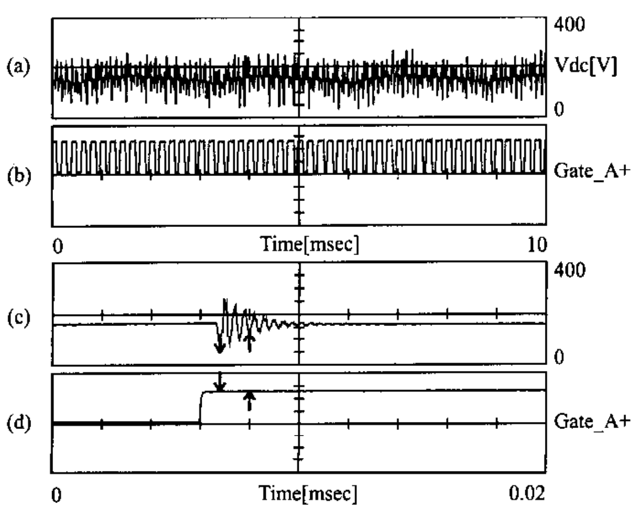


Fig. 7. Spikes in the dc link when the snubber capacitor do not exist. ((c) and (d) are time magnified version of (a) and (b), and it is 1.2[μsec] between the down arrow and the up arrow in (c) and (d).)

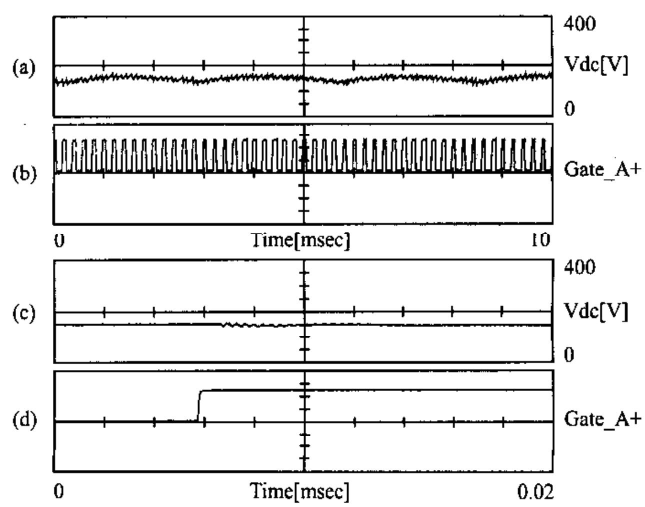


Fig. 8. Spikes in the dc link when the snubber capacitor exists. ((c) and (d) are time magnified version of (a) and (b).)

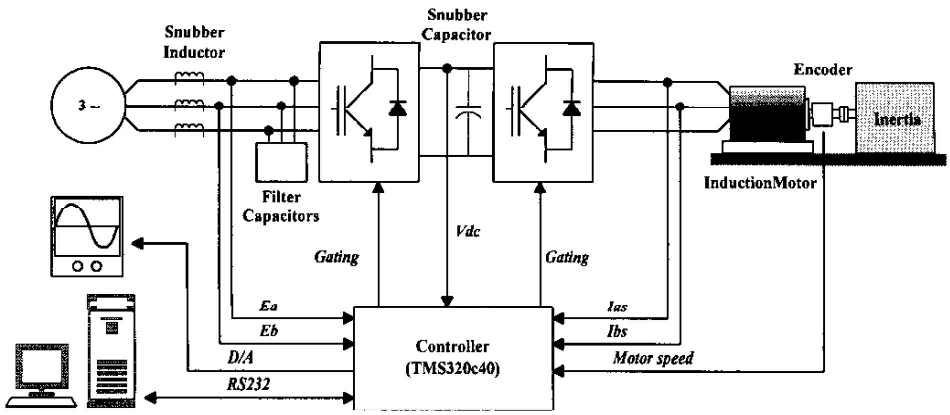


Fig. 10. Experiment configuration

V. EXPERIMENTAL RESULT

With consideration of the practical implementation issues, a prototype converter was built and tested with a field oriented induction motor drive system. The parameters of converter and motor are in Table 2. Total power rating of reactive component except dc link capacitor is only 1.6 % of the rated power of the converter. The hardware block diagram is shown in Fig. 10, where all control is carried out by a digital signal processor.

TABLE 2.
EXPERIMENT PARAMETERS

1. Converter

Rated power	10[kVA]
Source voltage	220[V] (line to line, RMS)
Line inductance	about 30[uH]
IGBT module	600[V], 150[A] (six in a pack)
Switching freq of inverter bridge (Sampling freq.)	5[kHz] (10[kHz])
Snubber capacitor	4[uF], 600[V]
Snubber inductor	30[uH] (at 60[Hz], X_L = 0.23 % kVA rating : 0.023 %)
Filter capacitor	25[uF] (Δconnection, X_C = 7.3 [pu] kVA rating : 0.023 %) (Total kVA rating except snubber capacitor : 1.60%)

2. Motor

Num. 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 [Wb]
Speed sensor	Optical Encoder, 1024[ppr]

In Fig. 11 the overall operation of converter is shown. The motor speed is varied from -1500 to +1500[rpm]. At that time the motor torque is about 42[N/m]. The left side from the center of the plots shows the generating mode of the motor, that is, the power flows from the motor to the source. And the right side shows the motoring mode. At the beginning of the generation, the power generated at the motor

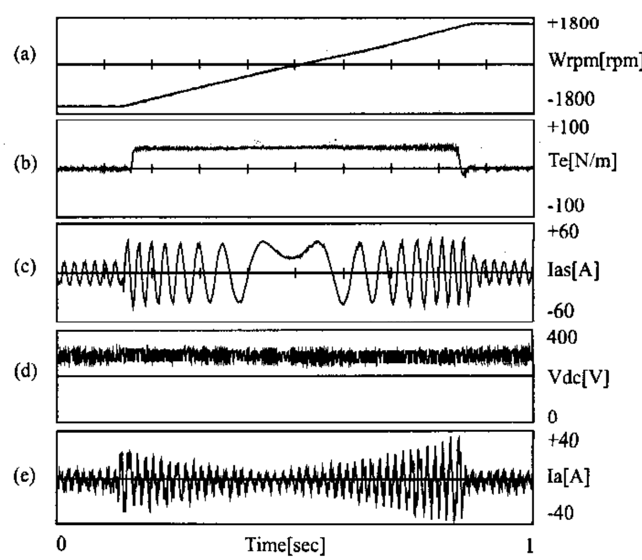


Fig. 11 (a) Motor Velocity (b) Motor torque (c) Motor phase current (d) DC link voltage (e) Input line current

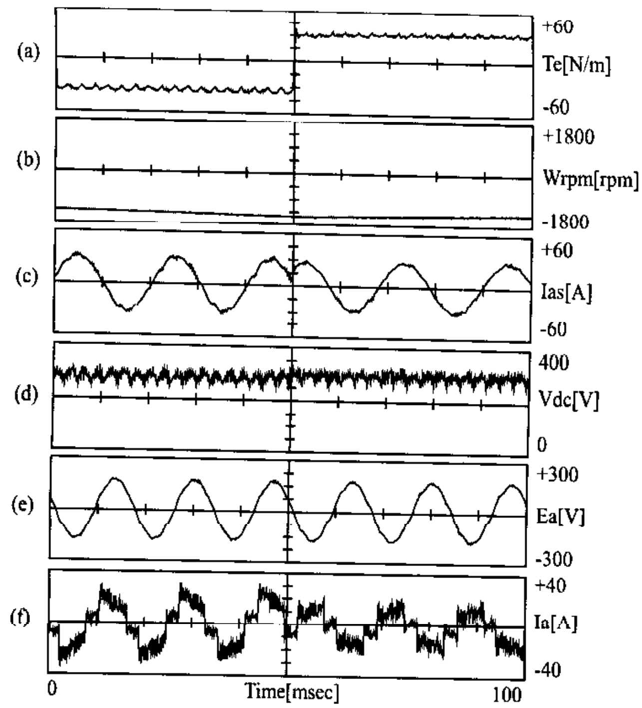


Fig. 12. (a) Motor Torque (b) Motor velocity (c) Motor phase current (d) DC link voltage (e) Filter capacitor phase voltage (f) Input line current

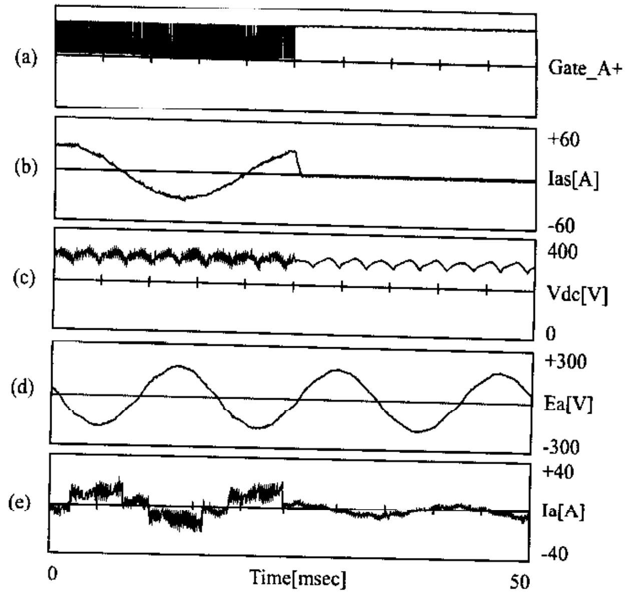


Fig. 13. (a) Gating signal of inverter bridge (b) Motor phase current (c) DC link voltage (d) Filter capacitor phase voltage (e) Input line currents

is 6.6[kW]. The dc link voltage has a ripple of 360[Hz], and the peak is about 305[V]. Regardless of the dynamic operation of load, the dc link has no overshoot and undershoot. The main ripple of the dc link is due to the six step waveform of full bridge diode rectifiers. The input line current in the generating mode is smaller than that of the motoring mode a part of the generated energy is consumed by the system loss.

Fig. 12 is a part of the square wave operation of the torque. The torque is changed at the pre-determined motor speed, 1500[rpm] in Fig 12(b). As shown in Fig. 12(c), the rapid torque reverse causes the phase of the input line current to be changed. At that point, the speed is -1500[rpm], and the operation mode is changed from motoring to generating. Nevertheless of the rapid power reversal, there is no overshoot voltage in the dc link. And the phase of the input line current to the source voltage changes and the displacement power factor is changed from 1 to −1.

Fig. 13 shows the operation of the converter at the case of motor faults. Even in the case the gating signals of the inverter bridge are cut off, there is no problem in the rectifier bridge. The motor currents and the input line current decay to zero, and the input lines have some phase leading currents caused by the filter capacitors.

VI. CONCLUSIONS

In this paper a new ac to ac conversion circuit has been proposed. It has been derived from the matrix converter but consists of uni-directional switches. The characteristics of the converter was investigated by the computer simulations and experimental results. Through the experiment the feasibility of the converter was confirmed. And some issues in a real implementation, which are inevitable problems, were also addressed.

The proposed converter has the following features.

- There is no dc link component except a small snubber capacitor , and it consists of only unidirectional switches.
- The displacement power factor of the input is unity.
- The operation of the prototype converter demonstrated satisfactory performance in the ac machine drive system
- In spite of remarkably reduced reactive components the dc link voltage is well regulated at a rapid power reversal.

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