A unity power factor four-quadrant single-phase DC drive system

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DC drive systems controlled by Pulse-Width Modulation (PWM) techniques are expected to replace the conventional phase-controlled systems. This is due to their simple control, high reliability, low cost and fast response. This paper presents the performance of a new four-quadrant single-phase DC drive system controlled by a sinusoidal PWM full-bridge DC-DC converter and provides an active input power factor correction. Two different new sinusoidal PWM control techniques are considered; PWM with bipolar voltage switching and PWM with unipolar voltage switching. The overall system is simulated using PSpice where the different modes of operation, circuit voltages and currents and current harmonic spectrum are presented. Experimental verification of the proposed system has been developed, where the motor performance characteristics and the converter waveforms have been presented and discussed.

يقـــدم هـــذا البحـــث نظـــام تحريك تيار مستمر مغذى من مصدر تيار متردد أحادى الوجه يعمل في القطاعات الأربعة لجهد وتيار المحـــرك وبمعامل قدرة مساويا للوحدة. يعرض البحث طريقتين للتحكم في جهد المحرك: الطريقة الأولى يتأرجح جهد المحرك بين القيمة الموجبة والقيمة السالبة لجهد وصلة التيار المستمر، وفى الطريقة الثانية يتأرجح جهد المحرك بين جهد وصلة التيار المستمر والصـــفر. وقد تم تمثيل النظام كاملا على الحاسب الآلي وعرض للنتائج النظرية. كما تم بناء نموذج معملي كامل للنظام موضوع البحث وعرض للنتائج المعملية ومقارنتها بمثيلاتها النظرية.

Keywords: DC drive systems, Power factor correction, Pulse-width modulation

1. Introduction

Phase-controlled DC drive systems gained a high popularity due to their simple implementation despite the disadvantages of their poor input power factor especially for large values of phase delay angle, and the high harmonic content in the input AC line current due to its discontinuous nature. Therefore large size reactive components become essential on the expense of cost, efficiency and slower current response of the system [1, 2]. The harmonic-free utility/dc interface provides to the drive systems a means to extract more power from the main supply than the normal rectifier, with its heavily distorted current, will allow. Therefore, it is beneficial to incorporate active input power factor correction techniques in the converter circuits [3, 4].

Also, the current through phase-controlled converters is unidirectional, while the output voltage can reverse polarity. The two-quadrant operation with the reversible voltage is not suited for DC motor braking, which requires the voltage to be unidirectional but the current to be reversible. Therefore, if regenerative braking is required, armature reversal or field reversal techniques are usually employed. Two back-to-back connected thyristor converters can also be used. This, in fact, gives a capability to operate in all the four-quadrants irrespective of the extra cost and increased circuit complexity.

Uniform and sinusoidal Pulse-Width Modulation (PWM) techniques are now extensively used in converter circuits due to the simple implementation of their control circuits and the advantages gained from increasing the switching frequency [5, 6]. However, in all PWM converters the switching power devices have to turn-on and turn-off the entire load current during each switching transition. This in turn increases the switching losses, switch stresses and EMI due to the large dv/dt and di/dt associated with the switching process. The increasing availability of high frequency high power switching devices, such as IGBT, MOSFET and MCT, are expected to reinforce selfcommutated AC-DC converters with PWM control techniques to replace the conventional phase-controlled converters within the available power ratings [7, 8].

This paper present the performance characteristics of a new four-quadrant single-phase DC drive system controlled by a sinusoidal PWM full-bridge DC-DC converter and provides an active input power factor correction. Two methods of control are presented where the motor voltage may have a bipolar or a unipolar voltage waveform. Simulation of the system on PSpice is carried out such that the converter modes of operation and the AC input current harmonic spectrum are presented for the two above mentioned control techniques. A complete experimental setup of the proposed system has been developed where the experimental results are presented and compared to the simulation results.

2. System description

The detailed circuit diagram of the proposed single-phase DC drive system is shown in fig.1. Since the input bridge diode rectifier is uncontrolled, its DC output voltage is of almost constant amplitude. The motor voltage can be controlled in magnitude as well as polarity. Similarly, the magnitude and direction of the motor current can be controlled. Therefore, this drive system allows the operation to be in the four quadrants of V_o-I_o plane, and the power flow can be either from the supply to the motor or from the motor to the supply. Since the DC link current changes direction instantaneously, it is important that the input to the converter be a DC voltage source with low internal impedance. This is achieved by inserting a capacitor filter as shown in fig.1 to provide this low impedance path to the DC input current. The DC motor load is powered through full-bridge dc-dc converter which consists of two legs, each leg consists of two MOSFET switches (M_1, M_2 and M_3, M_4) and their respective anti-parallel diodes (D_1, D_2 and D_3, D_4). The switches in the same leg cannot be turned-on simultaneously to avoid short-circuiting the AC mains supply.

In single-quadrant DC drive systems, the polarity of the motor voltage is unidirectional, hence the switching device is pulse-width modulated by comparing a switching frequency saw-tooth with the control voltage. In contrast, the motor voltage supplied by full-bridge converters is reversible in polarity and, therefore a switching frequency triangular waveform is used for PWM of the converter switches. In order to achieve an active power factor correction, the reference control signal has to be synchronized with the AC supply.

Two sinusoidal PWM control techniques are proposed. In the first one, the diagonally opposite switches M_1, M_4 and M_2, M_3 are treated as two switch pairs where each pair of switches is turned-on and turned-off simultaneously such that the motor voltage is of a bipolar nature. In the second technique, the switches in each leg are controlled independently of the other leg such that the motor voltage is of a unipolar nature.

3. Principle of operation and system simulation

The proposed sinusoidal PWM technique is established by comparing a carrier triangular wave (V_{tri}), at a relatively high frequency (f_c),

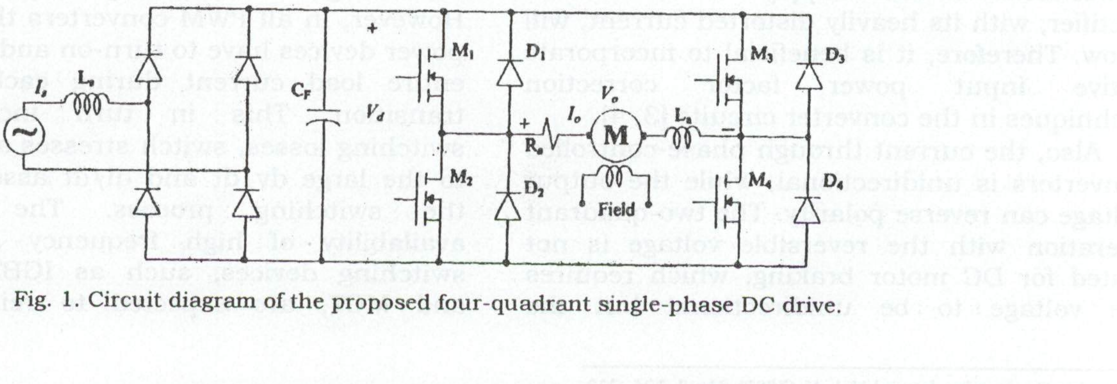

Fig. 1. Circuit diagram of the proposed four-quadrant single-phase DC drive.

with two reference control voltages synchronized with the AC mains supply at the reference frequency (f_r). The first control voltage (V_c) is obtained by rectifying a signal from the AC mains supply, while the second control voltage is the negative of the first one ($-V_c$). The ratio of the maximum value of the reference control voltage to the maximum value of the carrier triangular wave is defined as the amplitude modulation index M_a. The ratio of the frequency of the carrier triangle wave to the frequency of the reference control voltage is defined as the frequency modulation ratio M_f. The amplitude of the carrier wave is kept constant while the amplitude of the control voltage can be changed such that M_a can be varied from 0 to 1. This in turn controls the motor armature voltage from zero voltage to the rated voltage with both polarities positive and negative according to the required direction of motor rotation. This obviously provides soft starting capability of the drive system. For the proposed control strategy it is essential that M_f to be an odd number in order to achieve waveform symmetry.

The switching patterns of the four converter-switches are directly obtained from the above mentioned comparison, where four switching patterns are obtained (two from each comparison) where the two power switches in the same leg have complement switching patterns to avoid short circuiting the AC supply. The generation of the four switching patterns (S_1-S_4) are illustrated in fig.2 for M_a=0.7 and M_f=7, where the carrier frequency is reduced to 350Hz in order to provide clear illustrative waveforms. The switching patterns are generated in such a way that when $V_{ref} > V_{tri}$, switches M_1 and M_4 are turned on. Otherwise, switches M_2 and M_3 are turned on.

3.1. Sinusoidal PWM with bipolar voltage switching

In this control technique, the switch pairs M_1, M_4 and M_2, M_3 are turned on and off simultaneously by S_1 and S_2 respectively. A complete simulation of the drive system is carried out using PSpice for M_a= 0.6 and M_f=21. An expanded waveform of the currents carried by the converter switches and the load current are shown in fig.3, where the negative parts of switch current represents the current carried out by the corresponding anti-parallel diode. Two modes of operation can be defined:

1. Powering mode; in which the motor current is carried by either switch-pairs M_1, M_4 or M_2, M_3 according to the polarity of the motor voltage.
2. Regenerating mode; in which the energy stored in the reactive element is returned back to the supply through either diode pairs D_1, D_4 or D_2, D_3.

It has to be noted that during loading conditions, the motor current will fluctuate between two positive boundaries without affecting the abovementioned modes of operation.

The load voltage with its average value and the load current are shown in fig.4, where it has a bipolar sinusoidally modulated nature. The AC supply voltage and current are shown in fig. 5, where the supply current has a carrier-frequency sinusoidally modulated pulses enveloped within the 50Hz supply frequency component with almost a zero displacement. The harmonic spectrum of the supply current is shown in fig. 6, where the first dominant harmonics (LOH) associated with the 50Hz component appears almost at the carrier frequency at $f_c \pm f_r$ ($\cong$1kHz)

3.2. Sinusoidal PWM with unipolar voltage switching

In this control technique, the switches in each leg are controlled independently of the other leg such that switches M_1 and M_2 are controlled by S_1 and S_2 while switches M_3 and M_4 are controlled by S_3 and S_4. The currents of the converter switches are shown in fig.7, where the following modes of operation can be defined:

1. Powering mode; in which the motor current is carried by switch-pair M_1 and M_4.
2. Free-wheeling mode; in which the motor current continues to flow in an anti-parallel diode when the conducting switch is turned off as in M_1, D_3 and M_4, D_2.

A regenerating mode may arise during light loading or braking conditions as explained in the bipolar voltage switching.

The load voltage with its average value and the load current are shown in fig.8, where the voltage has a unipolar sinusoidally modulated nature. The AC supply voltage and current are shown in fig. 9, where the supply current has a sinusoidally modulated pulses enveloped within the supply frequency component. The harmonic spectrum of the supply current is shown in fig. 10, where the first dominant harmonics associated with the 50Hz component appears almost at twice the carrier frequency (2kHz).

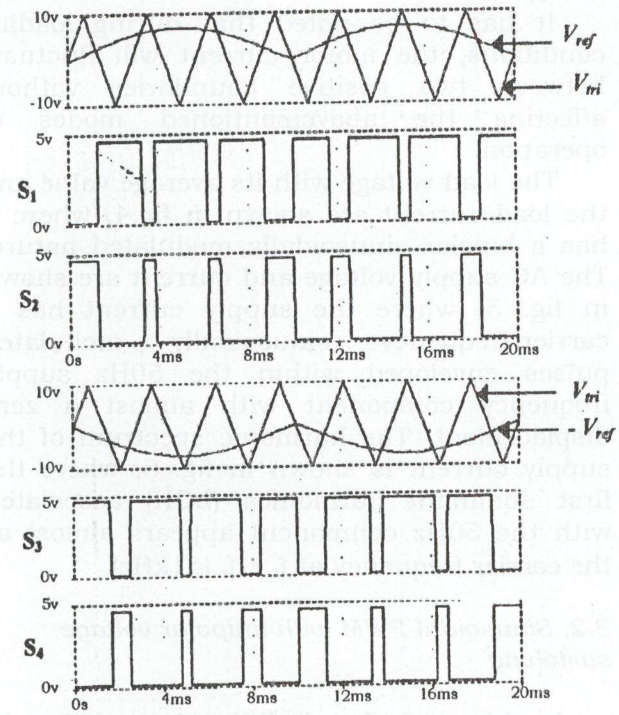

Fig. 2. Generation of the switching patterns.

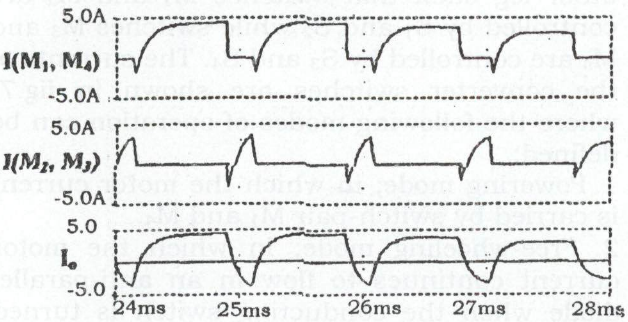

Fig. 3. Converter and load currents (bipolar voltage switching).

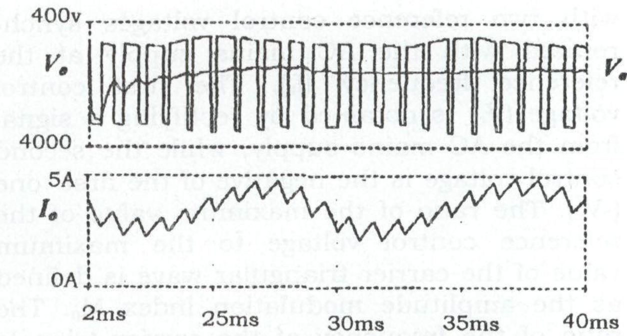

Fig. 4. The motor voltage and current (bipolar).

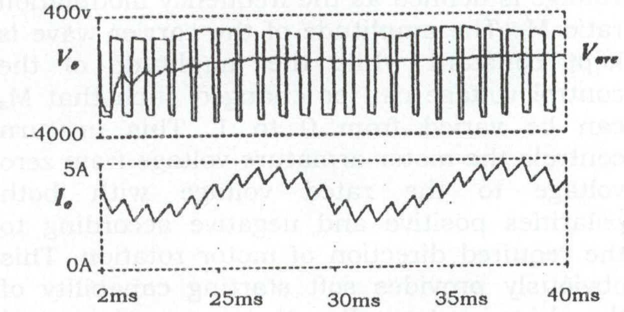

Fig. 5. The as supply voltage and current (bipolar).

Therefore, if the switching frequency of the two PWM techniques is the same, then the unipolar voltage switching results in a better output voltage waveform and in a better frequency response, since the effective switching frequency of the output voltage is doubled and the ripple voltage is reduced. Also, it has a lower rms ripple content in the output voltage than that with bipolar voltage switching.

The motor performance characteristics using unipolar voltage switching for different values of duty ratio and without feed-back control are shown in figs. 11, 12 and 13. The motor current response shown in fig. 11 shows that soft starting is achieved when the motor starts at a small value of duty ratio. The corresponding speed response is shown in fig. 12 and the motor torque-speed curves for different values of duty ratio are shown in fig. 13.

4. Experimental results

A prototype of the proposed system was built for a motor power level of 2kW at 220V and 1500rpm. Fast recovery diodes RUR2060 are used in the uncontrolled rectifier diode bridge since they are switched at the switching frequency or at twice the switching frequency for bipolar and unipolar voltage switching respectively. The same diodes are also used as antiparallel diodes in the dc-dc converter circuit. MOSFET switches IRF730 are used as the main switching devices of the dc-dc converter. Switching patterns are generated using hardware circuits comprising a small transformer for sensing the AC supply voltage to produce the synchronized reference signals, carrier signal generator ICL8038, comparators, drivers and buffers. The output waveforms are obtained and recorded using a digital storage oscilloscope.

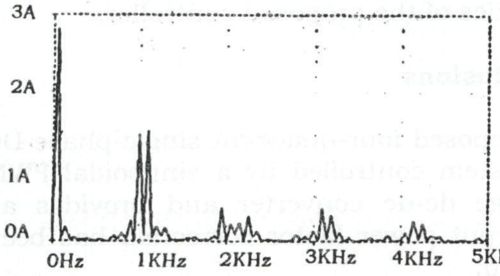

Fig. 6. Harmonic spectrum of the as supply current (bipolar).

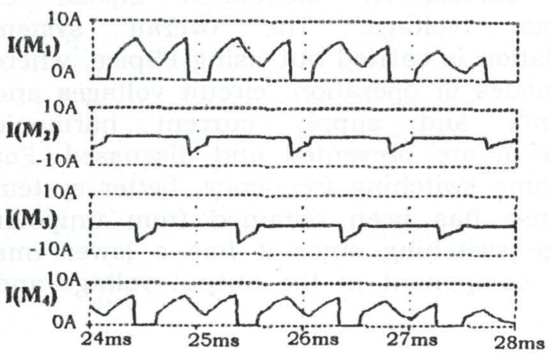

Fig. 7. Converter currents for unipolar voltage switching.

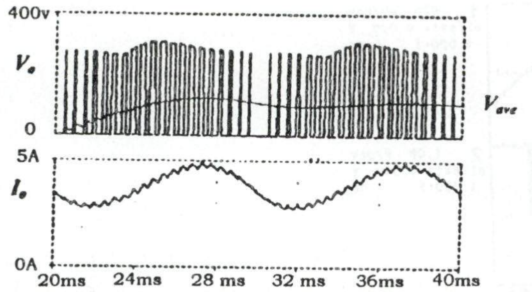

Fig. 8. The motor voltage and current (unipolar).

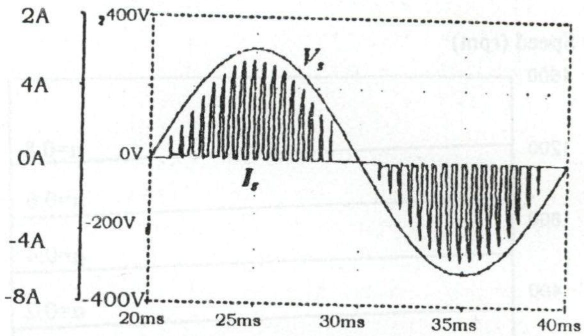

Fig. 9. The AC supply voltage and current (unipolar).

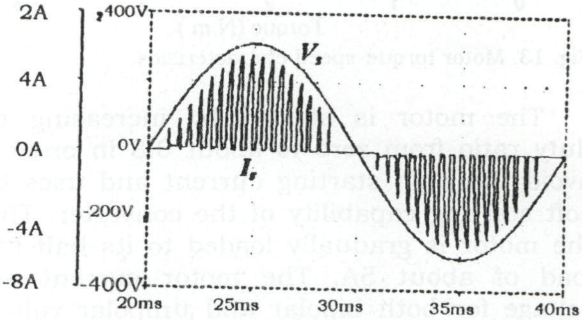

Fig. 10. Harmonic spectrum of the AC supply current (unipolar).

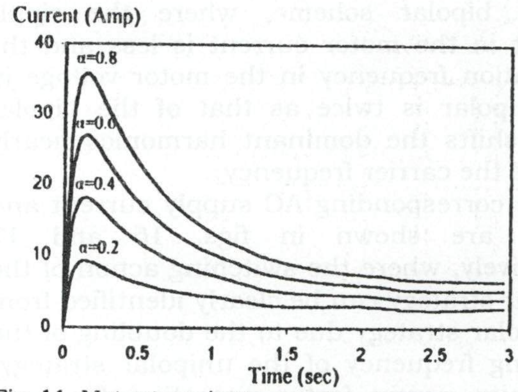

Fig. 11. Motor transient current response.

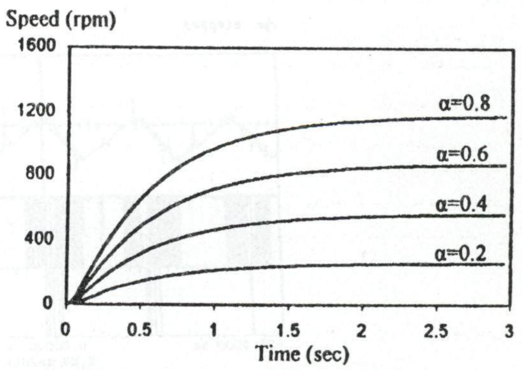

Fig. 12. Motor transient speed response.

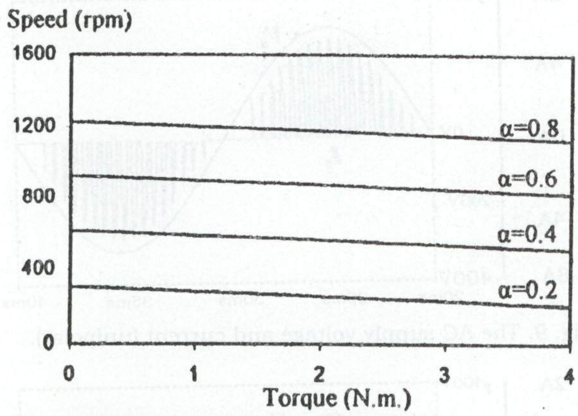

Fig. 13. Motor torque-speed characterisics.

The motor is started by increasing the duty ratio from zero to about 0.8 in order to avoid the high starting current and uses the soft starting capability of the converter. Then the motor is gradually loaded to its half full-load of about 5A. The motor current and voltage for both bipolar and unipolar voltage switching are shown in figs. 14 and 15, respectively. It can be seen that the waveforms of the unipolar scheme are better than those of the bipolar scheme, where the ripple content in the motor current is less and the modulation frequency in the motor voltage in the unipolar is twice as that of the bipolar which shifts the dominant harmonics nearly at twice the carrier frequency.

The corresponding AC supply current and voltage are shown in figs. 16 and 17 respectively, where the switching action of the unipolar strategy can be clearly identified from the bipolar strategy due to the doubling of the switching frequency of the unipolar strategy, and unity power factor operation for both types of switching strategies is clearly seen where an almost zero displacement factor can be observed from the supply voltage and the corresponding supply current. The harmonics associated with the supply current can be easily eliminated by the use of a small capacitor. These harmonics can further be shifted to a higher order by increasing the carrier frequency.

Four-quadrant operation of the proposed system is checked for the speed reversal process shown in fig.18, where the motor is regeneratively braked from 500rpm to zero speed and then reversed its speed to 500rpm in the other direction in about 4 seconds which reflects the speed and the regeneration capabilities of the proposed controller.

5. Conclusions

A proposed four-quadrant single-phase DC drive system controlled by a sinusoidal PWM full-bridge dc-dc converter and provides an active input power factor correction has been presented.

The full-bridge dc-dc converter can be controlled such that the motor voltage may have sinusoidally modulated bipolar or unipolar voltage. The overall system simulation is carried out using PSpice, where the modes of operation, circuit voltages and currents and supply current harmonic spectrum are presented and discussed. For the same switching frequency, better system response has been obtained from unipolar voltage switching since it has a lower rms ripple component in the output voltage and

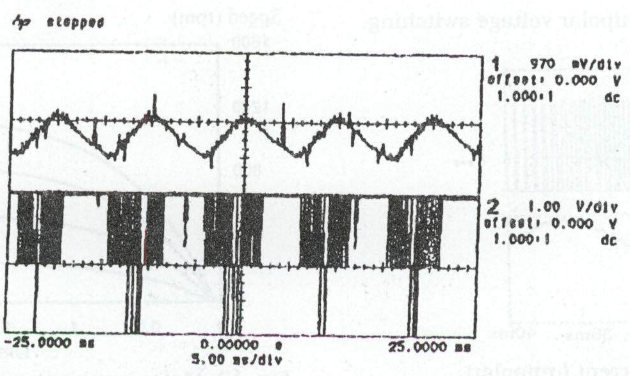

Fig. 14. Experimental motor current and voltage (bipolar).

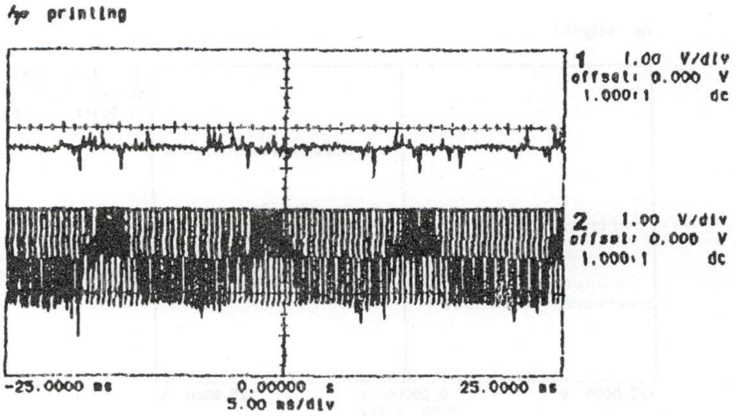

Fig. 15. Experimental motor current and voltage (uniplar).

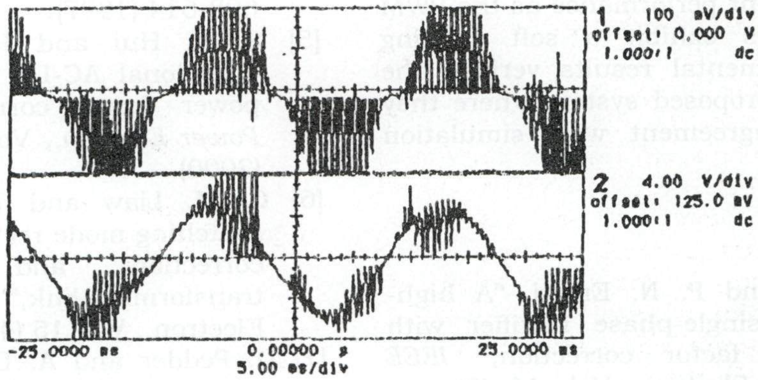

Fig. 16. Experimental AC supply current and voltage (bipolar).

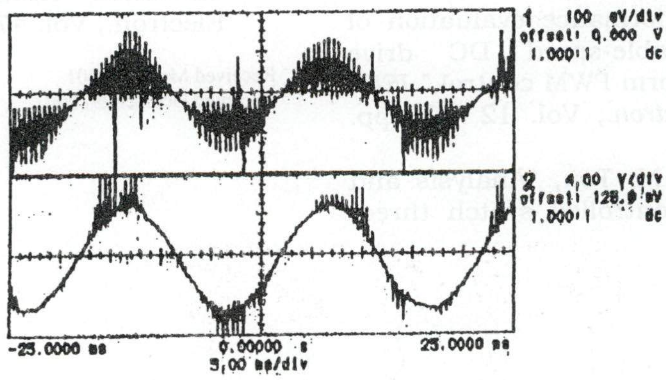

Fig. 17. Experimental AC supply current and voltage (unipolar).

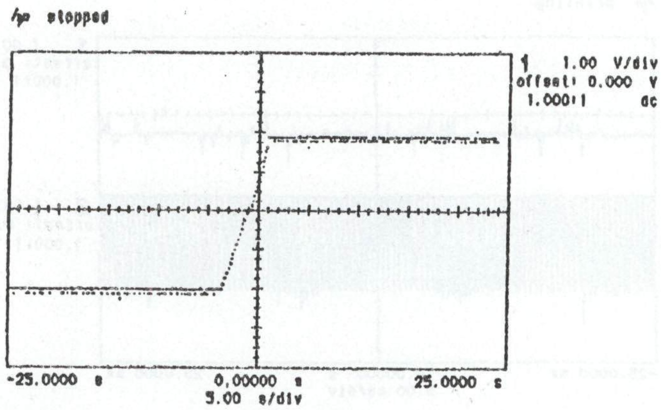

Fig. 18. Speed reversal response of the proposed DC drive system.

the dominant harmonics in the AC supply current are shifted at almost twice the switching frequency. The DC drive system also has a good transient performance as the PWM control techniques exhibit a soft starting capability. Experimental results verified the feasibility of the proposed system where they found in close agreement with simulation results.

References

[1] R. Martinez and P. N. Enjeti, "A high-performance single-phase rectifier with input power factor correction," *IEEE Trans. Power Electron.*, Vol. 11 (2), pp. 311-317 (1996).

[2] M. P. Kazmierkowski and L. Malesani, "Current control techniques for three-phase voltage-source PWM converters: A survey," *IEEE Trans. Ind. Electron.*, Vol. 45 (5), pp. 691-703 (1998).

[3] S. A. Hamed, "Performance evaluation of three-phase variable-speed DC drive systems with uniform PWM control," *IEEE Trans. Power Electron.*, Vol. 12 (2), pp. 228-242 (1997).

[4] K. Al-Haddad and M. Tou, "Analysis and design of single-controlled switch three-phase rectifier with unity power factor and sinusoidal input current," *IEEE Trans. Power Electron.*, Vol. 12 (4), pp. 608-614 (1997).

[5] S. Y. Hui and H. S. Chung, "A bi-directional AC-DC power converter with power factor correction," *IEEE Trans. Power Electron.*, Vol. 15 (5), pp. 942-949 (2000).

[6] C. M. Liaw and T. H. Chen, "A soft-switching mode rectifier with power factor correction and high frequency transformer link," IEEE Trans. Power Electron., Vol. 15 (4), pp. 644-654 (2000).

[7] D. Pedder and A. D. Brown, "A parallel-connected active filter for the reduction of supply current distortion," *IEEE Trans. Ind. Electron.*, Vol. 47 (5), pp. 1108-1117 (2000).

[8] B. Lin and H. Lu, "A novel PWM scheme for single-phase three-level power-factor correction circuit," IEEE Trans. Ind. Electron., Vol. 47 (2), pp. 245-252 (2000).

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