A VARIABLE SPEED SINGLE-PHASE INDUCTION MOTOR DRIVE USING A SMART POWER MODULE

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Abstract: A variable-speed single-phase induction motor drive which utilises just one smart (intelligent) power module (IPM) incorporating six switches has been described. The main and auxiliary windings of a single-phase motor are driven by a two-phase inverter with unbalanced voltage/frequency control to produce smooth torque. The remaining leg of the IPM is used as a current-forced reversible rectifier which supplies the required dc link voltage to drive the two windings up to the full voltage ratings. The drive system has a wide speed range in both directions and operates with near unity power factor regenerative braking. Simulation and experimental results are presented.

I. INTRODUCTION

In applications where a three phase supply is not available, the single-phase induction motor with two unbalanced windings is one of the most widely used. Examples are in appliance and a host of other applications, especially in the household. In most of the applications the motor usually runs at fixed speed. At most two or three speeds are provided by means of winding tap changing brought about by manual intervention. Often, the motor operates at non optimum efficiency and at low power factor especially at speeds and loads for which the motor winding parameters are not selected. A truly variable speed operation from such a motor with a wide speed range and load variations will help the application designers to incorporate many new features in their products. It would also mean operation with high efficiency and motor utilisation.

Traditionally, variable speed operation of a single-phase induction motor has been obtained through voltage control using triacs or back-to-back thyristors, however these suffer from large harmonic injection into the supply and low power factor, in addition to the limited speed range as reported by Colins et al (1) and Muljadi et al (2). Recently, efforts on wide speed range operation using variable frequency converters (or inverters) have also been reported by Holmes and Kotsopoulos (3). However, the control system reprted use a two-phase full-bridge inverters and a diode bridge rectifier as the input stage. This approach is unattractive for an inexpensive single-phase induction motor drive. In addition, the input power factor and regenerative operation of the motor are not included.

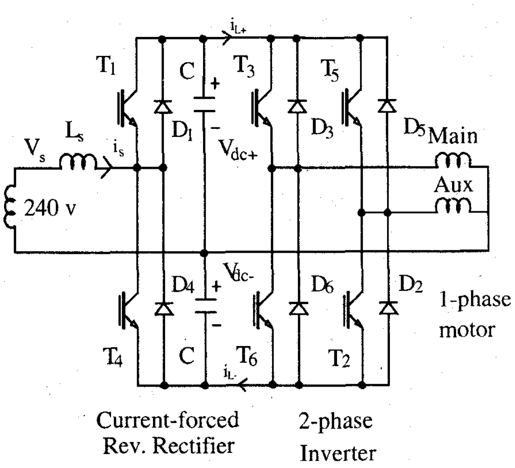

Figure 1. The current-forced rectifier fed single-phase induction motor drive configuration

Recently, Ramsden et al (4), Tenti and Rahman (5) and Covic et al (6) have sugessted a number of topologies with a view to offering low-cost three-phase inverter for three phase motors to be driven from a single-phase supply. However such schemes reduce attainable the output rms voltage at the motor terminals by a factor of $\sqrt{3}$ compared to the bridge type inverters fed from a diode rectifier.

This paper describes a compact variable-speed single-phase induction motor drive which utilises just one smart (intelligent) power module (IPM) incorporating six switches. The input current to the drive is sinusoidal and remains in phase with the supply voltage (when motoring) and out of phase to the supply voltage (when braking) at all time, with a view to meeting the recent harmonic standard (IEC555). Wide speed range in both directions has been obtained by driving the main and auxiliary windings of the motor with centre-tap two- phase inverters.

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Both windings of the motor are driven up to their full rated voltages. All functions of rectification, regeneration and inverter operation of the motor are obtained through the use of the six switching devices in a single smart IGBT module.

II. SYSTEM CONFIGURATION

The topology of the power circuit of the drive is indicated in figure 1. All six IGBTs and their parallel diodes and the switching and protection circuits are included the smart module. Two of the transistors, namely T_1 and T_4 are used for a boost rectifier for input power factor correction, line current wave shaping and inversion as proposed by Boys (7). The other four switches are used for the two-phase inverter drive for the two windings of the single-phase motor.

The IGBTs T_1, T_4, diodes D_1, D_4, the two capacitors C and the input source circuit inductance L_s (figure 1) comprise the reversible rectifier. The rectifier controller is shown in figure 2 in which the boost rectifier switches T_1 and T_4 are switched with pwm pulses. Before the pwm pulses are enabled, the rectifier capacitors C, in the absence of a load, will each charge up to the peak of the supply voltage V_s. For the input voltage of 240V rms, the rectifier output voltage without any load is then at 680 volts, each output capacitor sharing this voltage. By turning on the transistors T_1 and T_4 in a complementary manner, the inductor L_s is charged up in both half cycles. When a transistor is switched off, the inductor current forces the capacitor on the other side to be charged up. The rectifier output voltage is compared with a reference and the amplified error is multiplied by a synchronised source voltage waveform to form the source current reference for an inner current loop. The inner current loop forces the input current to the rectifier to its magnitude such as to restore the dc link voltage to the desired value which is set to a value above 680VDC. It also forces the input current to follow the reference waveform which is sinusoidal and in-phase with the source voltage.

It is possible for the two series connected capacitors to share the dc link voltage unequally. The difference between the capacitor voltages are used to augment the source current feedback in order to equalise the capacitor voltages as described by Boys (7). The control system for the current forced rectifier is indicated in figure 2.

III. MODELLING OF THE BOOST RECTIFIER

The boost rectifier with its controller has been modelled with a nonlinear simulation package called Simnon. The dynamic equations of the rectifier are as follow:

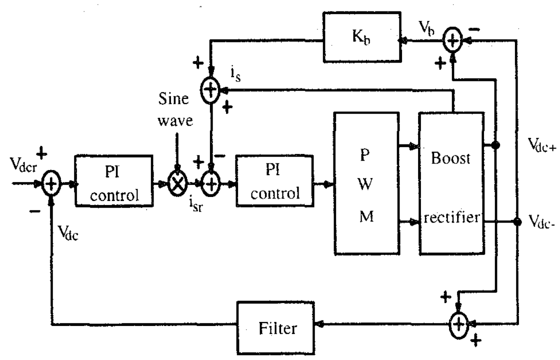

Figure 2. Control block diagram for the rectifier.

$$L_s \frac{di_s}{dt} = V_s - F_1 * E_{DC+} \text{ for } T_1 \text{ or } D_1 \text{ ON} \quad (1)$$

$$L_s \frac{di_s}{dt} = V_s - F_2 * E_{DC-} \text{ for } T_4 \text{ or } D_4 \text{ ON} \quad (2)$$

$$C \frac{dE_{DC+}}{dt} = F_1 * i_s - i_{L+} \quad (3)$$

$$C \frac{dE_{DC-}}{dt} = F_2 * i_s - i_{L-} \quad (4)$$

where $F_1 = 1$ for T_1 or D_1 ON and $F_2 = 1$ for T_4 or D_4 ON; else these are zero. For the two-phase inverter, the dc link currents are:

$$i_{L+} = i_{L+main} + i_{L+aux} \quad (5)$$

$$i_{L-} = i_{L-main} + i_{L-aux} \quad (6)$$

where

i_{L+} and i_{L-} are the positive and negative dc rail currents

i_{L+main} is the main winding current when T_3 or D_3 ON

i_{L+aux} is the auxiliary winding current when T_5 or D_5 ON

i_{L-main} is the main winding current when T_6 or D_6 are ON

i_{L-aux} is the auxiliary winding current when T_2 or D_2 ON

The dynamic equations of resistive and resistive-inductive loads fed from a voltage source across the capacitors have been written. The dynamic modelling of the rectifier/inverter fed single-phase motor in the stator reference frame has been carried out for a motor for which the main and auxiliary windings are identical and distributed.

IV. DYNAMIC MODELLING OF THE RECTIFIER/INVERTER DRIVE

Two different types of control strategies for the single-phase induction motor has been modelled. One is the pwm variable-voltage, variable-frequency (V-*f*) with a low frequency boost strategy as indicated in figure 3. Figures 4(a), (b) and (c) show the simulated speed response of the motor, the rectifier output voltage swing and the input voltage and input current waveforms of the rectifier, respectively, as the motor is started from rest to the full speed of 1500 rev/min. The rectifier reference voltage was set at 680V. The input voltage and current waveforms are in phase at all times except at the end of the acceleration when a speed overshoot occurs. The rectifier output voltage goes above 680V, and the input current then becomes 180° out of phase with the input supply voltage, implying reverse energy flow.

A rotor flux oriented vector control strategy was also investigated the control strategy for which is indicated in the figure 5. The motor is accelerated from rest to 750 rev/min and decelerated therefrom to zero speed as indicated in figure 6(a). The rectifier output voltage swing, which is quite tightly regulated, is shown in figure 6(b). The supply voltage and the current waveforms during the deceleration of the motor only is shown in figure 6(c). Clearly, the input current is sinusoidal and in anti-phase with the input supply voltage the motor is in deceleration.

V. EXPERIMENTAL RESULTS

An intelligent power module from Mitsubishi (IPM50RHA120) was used for the implementation of the drive control schemes mentioned above. The controllers for the rectifier and the two-phase inverters were both implemented on a digital signal processor (TMS320C31). The motor used for the testing was a capacitor

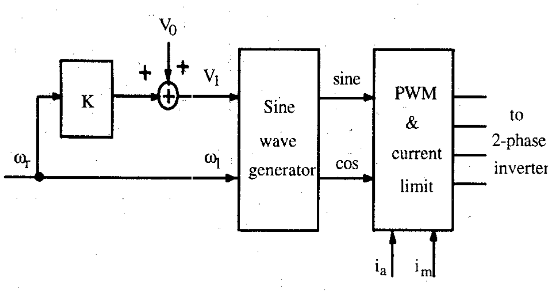

Figure 3. The V-*f* inverter controller with low frequency boost.

run type motor with the capacitor removed. The main and the auxiliary windings were nonidentical, so that the V-*f* controller of figure 3 was used for the results included in this paper. The motor data are included in the Appendix I. The V-*f* ratio for the two windings were selected according to

$$V_{aux} = a * V_{main} \tag{7}$$

where a is the turns ratio between the main and the auxiliary windings. This maintains the ampere-turns of the two windings roughly the same at all frequencies [5]. Voltages V_1 and V_2 for the two windings are of course at quadrature (sine and cosine

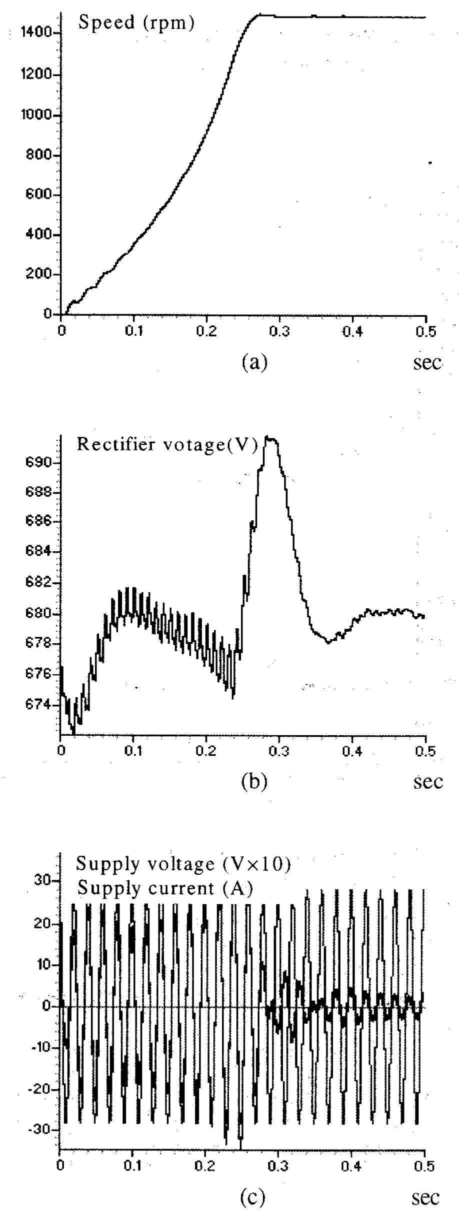

Figure 4. Dynamic response of (a) motor speed, (b) rectifier voltage and (c) supply voltage and current.

waveforms) at all times as indicated in figure 3.

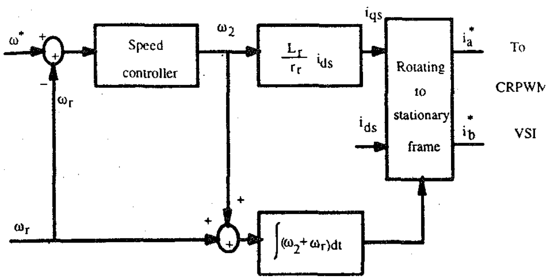

Figure 5. Rotor flux oriented vector controller for the 2-phase motor.

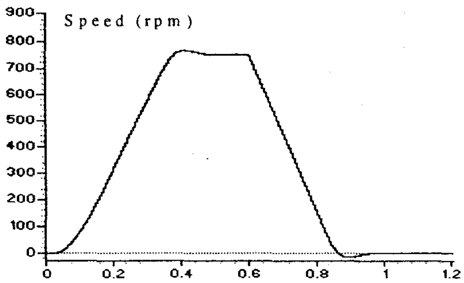

Figure 6(a)

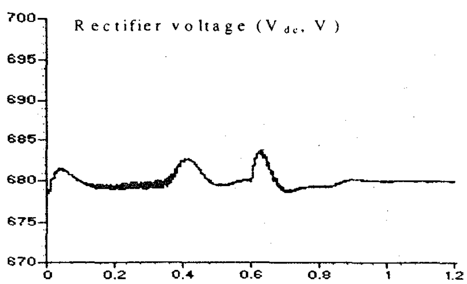

Figure 6(b)

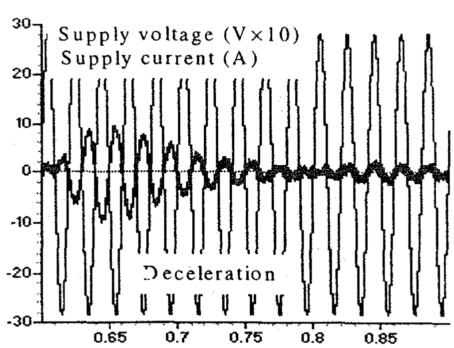

Figure 6(c)

Figure 6. Dynamic responses of the drive under the vector controller.

During steady-state running with a steady load, the motor supply voltage and current waveforms are in phase as shown in figure 7. The rectifier output voltage has 100 Hz ripple on it as expected. During braking, the supply current becomes out of phase with the supply voltage as indicated in figure 8. Figure 9 shows the input voltage and current waveforms when the motor goes through a complete acceleration and deceleration cycle. Figure 10 shows the motor speed, the rectifier voltage and the input waveforms in greater detail during a deceleration from 1500 rev/min to zero speed. Figure 11 shows the speed response of the motor when its speed reference is changed from +1500 to -1500 rev/min.

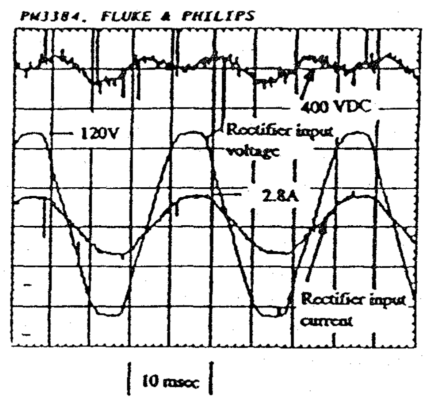

Figure 7. Boost rectifier output voltage ripple, input supply current and voltage waveforms during steady motoring.

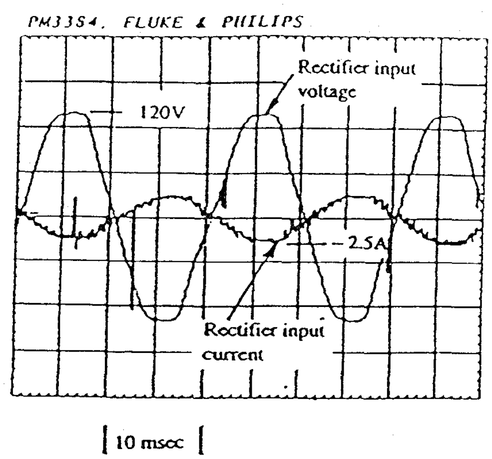

Figure 8. Boost rectifier supply voltage and current during braking.

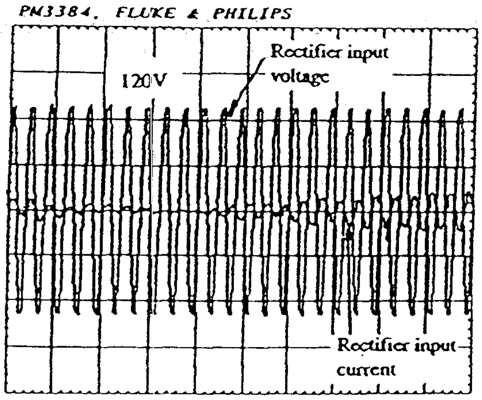

Figure 9. Boost rectifier supply voltage and current during acceleration and deceleration.

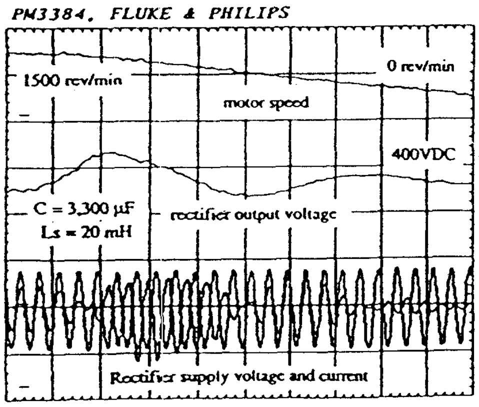

Figure 10. **Motor speed, rectifier output voltage, and supply voltage and current during deceleration from 1500 rev/min to zero.**

VI. CONCLUSION

The paper presents a compact, single-phase continuously variable-speed induction motor drive with sinusoidal input. The drive power control, consisting of a reversible input rectifier, requires just six switches and is implemented on a smart IGBT module, and a digital signal processor. Such a six-switch intelligent power module adequately covers both the rectifier and the inverter functions of the drive as demonstrated in this paper. The dynamic model of the rectifier/inverter/drive, as reported in this paper, should enable optimisation of the parameters of the complete drive for a particular application.

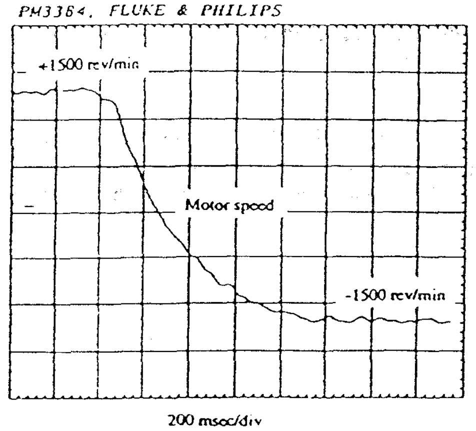

Figure 11. Motor speed response for a speed reference step change from +1500 to -1500 rev/min.

VII. APPENDIX I - MOTOR DATA

Betts 9252UTB-11 motor, Capacitor Run.
1.5kW, 240V, 50 Hz, 8.3A, 2 pole.
Main/Aux Turns Ratio: 1.56.

VIII. REFERENCES

1. E. R. Collins Jr, H. B. Puttgen, W. E. Sayle II, "Single Phase Induction Motor Drive: Direct Phase Control of the Auxiliary Winding Supply", Proc. the IEEE IAS-88 Annual Meeting, Pittsburgh, 1988, pp 246-252.

2. E. Muljadi, Y. Zhao, T. H. Liu and T. Lipo, "Adjustable AC Capacitor for a Single Phase Induction Motor", Proc. of the IEEE IAS-91 Annual Meeting, Detroit, 1991, pp 185-190.

3. D. G. Holmes and A. Kotsopoulos, "Variable-Speed Control of Single and Two Phase Induction Motors Using a Three Phase Voltage Source Inverter", Proc. of the IEEE-IAS Annual Meeting, 1993, pp 613-620.

4. Ramsden V. S., Hunter G. P. and Zhang J, "Impact ofn power system of single-phase input cycloconverter motor drives", Proc. of IEE, Electr. Power Appl., Vol. 142, No. 3, May 1995, pp. 176-182.

5. Tenti, P. and Rahman, A., "A New Single to Three Phase Converter with Active Current Shaping for Low Cost AC Motor Drives", IEEE Transactions

on Industry Applications, Vol. IA-29, No. 4, 1993, pp. 806-813.

6. Covic G. A., Peters G. L. and Boys J. T., "An Improved SinglePhase to Three Phase Converter for Low Cost AC Motor Drives", Proc. of Intl. Conference and Variable-Speed Drives, PEVD'95. Singapore, February 1995, pp. 549-554.

7. Boys J. T., "Current-Forced Single-Phase Reversible Rectifier", Proc. of the IEE, Pt. B, Vol 136, No. 5, 1989, pp. 205-211.