Design Considerations for Single Phase Induction Motor Packaged Drives

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Abstract— **This paper compares some possible topologies for single phase permanent split capacitor induction motor adjustable speed drive from the aspects of number of inverter legs, minimum DC bus voltage requirement and DC bus current rms value, etc. The topology with voltage doubler and three-leg inverter is selected for hardware implementation of a packaged drive. Other design considerations and experimental results are presented.**

I. INTRODUCTION

Single phase permanent split capacitor induction motor (SPIM) is widely used in HVAC&R applications. The adjustable speed drive (ASD) is attractive because it can significantly save energy at lower speed. Many topologies have been proposed for SPIM ASD[1-12]. Generally, the drive system is composed of front-end converter, dc link and inverter. The front-end converter can be a rectifier, voltage doubler or rectifier plus boost converter. It can be either controlled by using power switches, or uncontrolled by using power diodes. The power factor correction (PFC) can be considered or not included. The inverter can have three, two or one legs. Often, the middle point of the DC bus is used.

The motor we have used here has the parameters as follows: power - 3/4HP, number of poles - 6, rated voltage (rms) - V_R = 230V, rated frequency-60Hz, capacitor for the auxiliary winding - 10uF, rated speed - 1100 rpm, rated current (rms) - 3.5A, turns ratio - α=1.36 (auxiliary/main). The key parameters of the motor for the purpose of inverter design are the voltage ratio for auxiliary and main windings and the phase shift. The overall goal is to have a circularly rotating flux vector and therefore the current ratio must be:

$$\frac{I_{aux}}{I_{main}} = \frac{1}{\alpha} \tag{1}$$

and I_{aux} must lead I_{main} by 90°. Assuming that the impedance angles for both windings are the same at rated frequency, then the relationship between the supplied voltages for both windings are:

$$\frac{V_{aux}}{V_{main}} = \alpha \tag{2}$$

and V_{aux} must lead V_{main} by 90°.

II. MODULATION TECHNIQUE AND DC BUS VOLTAGE

Modulation technique must first be determined in order to determine the minimum DC bus voltage requirement. The motor has three terminals: A (for auxiliary winding), M (for main winding) and C (for common). The voltage vector diagram is shown in Fig. 1, where the vector length is the amplitude of the fundamental voltage waveform. If the middle point of the DC bus is taken as the reference point, A, M and C can be anywhere inside the circle with O (reference point) as the center and Vdc/2 as the radius, as shown in Fig. 1(a), but subject to the following constraints:

$$\overrightarrow{AC} \perp \overrightarrow{MC} \tag{3}$$

and

$$|AC| = \alpha |MC|, \tag{4}$$

where $\alpha > 1$.

$$\overrightarrow{AC} = \overrightarrow{OA} - \overrightarrow{OC} \tag{5}$$

$$\overrightarrow{MC} = \overrightarrow{OM} - \overrightarrow{OC} \tag{6}$$

It can be easily proved that

$$\max(|AM|) = V_{dc}, \tag{7}$$

when AM is the diameter of the circle. Therefore the optimized voltage vector diagram is shown in Fig. 1(b). The minimum DC bus voltage is then

$$V_{dc} = V_R \sqrt{2(1+\alpha^2)} = 2.40 V_R = 552\text{V}. \tag{8}$$

An approach is proposed in [12] for this case by using three-leg inverter.

When two-leg inverter is used and C is connected to the middle point of DC bus [5][11], the voltage vector diagram turns into Fig. 1(c) and the minimum DC bus voltage requirement is:

$$V_{dc} = 2\sqrt{2}\alpha V_R = 3.87 V_R = 891V \tag{9}$$

Similarly, when one-leg inverter is used to supply voltage for auxiliary winding while the main winding is supplied directly by AC supply and C is connected to the middle point of DC bus [13], the voltage vector diagram becomes Fig. 1(d). The minimum DC bus voltage requirement is given in (10).

$$V_{dc} = 2\sqrt{2}\alpha V_R = 3.87V_R = 891V \quad (10)$$

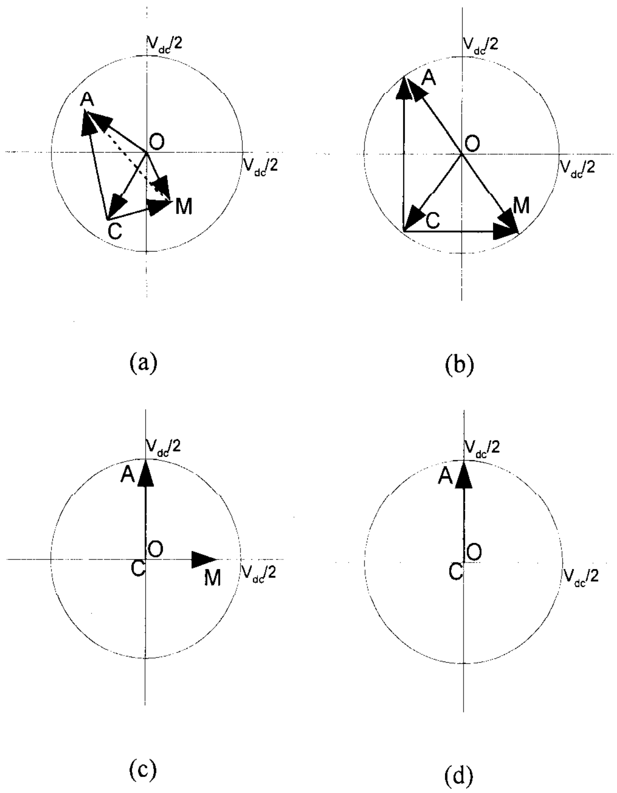

Fig. 1 Voltage vector diagrams for (a) three-leg inverter, (b) optimized version, (c) two-leg inverter and (d) one-leg inverter.

III. DC Link Current Consideration

Assuming that the motor winding currents are sinusoidal current sources, three-leg inverter DC link current can be expressed as:

$$I_{DC} = (S_{ap} + D_{ap})I_a + (S_{mp} + D_{mp})I_{mp} + (S_{cp} + D_{cp})I_{cp} \quad (11)$$

where S and D are the switching functions of the switches and diodes. The subscripts a, m and c stand for auxiliary, main and common and p stands for upper switches. Simulation is done based on the motor impedance parameters listed in Table I. The simulation result is shown in Fig. 2 and the dc link current rms value is computed to be 1.73A.

TABLE I

SPIM Impedance Parameters

R_{1M}	8.69Ω	R_{1A}	21.8Ω
R_{2m}	9.91Ω	R_{2a}	20.8Ω
L_{1m}	32.8mH	L_{1a}	60.7mH
L_{2m}	32.8mH	L_{2a}	60.7mH
L_{Mm}	366mH	L_{Ma}	677mH

Similarly, two-leg inverter DC current can be written as:

$$I_{DC} = (S_{ap} + D_{ap})I_a + (S_{mp} + D_{mp})I_{mp} \quad (12)$$

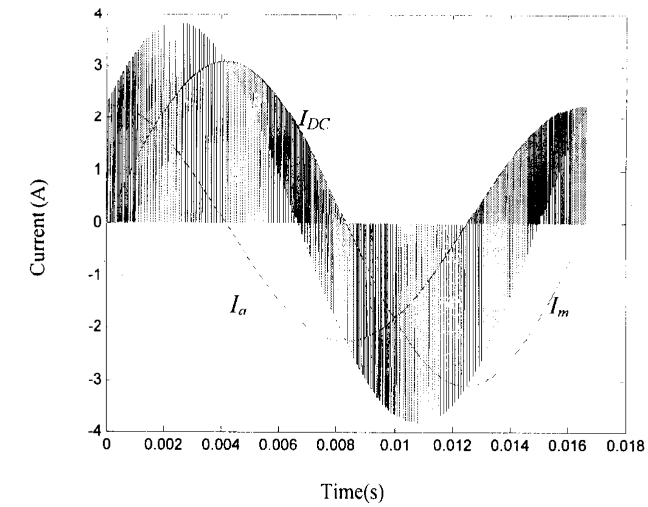

Fig. 2 Simulated current waveform for three-leg inverter.

And one-leg inverter dc link current can be expressed by:

$$I_{DC} = (S_{ap} + D_{ap})I_a \quad (13)$$

Fig. 3 and Fig. 4 shows the simulation results of DC bus currents for two-leg and one-leg inverters. The rms values of DC link currents for two-leg and one-leg inverters are 1.96A and 1.13A correspondently.

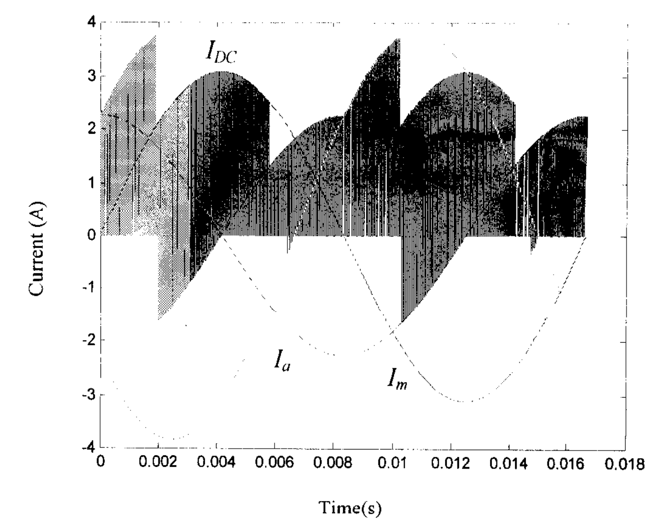

Fig. 3 Simulated current waveform for two-leg inverter.

IV. Comparison of Possible Topologies

There are many possible topologies for the drives. The most common one is the one composed of boost converter with PFC and a three-leg inverter, as shown in Fig. 5. It has unity power factor, boosted DC bus voltage and small DC voltage ripple. However, the inductor has relatively large size because of DC current component [4].

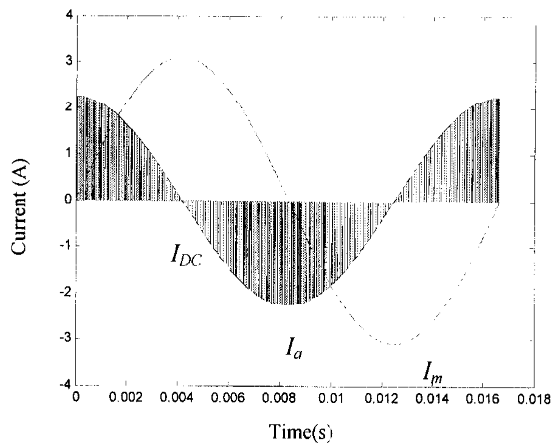

Fig. 4 Simulated current waveform for one-leg inverter.

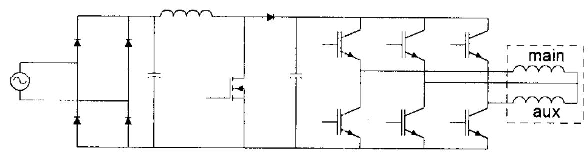

Fig. 5 Conventional ac drive with rectifier, boost converter and three-leg inverter.

An alternative way to improve it is to put the inductor at AC side (before rectifier). As shown in Fig. 6, it can have smaller inductor than the above one.

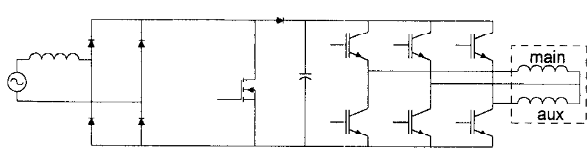

Fig. 6 Improved ac drive with rectifier, boost converter and three-leg inverter but the inductor for boost converter is at ac side.

Besides boost converter, another approach to boost DC bus voltage is to use voltage doubler. If there is no requirement for PFC, two diodes can be used [3][8], as shown in Fig. 7. As for PFC, two power switches should be used, as shown in Fig. 8. The voltage doubler and three-leg inverter can provide sufficient voltage for both windings.

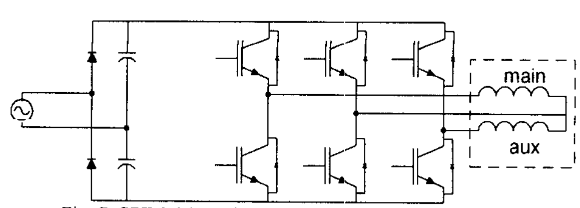

Fig. 7 SPIM drive with voltage doubler and three-leg inverter.

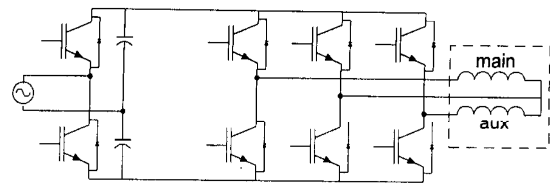

Fig. 8 SPIM drive with controlled voltage doubler and three-leg

As shown in Fig. 9, if voltage doubler and two-leg inverter is used and common terminal of the motor is connected to the middle point of the DC bus, the voltage is not sufficiently high for the auxiliary winding.

Fig. 10 shows the drive topology with controlled voltage doubler and two-leg inverter. The PFC is added but the DC bus voltage is still insufficient.

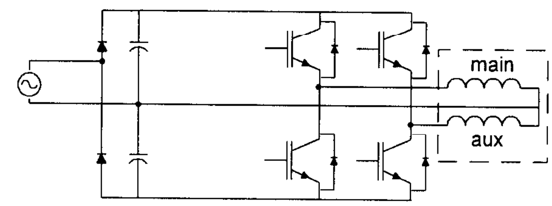

Fig. 9 SPIM drive with voltage doubler and two-leg inverter.

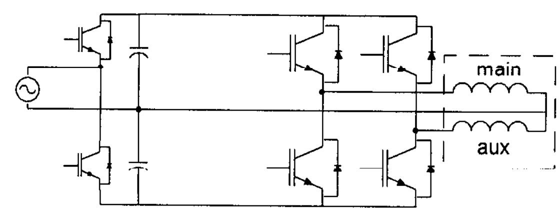

Fig. 10 SPIM drive with voltage doubler and two-leg inverter.

The way to boost the voltage is to add one inductor between the ac supply and controlled voltage doulber, which is shown in Fig. 11. The inductor, two switches and two freewheeling diodes can work in the similar modes as boost converter does.

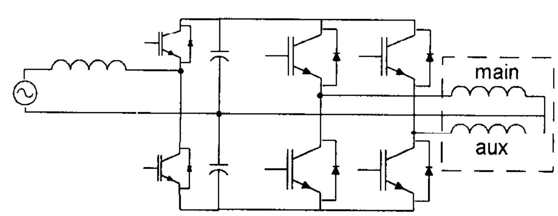

Fig. 11 SPIM drive with voltage doubler, two-leg inverter and boosted DC bus voltage.

One-leg inverter is also feasible with main winding supplied from AC power directly and the auxiliary winding supplied from one inverter leg. It can also operate at another speed if one AC capacitor is used. This drive circuitry, as shown in Fig. 12, has just two switches and can have two speeds operation [13]. Fig. 13 shows the same topology with controlled voltage doubler to provide PFC. The disadvantages for those topologies are that DC bus voltage is not sufficiently high and they require ac capacitors. Fig. 14 shows the version that can boost the DC bus voltage with inductor and two switches for voltage doubler.

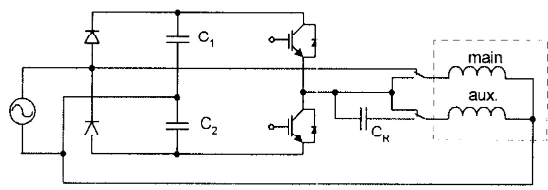

Fig. 12 SPIM drive for two-speed operation with only two power switches.

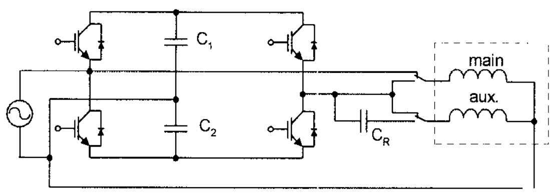

Fig. 13 SPIM drive for two-speed operation with PFC.

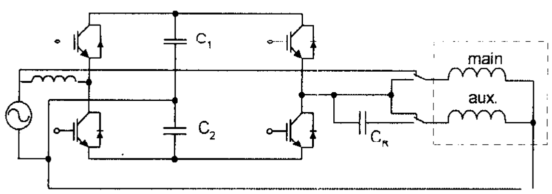

Fig. 14 SPIM drive for two-speed operation with PFC and boosted DC bus voltage.

If the auxiliary winding and main winding can be separated, the topology shown as in Fig. 15 can also be used. And the version with controlled voltage doubler is shown in Fig. 16. The DC bus voltage is sufficiently high for the drives.

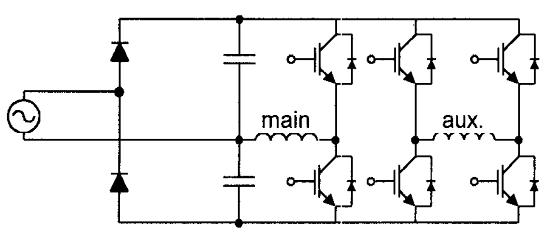

Fig. 15 SPIM drive with separated windings.

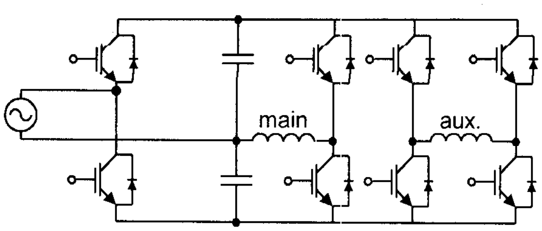

Fig. 16 SPIM drive with separated windings (PFC added).

Some other topologies are also possible as shown in Fig. 17-19, but they require very high voltage, which can be expressed as (14).

$$V_{dc} = 2V_R\sqrt{2(1+\alpha^2)} = 1104\text{V} \quad (14)$$

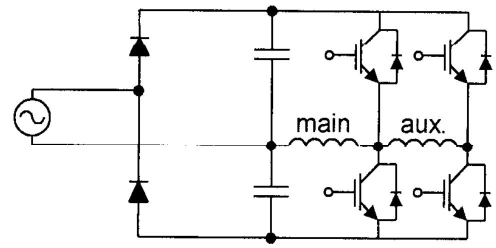

Fig. 17 SPIM drive with different connection of two windings.

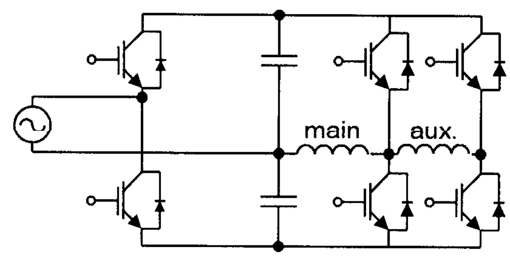

Fig. 18 PFC version of Fig. 17.

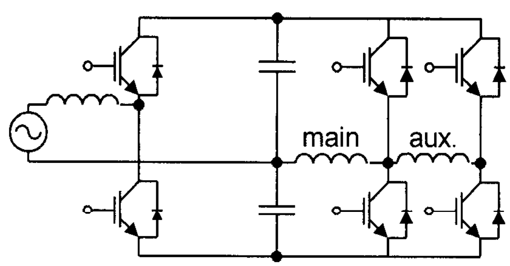

Fig. 19 PFC version of Fig. 17 with boosted DC bus voltage.

Table II summarizes the comparison of these topologies in the aspects of minimum DC bus voltage requirement, dc link current rms value and other comments.

V. Hardware Implementation and Results

The topology as shown in Fig. 7 with voltage doubler and three-leg inverter has been selected for hardware implementation. The drive system integrated with motor is shown in Fig. 20. The drive uses microcontroller as the controller. With the external control switches, it can have four-speed operation: 0, 30Hz, 45Hz, and 60Hz. For ASD, voltage/Hz is maintained constant. The experimental results for rated condition operation are shown in Fig. 21 and Fig. 22 for running with ac capacitor and driven by packaged drive correspondently.

TABLE II

COMPARISON OF POSSIBLE TOPOLOGIES FOR PACKAGED DRIVES

Topologies	Required DC bus voltage (V) *	DC link current rms (A)**	Pros	Cons
Three-leg inverter				
Fig. 5	$V_R\sqrt{2(1+\alpha^2)}$ =552V	1.73	Unity PF Low DC voltage ripple Boosted DC bus voltage	Big inductor
Fig. 6	$V_R\sqrt{2(1+\alpha^2)}$ =552V	1.73	Unity PF Low DC voltage ripple Boosted DC bus voltage	Smaller inductor
Fig. 7	$V_R\sqrt{2(1+\alpha^2)}$ =552V	1.73	Sufficient DC Bus voltage	Poor PF Higher voltage ripple
Fig. 8	$V_R\sqrt{2(1+\alpha^2)}$ =552V	1.73	Unity PF Sufficient DC bus voltage	Eight switching devices
Two-leg inverter				
Fig. 9	$2\sqrt{2}\alpha V_R$ =891V	1.96	Simple Only four switching devices	Poor PF Insufficient DC bus voltage
Fig. 10	$2\sqrt{2}\alpha V_R$ =891V	1.96	Unity PF	Insufficient DC bus voltage
Fig. 11	$2\sqrt{2}\alpha V_R$ =891V	1.96	Unity PF Boosted DC bus voltage	Six switching devices and inductor
One-leg inverter				
Fig. 12	$2\sqrt{2}\alpha V_R$ =891V	1.13	Simplest Only two switches Two operation modes	Poor PF Insufficient DC bus voltage AC capacitor value is tuned for only one particular frequency
Fig. 13	$2\sqrt{2}\alpha V_R$ =891V	1.13	Unity PF	Insufficient DC bus voltage AC capacitor value is tuned for only one particular frequency
Fig. 14	$2\sqrt{2}\alpha V_R$ =891V	1.13	Unity PF Boosted DC bus voltage	AC capacitor value is tuned for only one particular frequency
Miscellaneous				
Fig. 15	$2\sqrt{2}V_R$ =651V	—	Sufficient DC bus voltage	Poor PF Need modification of winding connection inside the motor
Fig. 16	$2\sqrt{2}V_R$ =651V	—	Unity PF Sufficient DC bus voltage	Need modification of winding connection inside the motor
Fig. 17	$2V_R\sqrt{2(1+\alpha^2)}$ =1104V	—	Simple Only four switching devices	Insufficient DC bus voltage Poor PF
Fig. 18	$2V_R\sqrt{2(1+\alpha^2)}$ =1104V	—	Unity PF	Insufficient DC bus voltage
Fig. 19	$2V_R\sqrt{2(1+\alpha^2)}$ =1104V	—	Unity PF Boosted DC bus voltage	The DC voltage bus voltage is too high

* for rated operation and modulation index of 1.

** for rated operation and at 10KHz switching frequency.

VI. CONCLUSION

The possible topologies for SPIM drives have been discussed according to minimum DC bus voltage requirements, dc link currents, the necessities for DC bus voltage boost and the ways to boost the DC bus voltages.

The approaches to get optimum output voltages and the simplified way to analyze the dc link current is discussed.

The design considerations determined the selection of the topology with voltage doubler and three-leg inverter. The completed packaged drive with motor and drive integration is presented.

The packaged drive achieve the goals of low cost, small size, "packaged" and ASD which is changeable by programming the microcontroller.

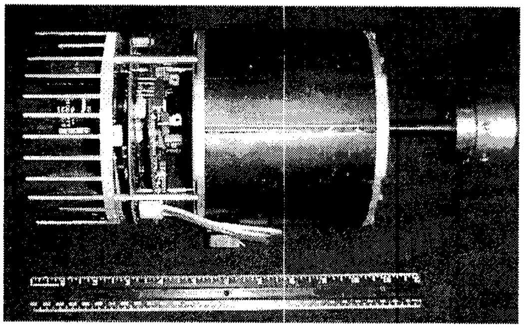

Fig. 20 Packaged drive.

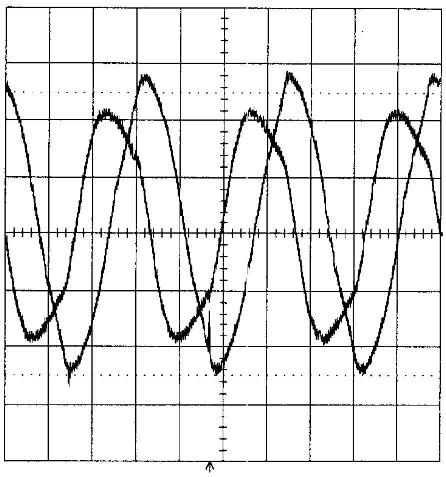

Fig. 21 Experimental results of currents for both windings with the motor running with capacitor. (1A/div, 5ms/div).

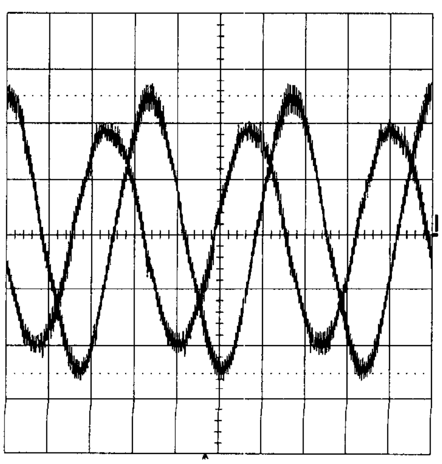

Fig. 22 Experimental results of currents for both windings with the motor running with packaged drive. (1A/div, 5ms/div).

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