

A Novel Variable Frequency Three-Phase Induction Motor Drive System Using Only Three Controlled Switches

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Abstract—This paper presents a novel variable frequency motor drive system for a three-phase induction machine. In this drive system, the machine is excited by unidirectional stator currents shaped and sequenced such that a rotating air gap flux is induced so that the machine can operate. Due to the unidirectional nature of the currents, an “inverter” that incorporates only three active, IGBT type switches, and three freewheeling diodes can synthesize them. The drive system requires an asymmetric induction machine that can easily be obtained by externally rewiring a motor with a dual wound stator. The inverter is supplied by a single-phase input via a voltage doubler diode rectifier; hence it can be operated with residential service. In this paper, theoretical control methods are presented and both simulation and experimental results are provided proving the validity of the proposed drive system.

I. INTRODUCTION

Variable speed drives have found widespread use in industrial applications. However, in the household and consumer market their adoption has been sparse. A significant reason that electronic drives have not penetrated the consumer market is their high cost. In a retail marketplace, consumers tend to put little emphasis on “total cost of ownership,” including energy costs, and tend to put more emphasis on the initial purchase price and inherent features of the product. In the heating, ventilating, and air-conditioning (HVAC) market, controlling the airflow with an adjustable speed drive would allow overall system optimization that could reduce energy consumption by 30% [1]. Without an adjustable speed drive, the remainder of the system needs to be oversized, and standby and startup/shutdown losses are significant. In addition to increased efficiency, an adjustable speed drive used in this application has the potential to hold a tighter temperature band since airflow will always be circulating. It can also be quieter since the system will not be plagued with the starting and stopping noise of both the motor and compressor, as they will operate continuously in a reduced capacity.

This paper proposes a new adjustable speed motor drive system containing a three-phase induction machine and an electronic drive. This paper also proposes a novel current control method for an induction machine that allows for the motor to be speed and/or torque controlled by only three active IGBT type switches. A similar system and control method was proposed in [2], but the system is not physically realizable. This proposed topology with the control method is significant because it has a lower parts count than traditional motor drives. The voltage source inverter with six

switches is standard practice and the use of four switches has also been demonstrated [3]. In addition to the novel topology, the system is focused around a common three-phase induction machine with trivial wiring modifications. As a result, the proposed system achieves full speed control, and maintains good efficiency, at a low comparative cost. The combination of increased performance and lower initial cost will allow for further penetration of adjustable speed drives into the consumer marketplace.

II. CURRENT CONTROL METHOD

A novel closed loop current control method is proposed for a three-phase induction machine. The currents are unidirectional in nature, as shown in Fig. 1. The harmonic spectrum of the phase currents (to the 15th) is given in Fig. 2. Since these phase currents are not sinusoidal, access to the stator neutral point of the machine is required in order to have full control over each of the individual phase currents.

The phase currents are composed of a fundamental component, a DC offset, and triplen harmonics. Only two phases are conducting at once and each phase conducts for 240° of an electrical cycle. Table 1 defines the sections that compose the phase currents. The DC offset and triplen harmonics are scaled such that the maximum value of the fundamental component can be obtained for a given amplitude of a unidirectional or unipolarity current source excitation.

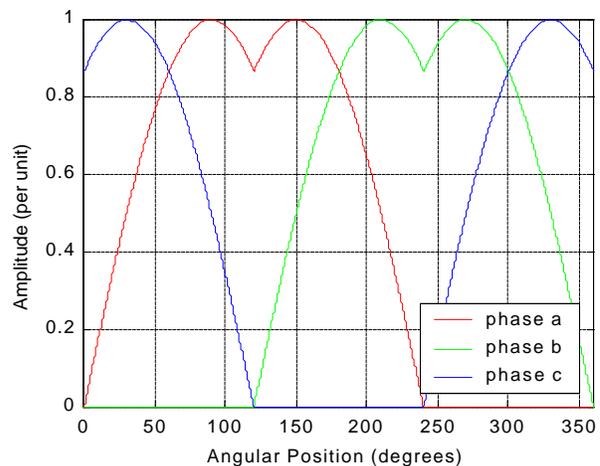


Fig. 1: Proposed Motor Phase Currents.

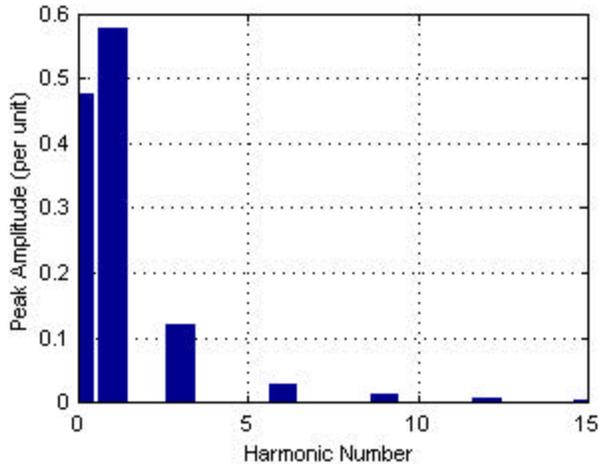


Fig. 2: Phase Current Harmonic Spectrum.

For an induction machine with a sufficient number of stator slots, lumped sinusoidally distributed stator inductances can be assumed and space harmonics can be neglected. For this case, the stator current vector which governs the air-gap mmf [4], is given as

$$\tilde{I} = \frac{2}{3} [i_{as} + i_{bs}\cos(120^\circ) + i_{cs}\cos(-120^\circ)]. \quad (1)$$

Upon substitution and simplification of currents given by Table 1 into (1), the stator current vector as seen by the a - s axis is

$$\tilde{I} = \frac{\sqrt{3}}{3} I_{\max}\sin(\omega t - 30^\circ). \quad (2)$$

Table 1: Phase current definitions over an electrical cycle.

Current	$0 < \omega t \leq 120^\circ$	$120 < \omega t \leq 240^\circ$	$240 < \omega t \leq 360^\circ$
Phase a (i_{as})	$I_{\max}\sin(\omega t)$	$I_{\max}\sin(\omega t - \pi/3)$	0
Phase b (i_{bs})	0	$I_{\max}\sin(\omega t - 2\pi/3)$	$-I_{\max}\sin(\omega t)$
Phase c (i_{cs})	$I_{\max}\sin(\omega t + \pi/3)$	0	$I_{\max}\sin(\omega t - 4\pi/3)$

Table 2: Comparison of the proposed current shape and sinusoidal operation.

Waveform	RMS Value (p.u.)	RMS Fundamental (p.u.)	DC Value (p.u.)	Relative Copper Losses for a Given Flux Level
Sine wave (amplitude 1)	0.707	0.707	0	1.0
Proposed wave-shape (amplitude 1)	0.631	0.408	0.447	2.4

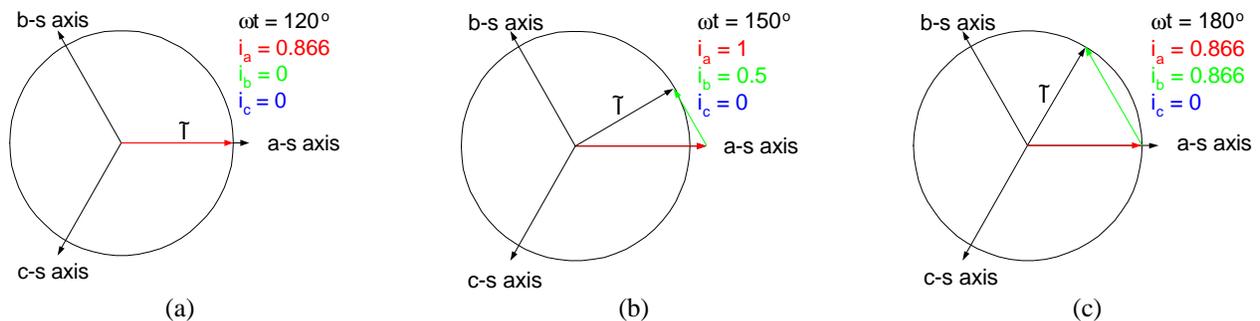


Figure 3: Rotating Constant Amplitude Stator Current Vector at Different Electrical Positions.

Equation (2) shows that the proposed current control method for a three-phase induction motor with stator neutral access creates a stator current vector of constant amplitude that is rotating with a constant angular frequency, ω . As a result, this will induce an air-gap mmf of constant amplitude rotating at the same frequency. Along with a squirrel cage rotor, the conditions of constant torque production have been satisfied. Essentially, due to the spatial sinusoidal distribution of the stator windings, the effects of the non-fundamental components of the currents are canceled out. Therefore, the current source excitation shown in Fig. 1 is better thought of as the combination of a fundamental component and a *zero-sequence* component rather than a fundamental component and a DC component.

Fig. 3 shows graphically how a constant amplitude rotating stator current vector can be formed with only two currents as opposed to three for normal sinusoidal operation. Currents in the figure correspond to those shown in Fig 1.

Table 2 compares the proposed wave-shape to that of the well-known sinusoidal operation. As seen in the table, the stator copper losses will be 2.4 times larger than for sinusoidal operation. While undesirable, the extra losses are concentrated where the heat can be removed. Rotor losses are unchanged since the air-gap mmf can be the same as sinusoidal operation. Due to the extra losses, this drive is ideally suited to an application that runs at reduced power most of the time, such as an HVAC installation.

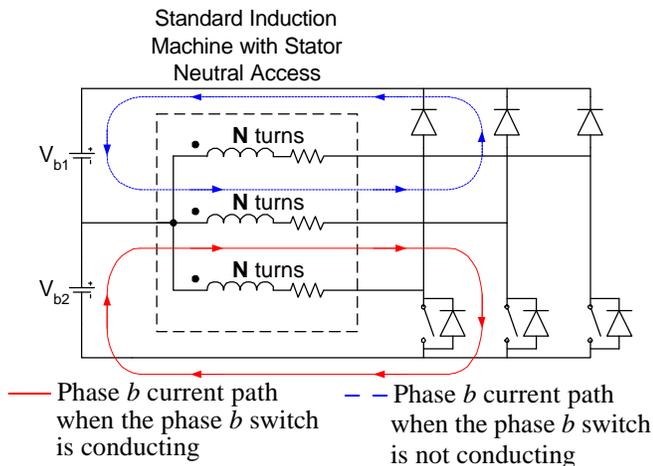


Figure 4: Ideal Implementation of the Proposed Induction Machine Current Control Method.

III. IDEAL IMPLEMENTATION

An ideal implementation of a converter to implement the proposed method is shown in Fig. 4. This figure clearly shows the phase leg structure consisting of an IGBT or MOSFET and a diode. This is a shoot through free leg structure since there is no danger of shorting out the DC bus via inadvertent switching. Shown as a solid line is the current path when the switch is conducting. When on, a positive voltage, V_{b2} , is applied across the phase of the motor. This will serve to increase the current in the phase. Shown as a dashed line is the current path when the diode is conducting. When the switch turns off, the diode in turn, is forced on, and a reverse voltage, V_{b1} , is applied across the phase. This will serve to drive the current in the phase down. As a result of the two different bus potentials that can be applied across each phase of the motor, the current in the phase can be controlled to be any positive value and the current shapes given by the proposed method can be obtained.

While simple and symmetric, the ideal implementation as shown in Fig. 4 cannot be implemented with a passive DC link. Visual inspection of the circuit reveals that the upper DC link supply, V_{b1} , does not have a discharge path. For all of the possible switching states, it is either inactive, or absorbing energy from the motor. No passive source such as a battery or a capacitor supplied by a diode rectifier can sustain a constant charging condition. While it would be possible to create such a link with an active AC-to-DC front end converter, the reduction in the number of active switches, and cost savings, obtained from using this drive topology would be lost.

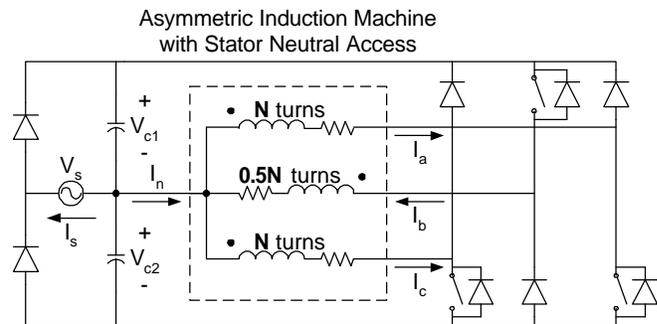


Fig. 5: Proposed Drive Topology for Unidirectional Current Control of a Three-Phase Induction Machine.

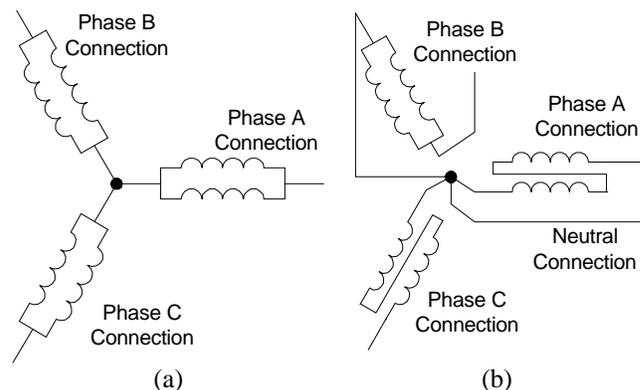


Fig. 6: Wiring Modifications of a Dual Stator Winding Machine (a) to obtain the Asymmetric Machine (b).

IV. PRACTICAL IMPLEMENTATION

The practical implementation of the proposed current control method is shown in Fig. 5. From the power converter, or “inverter” standpoint, the only difference between this and the ideal implementation of Fig. 4 is the flipping of one of the phase legs. Phase b is now actively connected to the upper DC link while phases a and c are still actively connected to the lower DC link. The choice of flipping phase b is arbitrary. However, the arrangement of having one phase connected to the upper bus and two to the lower bus is advantageous over having one connected to the lower bus and two to the upper bus because then only one floating gate drive power supply is required.

In this circuit, the split rail DC link is obtained from a voltage doubler diode rectifier. This represents the lowest cost solution since it has only two diodes. Improved power factor and harmonic spectrum could be obtained if the diodes were replaced with PWM boost converter to supply the split DC bus.

The induction machine used is a non-standard three-phase machine, although it is easily obtained. Many induction machines are wound with two pairs of stator windings so that the windings can be configured (externally) to operate off either of two specified voltages. Fig. 6a shows the lumped stator windings of a dual winding machine that has been

configured to operate on the lower rated voltage. Fig. 6b shows how an asymmetric machine was obtained for unidirectional current control. The two windings of phase *b* are connected in parallel for low voltage operation and phases *a* and *c* are connected in series for high voltage operation. Connecting the opposite end of the windings to the neutral point reverses the magnetic polarity of phase *b*. Finally, the neutral point is brought out of the machine so it can be used by this motor drive.

To compensate for the reverse in polarity of the windings of phase *b*, the direction of current flow from the motor drive in this phase is reversed, as shown in Fig. 5. The reversal of current negates the reverse of the polarity of the winding so each of the three phases contributes an mmf that is rotating in the same direction. The phase *b* windings, connected in parallel, effectively create a winding with half the number of stator turns than that of phases *a* and *c*. In order to create the same contribution to the air-gap mmf, the current in phase *b* needs to be double in magnitude to that of phases *a* and *c*.

With phase *b* connected to the upper bus drawing twice the current of phases *a* and *c* which are connected to the lower bus, the current that is flowing in the stator neutral wire of the motor, shown as I_n in Figure 5, is a sinusoidal quantity. As a result, the amount of energy removed from each of the capacitors by the three phases is balanced, and on average, is a discharge path. The source diodes create a charge path and the result is a stable DC link system.

V. SIMULATION RESULTS

In order to investigate the proposed control method, simulations were performed using SIMULINK with post-processing of data in MATLAB. The system simulated was one that would typically be found in an HVAC application. A one horsepower machine with parameters given in the appendix was used.

For the simulations, the motor was connected up to a fan load in which the torque load varies inversely proportional to the square of the speed up to the rated speed. The output frequency of the drive was fixed at 15Hz, producing a nominal speed of 900rpm. The motor currents were controlled with simple hysteresis regulators.

The simulations shown in Figs. 7 – 11 indicate that the proposed unidirectional currents supplied via a three switch motor drive could be a useful control algorithm for low cost applications requiring variable speed.

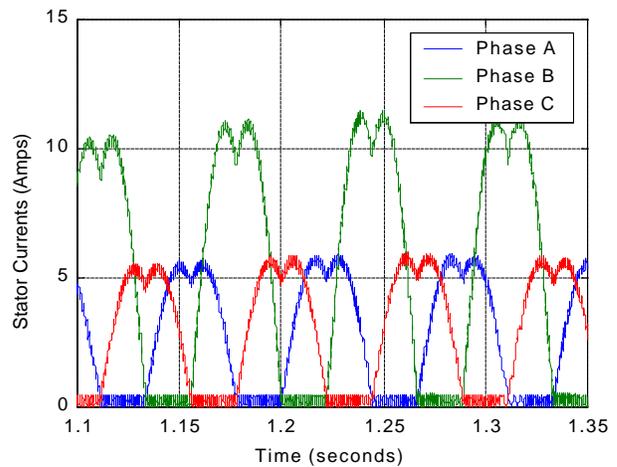


Fig. 7: Simulated phase currents.

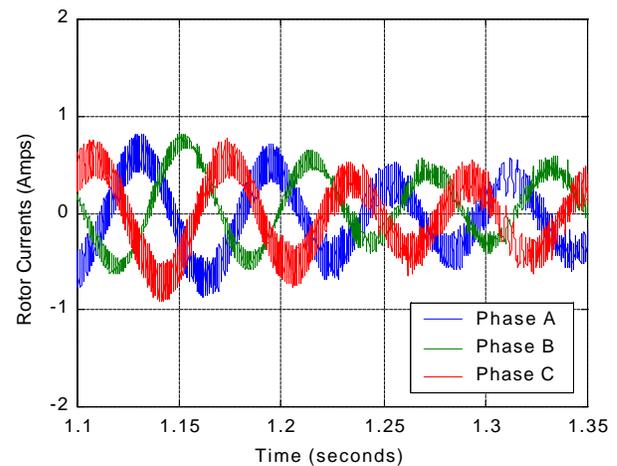


Fig. 8: Simulated rotor currents.

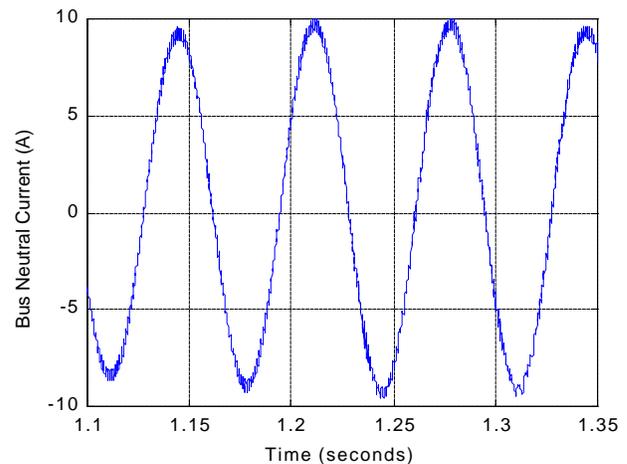


Fig. 9: Simulated bus neutral current.

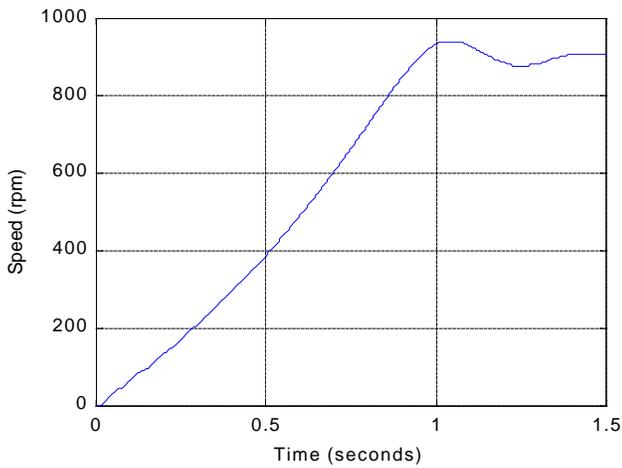


Fig. 10: Simulated motor speed showing startup.

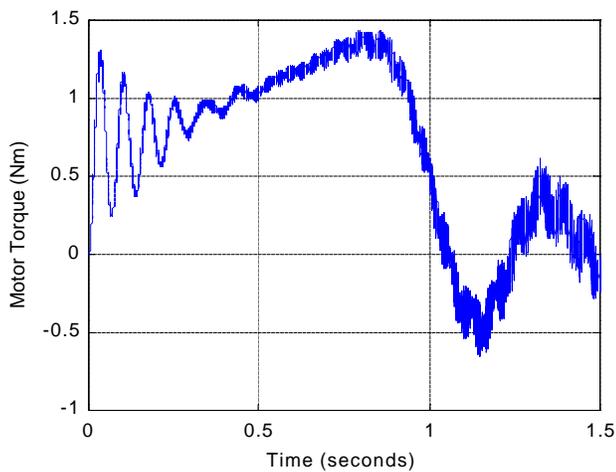


Fig. 11: Simulated motor torque showing startup.

VI. EXPERIMENTAL RESULTS

The proposed system was implemented in hardware. The control system was closed loop current control via hysteresis regulators and open loop velocity control. The input to the drive was single phase, 115VAC, supplied to the voltage doubler diode rectifier through an autotransformer. The autotransformer was used for this proof-of-concept drive as an additional safety precaution, and is not required for proper operation. The results presented here are for a fixed frequency of 15Hz excitation on the unloaded induction machine given in the appendix. The resultant speed was 892rpm.

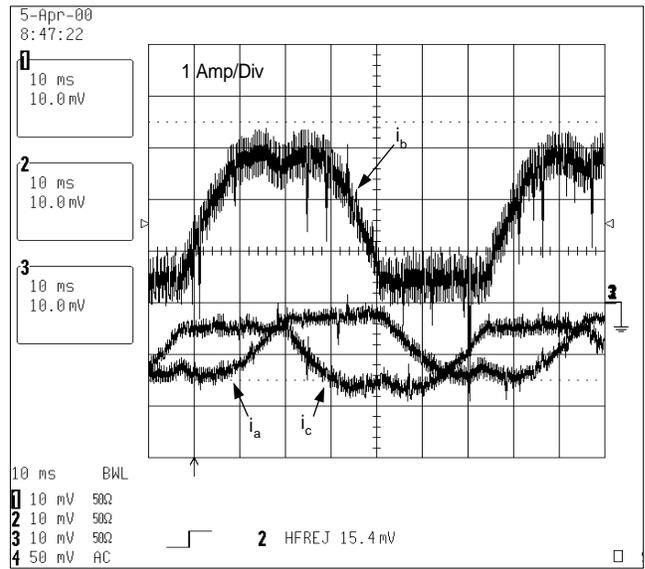


Fig. 12: Experimental stator currents. Polarities are positive from the drive to the motor.
 10mS/Div and 1A/Div.

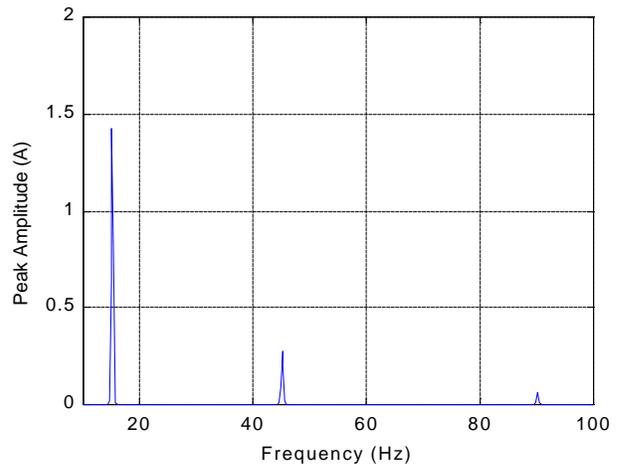


Fig. 13. Experimental harmonic spectrum of the phase *b* stator current. Data obtained with a Hanning window, 10rms averages, and $f_b = 0.25\text{Hz}$.

The stator currents in Fig. 12 show the hysteresis band that is characteristic of that type of controller. There is some DC offset in each of the phases due to the offsets in the analog hardware used as the controller. The corresponding harmonic spectrum for the phase *b* current is shown in Fig. 13. It shows that the currents contain only triplen harmonics of the fundamental component.

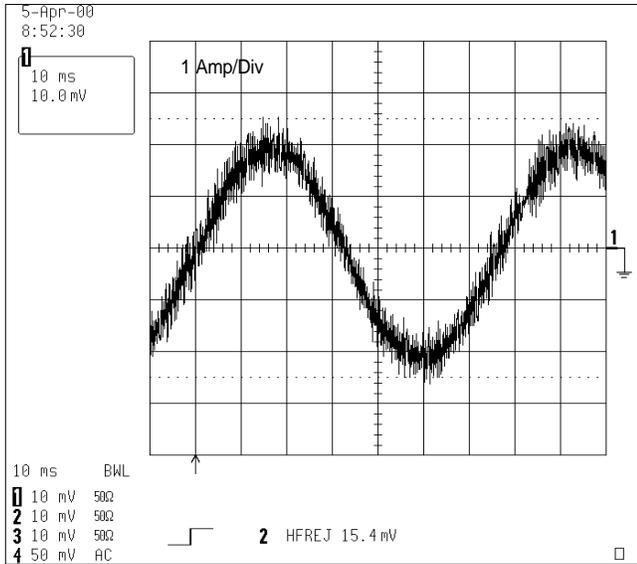


Fig. 14: Experimental stator neutral current. Polarity is positive from the drive to the motor. 10mS/Div and 1A/Div.

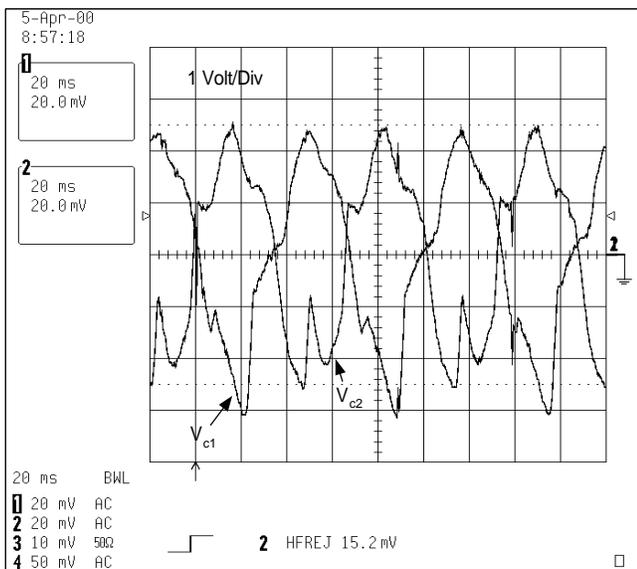


Fig. 15: Bus capacitor ripple voltages showing both a 60 Hz and 15 Hz component. 20mS/Div and 1V/Div. The reading is AC coupled. DC values are $V_{c1} = 40.5$ V and $V_{c2} = 39.8$ V.

Fig. 14 verifies that the neutral current is indeed a sinusoidal quantity as required for a stable DC link. The DC link capacitor voltages shown in Fig. 15 show an unusual property that is not normally a characteristic of a capacitor filter on a diode bridge. In the case of the unipolar drive, there exist multiple charging paths created by the asymmetry of the inverter circuit. As a result, the capacitor waveforms will exhibit ripple frequencies at both half the supply frequency and the output frequency in addition to switching frequency induced ripple currents.

VII. CONCLUSIONS

This paper has proposed a novel current source control method for a three-phase induction machine. The currents are unidirectional in nature and can be produced with only one switch per phase. Both simulations and experimental laboratory results verified the method.

Some features of a motor drive implementing this control method as a low cost alternative are the fact that it only requires three controlled switches and five diodes in a shoot through free leg structure, and one isolated power supply for the one high side switch. As a result of the reduced parts count, the cost to produce this product should be significantly less than a comparable six-switch inverter. The lower cost will be appealing to industries that desire variable speed operation to improve their products, but cannot tolerate the present day cost of the technology.

ACKNOWLEDGMENT

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APPENDIX: MACHINE PARAMETERS

The 115/230V, 3-phase, squirrel cage rotor, dual wound stator induction machine used for this paper for both the simulations and hardware experiments had the following characteristics when configured for high voltage operation.

$R_1 = 2.0 \Omega$	$R_2 = 1.4 \Omega$
$L_1 = L_2 = 7.7$ mH	$L_m = 218$ mH
$R_m = 465 \Omega$	Poles = 2
$P_{rated} = 1$ Hp	$f_{rated} = 87$ Hz