DSP Control of Multi-Use Induction Machines with Multiple Stator Windings: Closed-Loop Voltage Regulation and Speed

Al-Thaddeus Avestruz and Steven B. Leeb
Laboratory for Electromagnetic and Electronic Systems
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
Email: avestruz@mit.edu

Abstract— **We have investigated the voltage regulation and speed control of an induction machine with multiple stator windings using a digital signal processor (DSP). Multiple functionalities are integrated in one machine: mechanical drive, as well as electrical power generation and conversion. One stator is driven with a three-phase inverter while the voltages on the other stators are rectified to provide a dc output. By using zero sequence harmonics in wye-grounded windings, the control for dc output voltage regulation can be made orthogonal to that for speed. In this paper, we study some of the challenges and solutions to speed control in tandem with closed-loop voltage regulation in this type of machine.**

I. INTRODUCTION

We demonstrated a method to control the voltage of a rectifier output on a secondary stator winding by the addition of a zero sequence component to the drive voltage of an induction machine. This method is not only applicable to induction machines, but is also useful in other types of machines within numerous applications where both mechanical drive and electrical power are required. By combining these two capabilities in one machine, not only are the magnetics combined in one frame, but also the same inverter and DSP control electronics are used offering the potential for an overall size, weight, parts count, and ultimately cost savings. Applications include ISGs (integrated-starter generators) in hybrid electric vehicles, UAVs and AUVs (unmanned aerial and underwater vehicles), machine tools and HVAC (heating, ventilation, and air conditioning) systems, among others.

In [1], we had analyzed and demonstrated the decoupled open-loop control of rectified output voltage and rotor speed by superposing a third harmonic voltage on the drive. The dc output voltage can be controlled by either the phase or the amplitude of the third harmonic, but only amplitude control allows the regulation of the dc output over the full range of rotor speeds. In addition, a complete discussion of the inverter and DSP implementation used in this paper[1] is discussed in [1] and [2]. In this current paper and in [2], we focus on the closed-loop regulation of the dc output voltage using amplitude control and innovations in circuit topology, along with the challenges and methods for speed control in this multi-use machine.

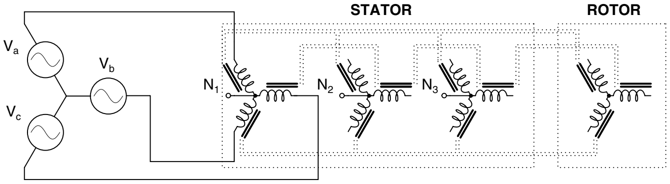


Fig. 1. Simplified Depiction of a Multi-Stator Induction Machine.

II. POWER CONVERSION CONTROL BY ZERO SEQUENCE HARMONICS

By introducing one or more triple-n harmonics into the drive voltage of a three-phase machine, the rectified output voltage from grounded-wye windings can be controlled and subsequently regulated. To first-order, these triple-n harmonic voltages produce triple-n harmonic currents, and introduce negligible net torque on the rotor, effectively decoupling voltage regulation from drive.

The rectifiers in Figure 2 are designed to operate in the discontinuous conduction mode. Figure 4 illustrates how the dc output voltage will vary with third harmonic

---

[1] The motor drive module used is the International Rectifier PI-IPM15P12D007 which contains a TI TMS320LF2406A DSP.

0-7803-9725-8/06/$20.00 ©2006 IEEE.

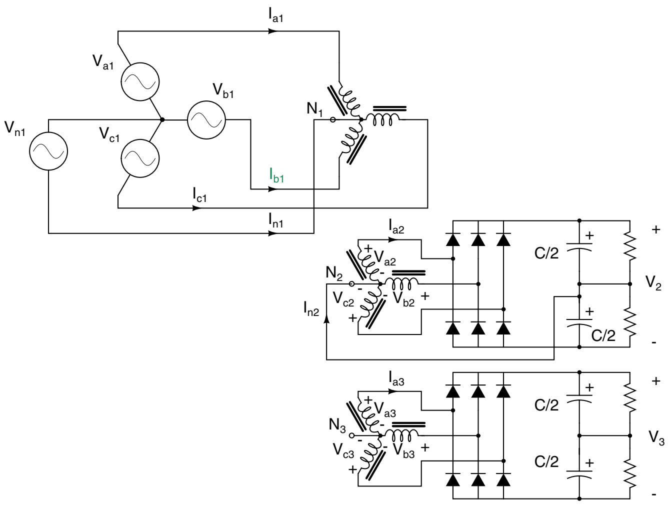


Fig. 2. Multiple Stator Connections Driving Three-Phase Rectifiers.

amplitude and phase for a rectifier operating in discontinuous mode. One notices that for a third harmonic phase $\phi_3 = \pi$, the dc output voltage is not only monotonic, but also linear with third harmonic voltage V_{k3}; the reason for this is immediately obvious from Figure 3, as the peaks of the fundamental and third harmonic occur coincidentally. While not proven, it can be plausibly argued that while V_2 is monotonic with V_{k3} over various intervals for different values of ϕ_3, linearity as well as the widest range of V_{k3} for monotonicity occurs only for $\phi_3 = \pi$.

The strategy used for π-phase harmonic control is founded on the fact that the peaks of the 3rd harmonic and the fundamental coincide. In this case, where we have assumed discontinuous current in the phase connections of the secondary windings and 1:1 turns ratio, the dc output voltage will be very nearly equal to the sums of the peak voltages, $V_{k1} + V_{k3}$. In the implementation, a closed-loop PI controller ensures as V_{k1} drops, which for example is the case when the speed is lowered, that the 3rd harmonic V_{k3} makes up the difference.

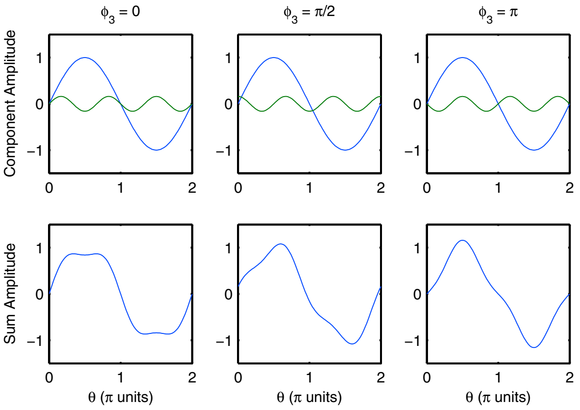


Fig. 3. Drive Waveform with Third Harmonic

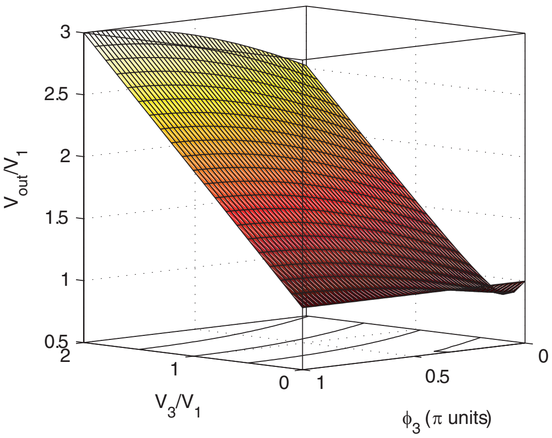


Fig. 4. Control surface for peak amplitude control using third harmonic voltage amplitude (V_3) and phase (ϕ_3) with fundamental voltage (V_1) held constant.

As lower fundamental, and hence lower 3rd harmonic frequencies, are encountered, the current through the magnetizing inductance, which is discussed in the following section, increases. This is exacerbated in a motor drive because as the speed and frequency are lowered, the voltage of the fundamental is also lowered, which means that the 3rd harmonic voltage must be increased. Increasing zero sequence magnetizing current at low fundamental frequencies can be circumvented by hopping to higher zero sequence harmonics; in the three-phase case, to higher triple-n harmonics. Not all triple-n harmonics will have peaks that coincide with the fundamental. Only the odd triple-n harmonics will work,

$$V_n(t) = V_{kn} \sin(n\omega t + \phi_n)$$
$$\phi_n = \frac{\pi}{2}(n-1)$$

where the harmonic number n is odd and a multiple of 3.

For example, for a system with a base frequency of 60 Hz, as the frequency drops to 20 Hz, we hop to the 9th harmonic, at 12 Hz to the 15th, and so forth. In this way, the zero sequence frequency will be between 60 Hz and 180 Hz.

A. Zero Sequence Circuit

A key issue in driving a zero sequence current through two magnetically coupled windings with grounded wyes is the effective magnetizing inductance, which is the phase-to-phase leakage in an induction machine, hence typically kept as small as possible for good machine performance [3]. The stator windings of this induction machine is electrically identical to a three-phase, three-legged transformer. Figure 5 shows a zero sequence circuit model for an induction machine with two identical stators.

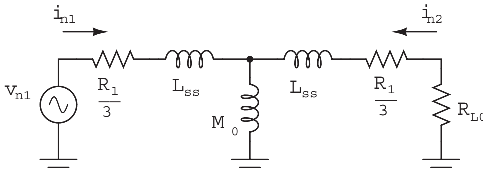


Fig. 5. T-Model for the Zero Sequence Circuit.

M_0 is derived from the leakages among the phases within a winding. The leakage inductance from one phase to the other two can be found by measuring the inductance across one phase (phase to wye) while shorting the other two phases (phases to wye). $L_{ss}+M_0$ can be found by measuring the inductance from wye to the shorted phase connections (a-to-b-to-c) with all the secondaries open. L_{ss} can be found by making the identical measurement with the secondary phases shorted to wye. In our prototype induction machine $M_0 = 3.5$ mH and $L_{ss} = 400\ \mu$H at 60 Hz with small test currents. This results in a magnetizing reactance of only 4Ω at the nominal third harmonic frequency of 180 Hz. The small magnetizing inductance M_0 results in high zero sequence reactive current and represents additional loss in the stator resistance $R_1/3$, as well as additional switch stress in the power electronics.

Small phase-to-phase stator leakage is a consequence of a good design for a round-rotor machine. One can envision designing a machine with higher leakage from phase to phase. In the limiting case, the three-legged transformer analogy becomes three separate single-phase transformers, each supporting twice the flux previously supported by each leg, hence resulting in a core that is twice as big. In addition, a machine with an acceptable phase-to-phase leakage is likely to incur an unacceptable amount of space harmonics.

We can increase the magnetizing inductance M_0 without affecting the circuit path of the fundamental by using a zero sequence transformer in the wye connection as shown in Figure 6; a turns ratio other than unity offers an additional degree of freedom in optimizing machine design through the scaling of the zero sequence voltage and current. This zero sequence transformer can be integrated into the machine back-iron, although this is not currently implemented.

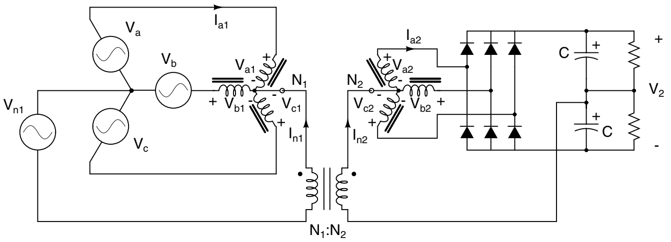


Fig. 6. Zero sequence transformer.

Power can also be derived directly from the wye point as illustrated in Figure 7. In this topology, fewer rectifiers are required and a split-capacitor ground is not needed; power to the output is derived solely from the zero sequence harmonics, so rectifier currents do not contribute to torque ripples, even without special accommodations in the control. Because the rectifiers only draw zero sequence current, standard field-oriented control schemes with fewer current sensors are more easily implemented.

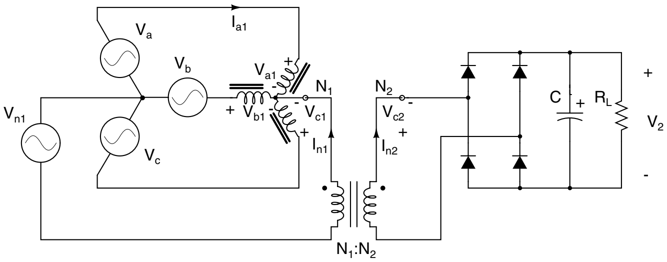


Fig. 7. Direct zero sequence transformer.

Although using a direct zero sequence transformer offers a number of advantages, the tradeoff is that all of the dc output power is converted solely through a single-phase circuit, whereas the topology shown in Figure 6 allows, in certain regimes of operation, a portion of the power to be transferred to the output through the three phase circuit.

Under instances where the stator is not driven by an inverter, such as in an alternator, zero sequence harmonics can be exogenously driven through the wye as illustrated in Figure 8.

B. Closed-Loop Voltage Control Using Harmonic Amplitude with Coincident Fundamental Peaks

The dc rectifier output is controlled by a conventional PI (proportional-integral) controller that is implemented

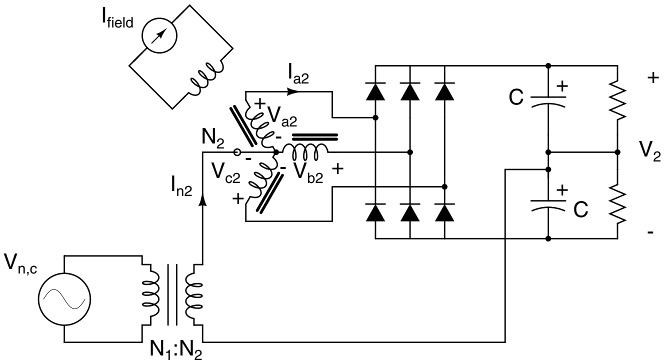


Fig. 8. Exogenously driven zero sequence transformer.

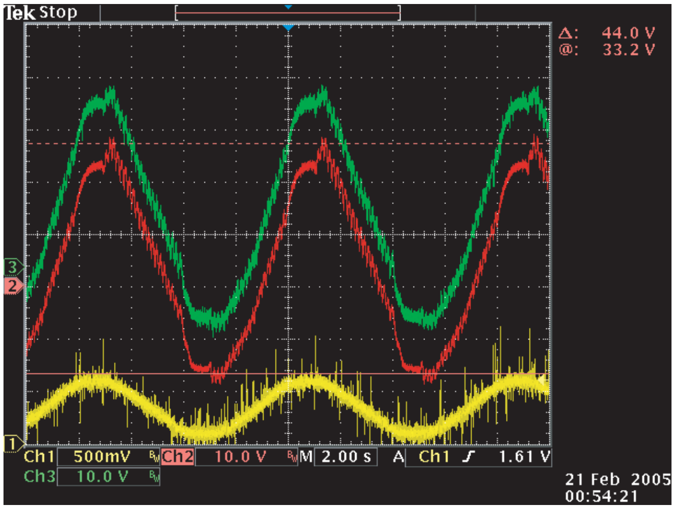
in the DSP. When the three-phase, full-wave rectifier operates in the discontinuous mode with a controlling zero sequence harmonic, the plant dynamics are dominated by the delay between the firing of each of the rectifier diodes, which can have a worst-case of $1/6$ of the fundamental cycle.

At low fundamental frequencies, one might expect an unacceptably poor disturbance rejection for dc voltage regulation, along with higher ripple. However, as mentioned above, low fundamental frequencies for a motor drive also mean a low fundamental voltage and a subsequently higher zero sequence voltage, and perhaps a higher zero sequence frequency from hopping. In the limit of zero fundamental frequency, the voltage will consist of only zero sequence, perhaps at some nominal frequency like 180 Hz. In this case, the delay is only 2.8 ms, which is the delay when the fundamental is at its base frequency of 60 Hz.

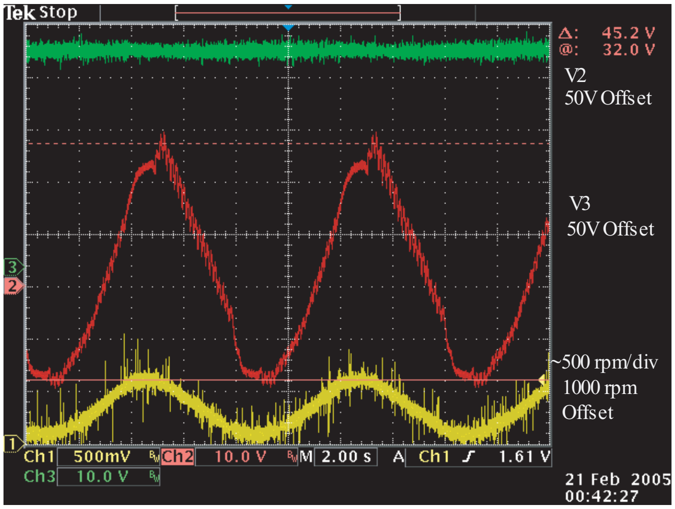
A delay of $1/6$ of the fundamental is a conservative estimate for the worst-case delay. The actual delay depends on the size of the disturbance and the voltage ripple on the output dc bus, in addition to the relative frequencies and magnitudes of the fundamental and zero sequence harmonics. A more detailed study of this delay will be discussed in a following paper. The controller used in Figure 9 was compensated by using the conservative delay estimate of 5.5 ms for a lower bound on the fundamental of 30 Hz.

III. CLOSED-LOOP SPEED CONTROL OF A MULTI-USE INDUCTION MACHINE

The electrical parameters for the induction machine are listed in Table I. These parameters were derived in [4] from a non-linear least square fit to the start up transient of the induction machine using IEEE blocked-rotor and no-load tests as well as impedance measurements for



(a) No 3rd Harmonic



(b) PI Control with Third Harmonic

Fig. 9. PI Control of Dc Output Using Third Harmonic. The top trace in (a) and (b) shows V_2, the dc output of the grounded-wye secondary winding, and the middle trace, V_3, the dc output of the ungrounded-wye winding. The bottom trace is the speed sensor output during open loop, constant V/Hz ramps.

TABLE I

INDUCTION MACHINE PARAMETERS[4]

Pole Pairs	p	2
Stator Resistance	R_1	2.0Ω
Rotor Resistance	R_2	1.5Ω
Stator Reactance†	X_1	2.8Ω
Rotor Reactance†	X_2	2.8Ω
Mutual Reactance†	X_M	42.09Ω
Free Moment of Inertia	J_0	0.0168 kg · m^2

†Reactances are customarily referenced to 60 Hz.

values of the initial guess. These parameters are the basis for the design of a speed control system.

A. *Volts-per-Hertz Speed Control*

A conventional PI (proportional-integral) controller is used with trapezoidal integration whose z-transform is

$$\frac{1}{s} \rightarrow \frac{T}{2}\frac{1+z^{-1}}{1-z^{-1}}. \tag{1}$$

The recurrence relation for PI controller given by [5]

$$u[k] = \left(K_P + \frac{T}{2}K_I\right)e[k] + \left(\frac{T}{2}K_I - K_P\right)e[k-1] + u[k-1]. \tag{2}$$

The controller gains K_I and K_P are derived from a discrete time transformation of a continuous time design.

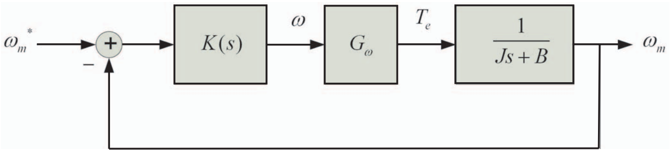


Fig. 10. Continuous time block diagram of the speed control loop.

In the closed loop, volts-per-hertz controller, the continuous time loop transmission is

$$L(s) = K(s)G_\omega\frac{1}{Js+B}, \tag{3}$$

where J is the moment of inertia, B is the damping factor, the controller transfer function

$$K(s) = K_I\frac{1+\frac{K_P}{K_I}s}{s}$$

and G_ω is the linearized gain from drive frequency to torque.

G_ω can be derived from differentiating the torque [6], [7] with respect to ω,

$$T_e = \frac{3p}{\omega_B}\frac{V_0^2\frac{R_2}{s_B}}{\left(X_1'+X_2\right)^2 + \left(R_1'\frac{\omega_B}{\omega} + \frac{R_2}{s_B}\right)^2}. \tag{4}$$

In a constant V/Hz controller, ω_B is the base frequency and V_0 is the base rms voltage such that V_0/ω_B is constant. $s_B = \omega s/\omega_B$ is defined as the *absolute slip* with $s = 1 - p\omega_m/\omega$ being slip; ω_m is the mechanical frequency. The primed variables are the series Thevenin equivalents [6] and the reactances are calculated at the base frequency ω_B; for $X_m \gg X_1$ and $X_m \gg R_1$, then $X_1' \approx X_1$ and $R_1' \approx R_1$, which is a reasonable approximations for the values shown in Table I.

When $R_1 \ll R_2/s$, then

$$\frac{\mathrm{d}T_e}{\mathrm{d}\omega} = \frac{\mathrm{d}T_e}{\mathrm{d}s_B}\frac{\mathrm{d}s_B}{\mathrm{d}\omega} \tag{5}$$

$$G_\omega \approx \frac{3p}{\omega_B}V_0^2R_2\frac{R_2^2 - s_B^2\left(X_1'+X_2\right)^2}{\left[s_B^2x_k^2 + R_2^2\right]^2}\frac{1}{\omega_B}. \tag{6}$$

From Equation 6, the maximum value of G_ω occurs when s_B is zero. G_ω is zero for some $s_B = s_{B,max}$, which is the absolute slip value the breakdown torque; above this value of s_B, G_ω is negative, making the system in Figure 10 become positive feedback and hence unstable. $s_{B,max}$ is about 0.27. Figure 11 illustrates the difficulty of attempting a hard limit on the absolute slip because of positive feedback. For the system to be robust, $s_{B,max}$ would be set below the breakdown value, hence making G_ω finite.

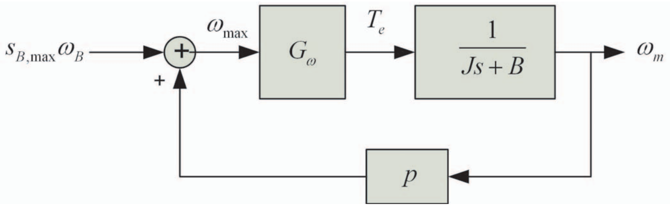


Fig. 11. Positive feedback loop in limiting absolute slip s_B.

The controller used in Figure 12 is designed with the compensation zero conservatively placed at a higher frequency than the mechanical pole.

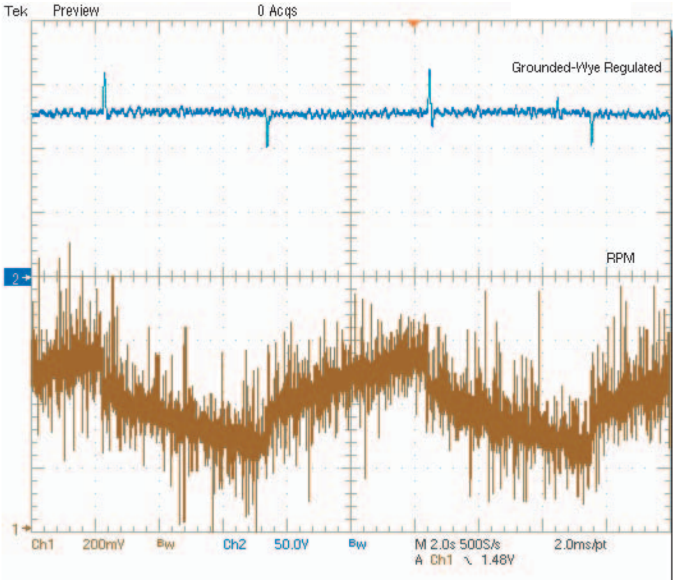


Fig. 12. Traces of speed step response using a closed-loop constant V/Hz controller and the corresponding regulated dc output.

B. Current Sensing for a Synchronous Current Regulator

The typical implementation to field oriented control commands current in the Cartesian dq-space [7]. A current control loop is used to create a three phase current source from what is intrinsically a PWM inverter, which is intrinsically a voltage source. To introduce a zero sequence harmonic in *voltage* that is exogenous to the current control loop, we first convert the Cartesian output of the current regulator through a polar transformation, resulting in the specification of the magnitude and phase of the fundamental in the inverter. This ensures that whatever triple-n harmonic we command directly to the inverter will have the correct phase. Details of the synchronous current regulator and the field-oriented controller will be discussed in a following paper.

The key to the field-oriented control of a multi-use machine is in deriving the stator current that links flux from the stator to the rotor. This current is not immediately available because the inverter output current contains not only this *rotor linking* current, but also the rectifier current, which consists of the fundamental and is rich in harmonics.

This *rotor linking* current is more easily derived if the following assumptions can be made: first, there is negligible leakage flux between the primary and secondary windings of the stator; second, good coupling exists between the primary and secondary zero sequence currents. These assumptions are reasonable in the existing machine implementation: the stator windings are wound *in-hand* and a zero sequence transformer with a large magnetizing, relative to the leakage, inductance is used. Because the turns ratios of the stator windings, as well as the zero sequence transformer, are 1 : 1, the *rotor linking* current can be derived by subtracting the secondary from the primary current using only two LEM™current sensors; one of which is illustrated in Figure 13.

IV. CONCLUSIONS AND FUTURE WORK

We have analyzed the issues with the simultaneous closed-loop control of both speed and dc output voltage in a multi-use induction machine and have demonstrated stable implementations of these decoupled loops. It is clear that the dynamic response using a closed-loop, constant V/Hz controlled is limited and ongoing work with the implementation of a field-oriented controller is expected to significantly improve upon this. In addition, further characterization of the dominant delay in discontinuous conduction in the plant dynamics and a general transfer function for continuous conduction of the dc output regulation loop is currently being pursued.

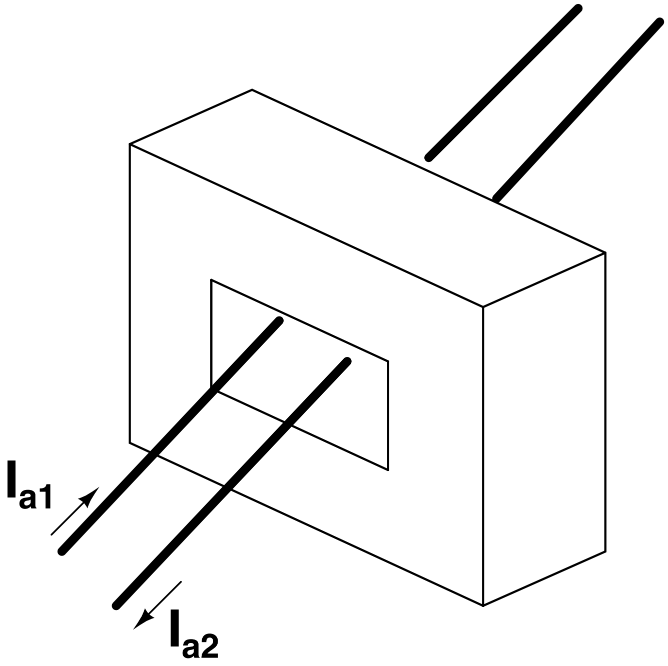
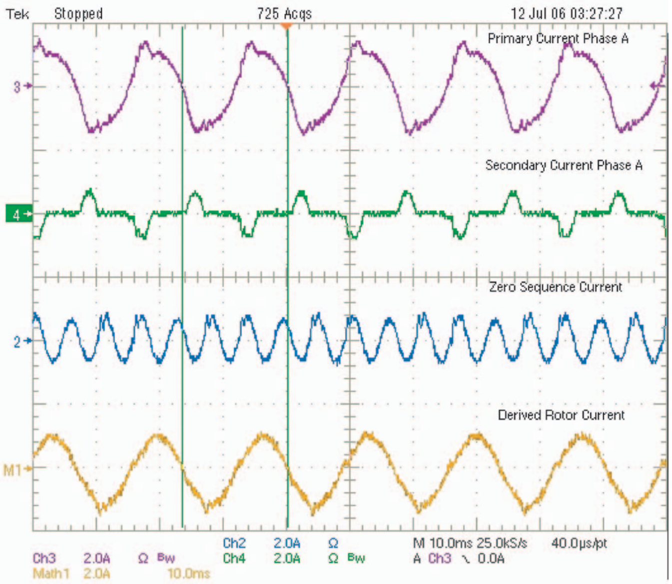


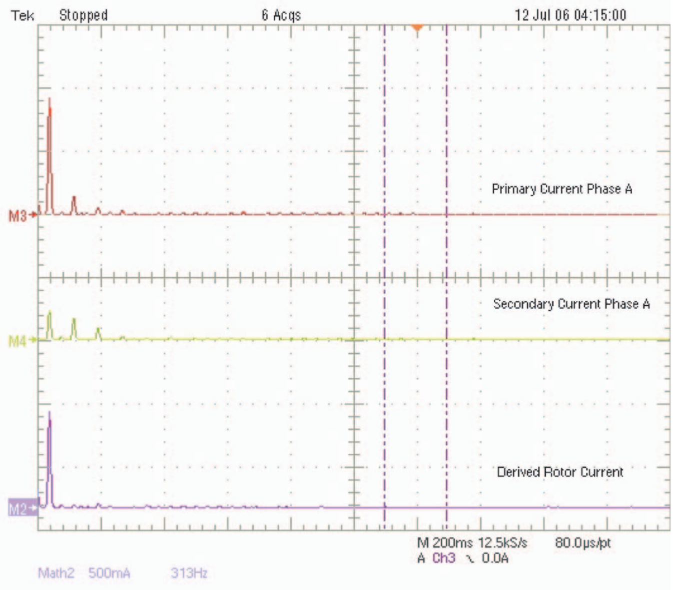
Fig. 13. Using a single current sensor to obtain the difference of two currents for synchronous current regulation in a field-oriented controller.

ACKNOWLEDGMENT

This work was supported by the Center for Materials Science and Engineering, a Materials Research Science and Engineering Center funded by the National Science Foundation under award number DMR 02-13282, and by the Grainger Foundation. The authors gratefully acknowledge the valuable advice of Professor James Kirtley.



(a) Time Domain



(b) FFT

Fig. 14. Traces of Phase A primary, secondary, and derived currents. A trace of the zero sequence current is also included

REFERENCES

[1] A.-T. Avestruz, J. Holloway, R. Cox, and S. Leeb, "Voltage regulation in induction machines with multiple stator windings by zero sequence harmonic control," in *Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE*, vol. 2, 2005, pp. 746–752 Vol. 2, tY - CONF.

[2] A.-T. Avestruz, "Control and design of multi-use induction machines: Traction, generation and power conversion," Master of Science and Electrical Engineer, Massachusetts Institute of Technology, 2006.

[3] P. L. Alger, *Induction Machines, Their Behavior and Uses*. New York: Gordon and Breach, 1970.

[4] J. W. Holloway, "Harmonic control of multiple-stator machines for voltage regulation," M.Eng, Massachusetts Institute of Technology, 2004.

[5] J. V. d. Vegte, *Feedback Control Systems*, 2nd ed. Englewood Cliffs: Prentice-Hall, 1990.

[6] A. E. Fitzgerald, C. Kingsley, and S. D. Umans, *Electric machinery*, 6th ed., ser. McGraw-Hill series in electrical engineering. Power and energy. Boston, Mau.: McGraw-Hill, 2002.

[7] H. W. Beaty and J. James L. Kirtley, *Electric Motor Handbook*. New York: McGraw-Hill, 1998.