Voltage Regulation in Induction Machines with Multiple Stator Windings by Zero Sequence Harmonic Control

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Abstract **– We have investigated a method to regulate the voltages in the secondary windings of an induction machine stator with multiple windings. By introducing one or more triple-n harmonics in a three-phase machine, the rectified output voltage of one or more grounded-wye windings can be controlled and regulated. Voltage regulation is achieved through triple-n harmonic current injection, so there is *no net torque* on the rotor, decoupling voltage regulation from drive. We demonstrate and analyze voltage control in a custom wound induction machine by the addition of third harmonic to the inverter drive waveform. The rectified output voltage depends not only on the amplitude, but also on the phase of the third harmonic. The ability to orthogonally control voltage is particularly important in applications where the machine is used as a generator, motor and/or power converter at the same time.**

I. INTRODUCTION

Motor and generator drives are of pivotal importance to a wide range of industrial and commercial products and manufacturing processes. Variable speed drives (VSDs) that can operate over a range of mechanical shaft speeds are especially prized in many applications. There are a variety of ways to vary the shaft speed of a motor. Advances in power electronic circuit design and components in the last 30 years have made it increasingly attractive and economical to combine motors with power electronic circuits to make VSDs for commercial and industrial products.

There are many common examples of products with VSDs. Modern air-handling and ventilation systems employ variable speed drives to run fans at an optimal speed and power level to achieve occupant comfort while minimizing energy consumption. Machine tools like computer-controlled milling machines and lathes use variable drives to create optimum cutting conditions for different materials and tasks. Electric and hybrid automobiles use variable speed drives as part of the vehicle traction system. All of these systems typically include at least one power electronic circuit to control power flow to the motor and, therefore, to vary motor speed.

These systems may also include other power supplies; that is, they typically have a multi-bus power distribution network for different parts of the system. For example, a supply fan system for a building ventilation system may include a power electronic circuit or "inverter" to run the fan motor with variable, controlled speed. It will also typically include other power supplies to produce low-voltage sources for control circuits, e.g., an internal computer.

A hybrid automobile is another example of a system with a VSD and several power supplies for different system components. A suggestive schematic of a conceptual hybrid vehicle power plant is shown in Figure 1. The VSD serves as an "integrated starter/generator" or ISG that can start the internal combustion engine, run as an alternator or generator during cruising, and assists in moving the vehicle by adding traction power while running as an electric motor. The ISG is electrically excited by an inverter/rectifier circuit from an internal electrical bus, shown as 42 volts in Figure 1. A separate, possibly costly power supply makes 12 volts from the 42-volt bus. The 12 volt bus energizes "legacy" loads like radios and headlights.

The system discussed in this paper could eliminate the need for distinct auxiliary power supplies like the one shown connecting the 42- and 12-volt busses. The drive motor in the VSD, e.g., the integrated starter/generator motor, can be redesigned with multiple stator windings. The inverter-rectifier circuit can control extra stator windings to produce necessary bus voltages in the system, eliminating the need for extra power supplies like the one shown connecting the 42- to the 12-volt bus. This approach could result in substantial cost and volume savings and potentially enhance the overall system reliability by eliminating components.

Induction motors are a high-power, reliable possibility for an ISG motor [1-5]. They are also ubiquitous in HVAC components, many machine tools, and other systems with high industrial and commercial relevance. In this paper, we make "dual use" of an induction machine, allowing it to serve both as a motor and as a transformer through additional stator windings. These additional stator windings potentially eliminate auxiliary power supplies in a system. This technique could also be applied to the stator of a permanent magnet machine.

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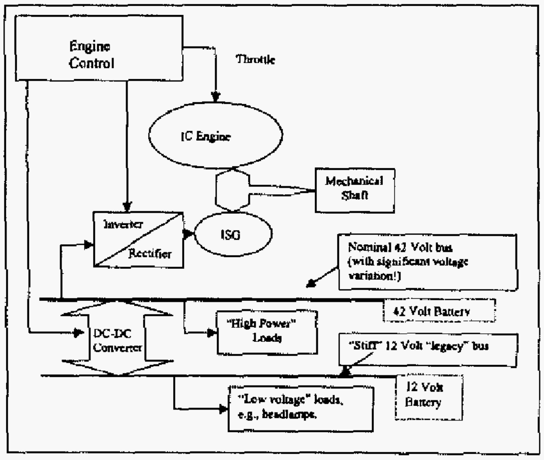


Figure 1: Block schematic of a hybrid (electrical-gas) vehicle traction drive.

A key issue in attempting to make dual use of electrical machines is maintaining voltage regulation in the electrical power windings without affecting the drive capability. That is, a true dual use of the motor would permit it to perform its motor and power supply functions without having one noticeably affect the other. Output voltage regulation must be maintained despite variations in load and rotor speed, for example.

There are several approaches to achieve this dual use. Adding an additional winding to the stator provides an isolated voltage bus energized like a transformer secondary. A simple approach to achieving a regulated output voltage is to use a series pass voltage regulator. This solution, of course, is not viable over a wide voltage swing range and at higher power levels. Another approach is the use of a switched-mode rectifier [6], but this entails the use of additional controllable power switches on the secondary side. Harmonic injection from the stator inverter can be used to achieve voltage regulation.

II. ORTHOGONAL CONTROL OF RECTIFIER OUTPUT VOLTAGE

The dual-use induction machine has a wye-wound stator with one or more additional windings wound "in hand" with the primary stator drive winding, as shown in Figure 2. Our test machine is wound with the same number of turns on each of three stator windings, yielding a one-to-one transformer ratio between the windings. Other winding ratios are possible. The rotor in our machine is a squirrel cage, although the rotor currents can be imagined to flow in an ungrounded wye-connected set of rotor windings if convenient for modeling.

Additional isolated dc system busses can be developed by regulating the output of the stator secondary windings. We have developed a method to regulate the rectified dc voltage from a stator secondary winding. The inverter that supplies the drive is also used to supply a zero sequence current to the output rectifiers. Zero sequence currents can only flow through grounded wye connections [7] and do not appear at the rotor (Figure 3). In particular, we have focused on the superposition of a third harmonic on the drive voltage because this is the lowest frequency harmonic that produces a zero sequence current. Third harmonic represents the minimal additional power loss in the magnetics from the addition of a higher frequency current component.

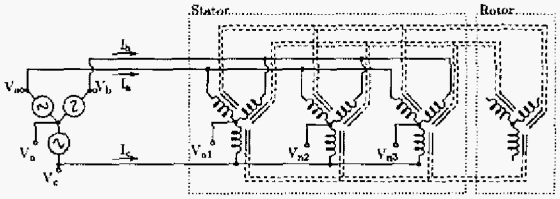


Figure 2: Induction machine model with multiple stator windings

The torque of electromagnetic origin for a symmetrical round-rotor machine such as an induction motor in the synchronous reference frame given by the Park's transform is

$$T_m = \frac{3}{2} P\left(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}\right) \tag{1}$$

where λ_{qr}, i_{qr} and λ_{dr}, i_{dr} are the quadrature and direct components of the rotor flux and rotor current, respectively, and P is the number of pole pairs. The torque is independent of zero-axis current. Although the form for torque in (1) assumes a flux distribution that is sinusoidal in space in the stator frame, design goals for a good motor design include the minimization of space harmonics, which happens to also minimize the coupling of zero-axis flux to the torque.

Because there are additional stator windings along with the rotor that present a parallel load at the stator terminals, tradition field-oriented control methods that use a current drive are not possible without additional current sensors on each secondary stator winding or other estimation schemes. These additional sensors are not required for schemes that drive a voltage at the stator terminals.

A. Third Harmonic Superposition

We have rewound a 1-hp squirrel-cage induction motor with three identical stator windings with the star-points brought outside the motor as shown in Figure 2. In the experiments discussed in this section, the primary stator winding 1 is driven by a programmable AC source, the HP-6834B, which creates waveforms with excellent harmonic control and spectral purity. The voltages on windings 2 and 3 are rectified to create auxiliary dc system busses.

Winding 1 is the drive winding and is connected to the inverter; winding 2 has a center-tapped connection of the wye;

and winding 3 has an ungrounded wye. The line-to-neutral voltages and connections to the rectifiers for these windings are shown in Figure 3.

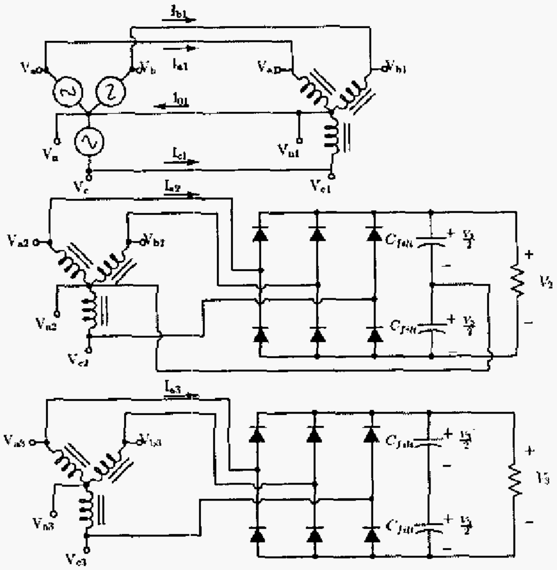


Figure 3: Multiple stator-winding induction machine driving three-phase rectifiers

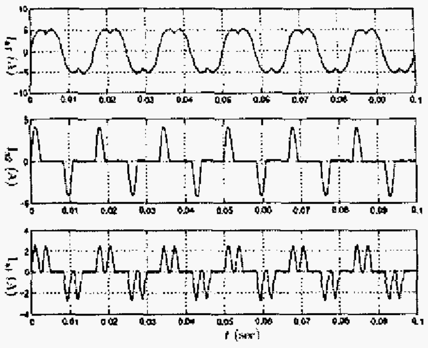
The rectifiers in Figure 3 were designed to operate in the discontinuous current mode. In this case, rectifiers in winding 2 behave as peak detectors of the line-to-neutral voltages, with the output voltage given by

$$V_2 = V_{k1}\sin\left(\theta_p\right)+V_{k3}\sin\left(3\theta_p+\phi_3\right) \qquad (2)$$

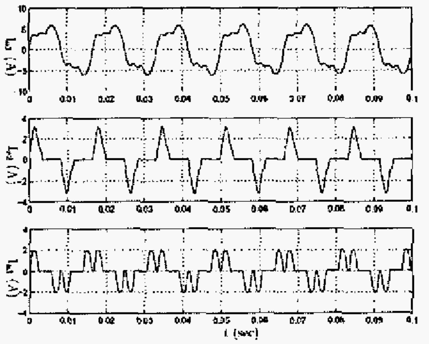
where V_{k1} and V_{k3} are the amplitudes of the fundamental and third harmonic voltages, respectively, ϕ_3 is the phase angle of the third harmonic relative to the fundament and θ_p is the phase angle where the drive voltage is at a maximum. The angle θ_p is given by the extremum relation for the drive voltage

$$\frac{dV_2}{d\theta_p} = V_{k1}\cos\theta_p + 3V_{k3}\cos(3\theta_p+\phi_3) = 0, \qquad (3)$$

which unfortunately is generally transcendental. Measurements of the line currents shown in Figure 4 confirm operation in the discontinuous current mode. The currents waveforms in winding 2 differ from that of winding 3 because diode turn-on in winding 2 is based on the line-to-neutral voltage as opposed to line-to-line voltage in winding 3.



(a) Fundamental Only Drive

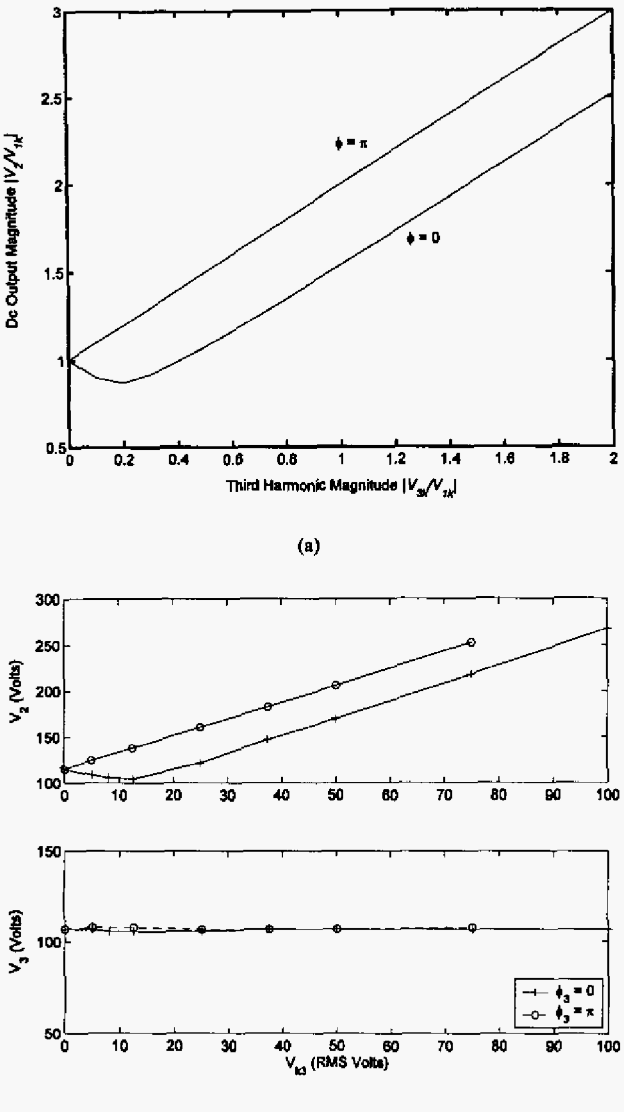


(b) Fundamental + 10% Drive

Figure 4: Rectifier-loaded line currents of stator windings.

B. Control by Third Harmonic Amplitude

The dc output V_2 of a grounded wye-connected rectifier can be controlled by varying the third harmonic voltage applied to the primary drive winding. For $\phi_3 = 0$, it can be exactly calculated (for a system that can be modeled as having no AC line inductance) that V_2 is monotonic with $|V_{k3}|$ for $|V_{k3}| > |V_{k1}/6|$ (at $|V_{k3}| = |V_{k1}|/6$, $V_2 = \sqrt{3}|V_{k1}|/2$). The dependence of V_2 on V_{k3} is plotted in Figure 5. The identical calculation can be performed for $\phi_3 = \pi$, with V_2 affine for $V_{k3} > 0$. At other values of ϕ_3, closed-form solutions to $V_2(V_{k3})$ are likely to not exist, but numerical methods can be used to estimate boundaries where this function is monotonic. Figure 5 shows that experimental data agrees well with calculations.



(a)

(b)

Figure 5: Rectifier output dependence on third harmonic. (a) Calculated for no ac-side inductance. (b) Experimental. V_2: Grounded wye winding. V_3: Ungrounded wye winding. (Using HP-6834B).

Within experimental error, the dc output V_3 of a rectifier from a winding with ungrounded wye is unaffected by third harmonic variation. The converse is not true; V_2 depends on both the fundamental and the third harmonic. In Figure 6, both V_2 and V_3 track the fundamental V_{k1} during a constant V/Hz ramp.

However, the grounded-wye winding with rectified output voltage V_2 can be affected or controlled through the application of third harmonic. In Figure 7, the motor is operated through a ramp of increasing stator RMS drive voltage with drive frequency (i.e., a constant volts per hertz ramp). At each stator drive frequency, four different levels of third harmonic are applied to the primary. Figure 7 shows that varying the third harmonic affects neither the motor mechanical operation or the V_3 voltage. The voltage V_2 can be independently varied by altering the third harmonic applied to winding 1.

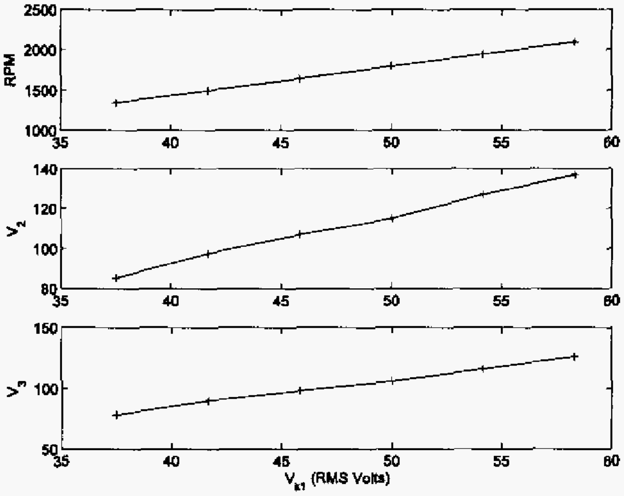


Figure 6: Rectifier output with no third harmonic during a constant V/Hz ramp. (Using HP-6834B).

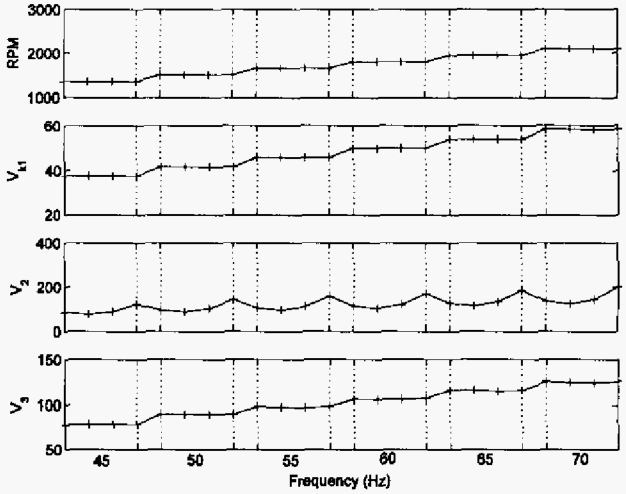


Figure 7: Rectifier outputs during a constant V/Hz ramp, as V_{k3} is discretely controlled: 0, 0.25V_{k1}, 0.5V_{k1}, V_{k1}. (Using HP-6834B). V_{k1}, V_{k3}, V_1 and V_2 in rms Volts.

Figure 8 shows a primary side (winding 1) phase current when both winding 2 and winding 3 are delivering power. Non-zero sequence currents shown in Figure 8 appear from rectifier loads on the secondary stators and could appear as torque fluctuations in the rotor. These current harmonics do not just occur for voltage inputs with third harmonic content, but are a consequence for any load with non-unity power factor, even with a fundamental-only drive.

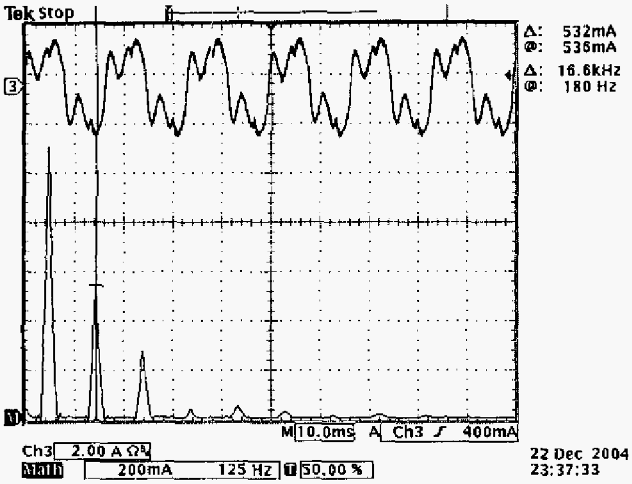
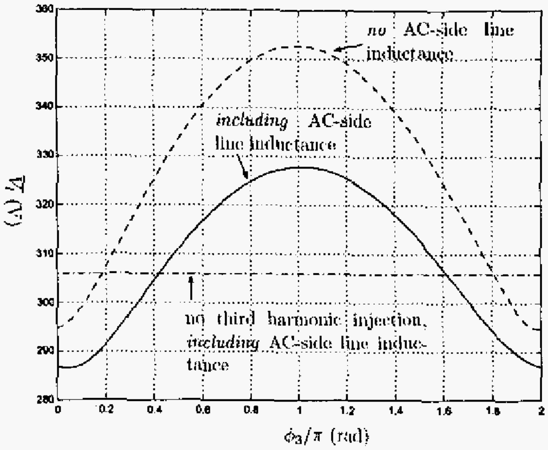


Figure 8: Stator drive current with 25% third harmonic. $\phi_3 = 0$. The top trace shows stator current, the bottom trace shows the FFT or frequency content of this current (including first, third, fifth, seventh, and higher harmonics). (Using HP-6834B).

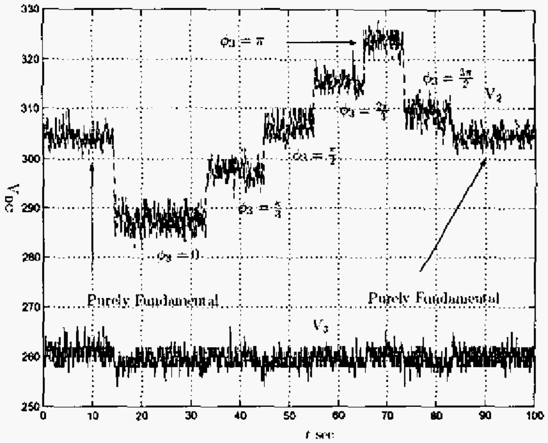
The turns ratio between the drive winding and the secondary windings can be chosen such that, at the maximum voltage drive level, there is a range of control over the dc output derived from the secondary winding. This is possible with $\phi_3 = 0$ because there is a range of V_3 where the dc output voltage can be below the fundamental. Using $\phi_3 = \pi$ is an option if a wider linear control range is desired, but to maintain the range of the drive level as well as have dc output control, one must switch to $\phi_3 = 0$ at maximum drive. It is a well-known added benefit that the addition of a third harmonic results in an increase in the inverter dc bus utilization without the need for overmodulation [8]. This increased voltage drive trades off a smaller dc output control range.

C. Control by Third Harmonic Phase

The dc output voltage of a rectifier from a grounded wye-connected winding can also be controlled by varying the third harmonic phase as shown in Figure 9. Simulations show that ac-line inductance reduces the available control range; more detailed studies are still in progress.



(a) Simulated



(b) Excitation Using an HP-6834B

Figure 9: Rectifier output voltage as third harmonic phase is varied.

Variation of third-harmonic phase permits voltage control over a more limited range than did varying the amplitude of third harmonic. However, generally, the harmonic spectrum for phase modulation is more compact than amplitude modulation. A combination amplitude-phase control is a possible design option.

III. DSP-BASED INVERTER

We designed a half-bridge inverter (Figure 10) using the IR's PIIPM15P12D007X programmable isolated integrated power module. This power module includes a three-phase inverter as well as a TI TMS320LF2406A DSP that allows for digital control of both the motor drive and rectifier output voltage.

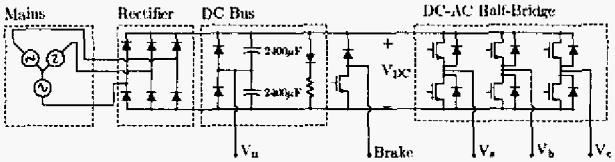


Figure 10: Inverter

A sine wave drive with low spurious harmonic content is important for rectifier output voltage control. The three-phase inverter is based on a 108-element sine reference table that drives a symmetric PWM. The size of the table was chosen to be both a multiple of 3 (aligned three-phase system) and 4 (quarter-wave symmetry). Although not yet implemented, an equivalent 27-element quarter-wave table could be used. The generation of the third harmonic is achieved by accessing every third table entry during each PWM update.

A key to the generation of a sine wave with low harmonic content is the alignment of the PWM switching instances with the table element entries, which ensures synchronous PWM. This is ensured by varying the PWM switching frequency about a nominal (e.g. 10 kHz) so that the switching frequency is always a multiple n of the generated sine wave; an algorithm for hysteresis about the transition points of n was included to eliminate switching frequency jitter. A discussion of synchronous PWM can be found in [9] and table-based implementations are presented in [8].

Figure 11 shows no harmonic content to at least 1.25 kHz with a 60 Hz fundamental and a third harmonic amplitude that is 50% of the fundamental. The algorithm is simple computationally because it performs only a direct table lookup and does not require interpolation. With this algorithm, the resolution for third harmonic phase modulation is determined by the size of the table. If a better resolution is required without the penalty of a large table size, interpolation for only the third harmonic lookup is required.

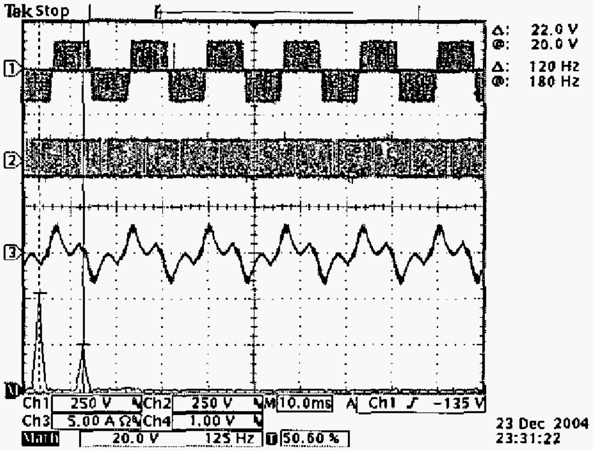


Figure 11: Inverter output waveforms with third harmonic 50% of V_1, $\phi_3 = \pi$. Trace 1: $V_a - V_b$. Trace 2: V_a - Neutral, Trace 3: I_a. Trace M: FFT of V_a - Neutral.

There are other considerations for the orthogonal control of the output rectifier of a stator secondary. Droop in the dc link due to third harmonic currents will appear as distortions in the fundamental. This effect can be reduced with large enough dc bus capacitors, by feedforward of the dc bus voltage for duty cycle corrections to the PWM, or by closed-loop feedback control of the inverter voltage output.

Another consideration is that third harmonic control, by either amplitude modulation or phase modulation, may introduce harmonics that are not zero sequence. This can be mitigated by updating the PWM only during third harmonic zero crossings, which is a variation of minimum shift keying in communications.

Figure 12 shows comparable performance of the DSP inverter to the HP-6834B. A three-phase, low-pass LC filter was required at the output of the inverter, before the input to the stator, because motor winding parasitics near or above the switching frequency were excited and affected the control independence as well as the controllability of the grounded wye-connected rectifier dc output voltage.

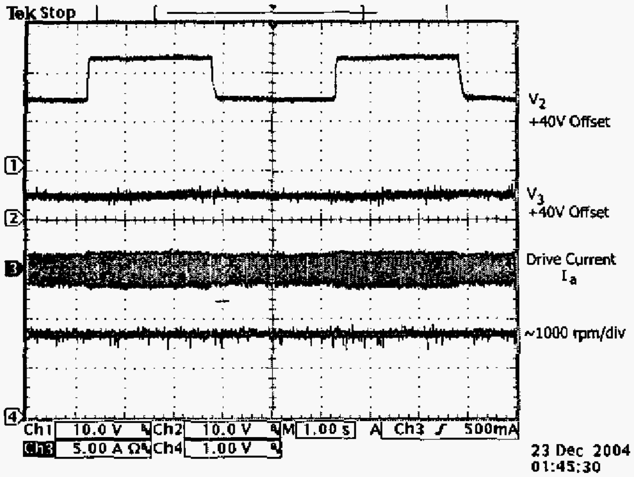


Figure 12: Rectifier output with $0.48V_{k1}$ step variations in V_{k3}, $\phi_3 = 0$. Trace 1: Grounded-wye winding. Trace 2: Ungrounded-wye winding. Trace 3: Speed Sensor Output (~1000 rpm/div).

IV. CONCLUSIONS

We have analyzed and demonstrated a method for dc output control from an induction motor with a stator with multiple windings. This method is not only applicable to induction motors, but potentially to any three-phase motor with multiple stator windings. There is imaginably a wide range of applications where this dual-use of a motor can reduce size and cost, and improve overall system performance.

Several avenues of research are currently being undertaken. Field-oriented control methods that use a stator voltage estimator, among other voltage drive techniques that are advantageous for this method, are being implemented. We are also exploring strategies for dc output regulation (e.g. PI, deadbeat and predictive controllers). Winding topologies in addition to the wye connections may offer additional control through different harmonics, e.g. 5th, 7th, etc. System design tradeoffs and comparisons to power systems that use multiple supplies in various applications are also being investigated.

ACKNOWLEDGEMENTS

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REFERENCES

[1] J. M. Miller, A. R. Gale, P. J. McCleer, F. Leonardi, and J. H. Lang, "Starter-alternator for hybrid electric vehicle: comparison of induction and variable reluctance machines and drives," presented at Industry Applications Conference, 1998. Thirty-Third IAS Annual Meeting. The 1998 IEEE, 1998.

[2] J. Kim and K. Nam, "Dual inverter control strategy for high speed operation of EV induction motors," presented at IECON 02 [Industrial Electronics Society, IEEE 2002 28th Annual Conference of the], 2002.

[3] H. Rehman, X. Xu, N. Liu, G. S. Kahlon, and R. J. Mohan, "Induction motor drive system for the Visteon Integrated Starter-Alternator," presented at Industrial Electronics Society, 1999. IECON '99 Proceedings. The 25th Annual Conference of the IEEE, 1999.

[4] C. P. Mudannayake and M. F. Rahman, "An integrated starter alternator for the 42 V PowerNet," presented at Power Electronics and Drive Systems, 2003. PEDS 2003. The Fifth International Conference on, 2003.

[5] P. J. McCleer, J. M. Miller, A. R. Gale, M. W. Degner, and F. Leonardi, "Nonlinear model and momentary performance capability of a cage rotor induction machine used as an automotive combined starter-alternator," *Industry Applications, IEEE Transactions on*, vol. 37, pp. 840-846, 2001.

[6] D. J. Perreault and V. Caliskan, "Automotive power generation and control," *Power Electronics, IEEE Transactions on*, vol. 19, pp. 618-630, 2004.

[7] J. G. Kassakian, M. F. Schlect, and G. C. Verghese, *Principles of Power Electronics*. Reading: Addison-Wesley, 1991.

[8] T. Abeyasekera, C. M. Johnson, D. J. Atkinson, and M. Armstrong, "Elimination of subharmonics in direct look-up table (DLT) sine wave reference generators for low-cost microprocessor-controlled inverters," *Power Electronics, IEEE Transactions on*, vol. 18, pp. 1315-1321, 2003.

[9] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics*, 2nd ed. New York: John Wiley and Sons, 1995.