

AC 2007-789: INTEGRATING MICROCONTROLLERS INTO A MODERN ENERGY CONVERSION LABORATORY COURSE

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Rick Haub received a B.S. degree in Physics from the University of South Dakota in 1986. In 1987, while studying for his M.E. in physics at South Dakota State University, he began working for Midwest Micro-Tek in Brookings S.D. There he designed 8 and 16-bit embedded controllers and wrote custom operating systems. He is fluent in several programming languages and many dialects of assembly. His controllers can be found in many applications from industry to military to NASA and in rides at Disney World. In 2003 Rick reentered academia at South Dakota State University to finish his M.E.; preparatory to his pursuit of a Ph.D. in Electrical Engineering. He also maintains a private consulting firm and is currently consulting for an ethanol group in South Dakota that is building small automated ethanol facilities.

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Integrating Microcontrollers into a Modern Energy Conversion Laboratory Course

Rick Haub, Robert Fournay and Steven Hietpas

Abstract

For six years South Dakota State University has implemented major revisions to the Energy Conversion Course to include advanced topics in the area of electric drives. With these changes, the course name has been changed to Electromechanical Systems (required 400-level course with lab) to better reflect the content of the course that emphasizes a systems approach to teaching machines, power electronics, and the use of microprocessors in an electric drive system. Over these six years the development of DC permanent magnet and AC inductions motor drive systems has provided more advanced study within the lecture and required laboratory course, wherein students model power electronic drives and motors, conduct simulations to predict system behavior, and then conduct experiments to verify these predictions. The last stage of development in the upgrading of this course and laboratory has focused on a meaningful integration of the microprocessor and its use in electromechanical systems. This paper describes three AC induction motor laboratory exercises, including the objectives and the required hardware and software needed. Exercise 1 follows more traditional exercises concerning the circuit modeling of a 3-hp 3-phase induction motor but with added emphasis in establishing key motor parameters useful in the design of a V/Hz motor drive. Exercise 2 builds on this model and allows students to design/establish key gain parameters for an in-house open-loop V/Hz motor drive that results in optimal speed performance of the induction motor for a given operating point. The in-house V/Hz motor drive has a user interface that allows direct manipulation of these key gain parameters. Exercise 3 provides students a culminating experience requiring them to use their knowledge of the motor and electric drive system to write and implement a pulse-width-modulation and frequency control algorithm that produces the required drive signals to the power stage of the electric drive. This approach is a distinct shift from a traditional machines laboratory approach, by providing an innovative means to exposing students to a realistic microprocessor-based application, while helping them to gain a complete understanding of a modern electromechanical system.

I. Introduction

South Dakota State University designed and constructed a unique electric machines laboratory, which was completed in 2002¹⁻² to accommodate major revisions to the required Energy Conversion Course that now includes advanced topics in the area of electric drives³⁻⁴. Additionally, efforts have been made to also include elements of control systems theory⁵. The final addition to the course provides an avenue for students to use their knowledge of microprocessors, assembly and C languages in the coding of a pulse-width-modulation and frequency control algorithm needed in a volts/Hertz (V/Hz) 3-phase induction motor drive.

Section II outlines the common (traditional) laboratory in the performance characterization of a 3-phase induction motor. This lab serves to give students a quick understanding of the 3-phase motor along with 3-phase induction motor terminology. Section III, is another traditional laboratory exercise involving the tests required to obtain a single-phase equivalent circuit model. However, additional objectives (requirements) are demanded of the students to acquire significantly more in-depth understanding of the circuit model that will allow them to consider the analysis and design of a V/Hz motor drive. Section IV details the objectives and requirements for the programming of a microcontroller that will supply sinusoidally shaped pulse width modulation (PWM) signals to the power stage of a V/Hz motor drive. This section provides a brief derivation of the functions needed for the development of the microcontroller algorithms. Each lab exercise clearly states a set of objectives and a discussion on the tasks students would be required to accomplish in order to meet the objectives. Section V ends with concluding remarks.

II. LAB 1: Steady-State Performance Characterization of a 3- Φ Induction Motor

The objective of this lab is for students to perform all necessary measurements to characterize the steady-state behavior of the motor, including

1. Motor torque vs. slip
2. Motor Power factor vs. loading
3. Motor Efficiency vs. loading

The performance characteristics of the motor will eventually be used to compare with simulated results obtained from the follow-on lab, which requires students to develop a computer model of the motor based on standard motor tests.

The system diagram of Fig. 1 contains each of the primary components of the test setup. The motor under test (MUT) is a 3-phase, 3-hp, 4-pole, 230 Vac, induction motor. The 3-phase source voltage is controlled through a 3-phase autotransformer. The MUT is connected to a cradled dynamometer, which is simply a DC machine for which the bearings are set on stationary mounts, i.e., the motor is suspended⁴.

In order to produce the required characterization plots, the following measurements are made by varying the loading on the generator from no-load up to 115% rated load.

- Motor Input Complex Apparent Power, \bar{S}_in
- Motor Power Out, P_{out1}
- Motor Torque, T_m
- Motor Speed, ω_m

Load adjustment is accomplished by setting the generator load power P_{out2} via a LabView interface to an automated load bank (ALB)⁴.

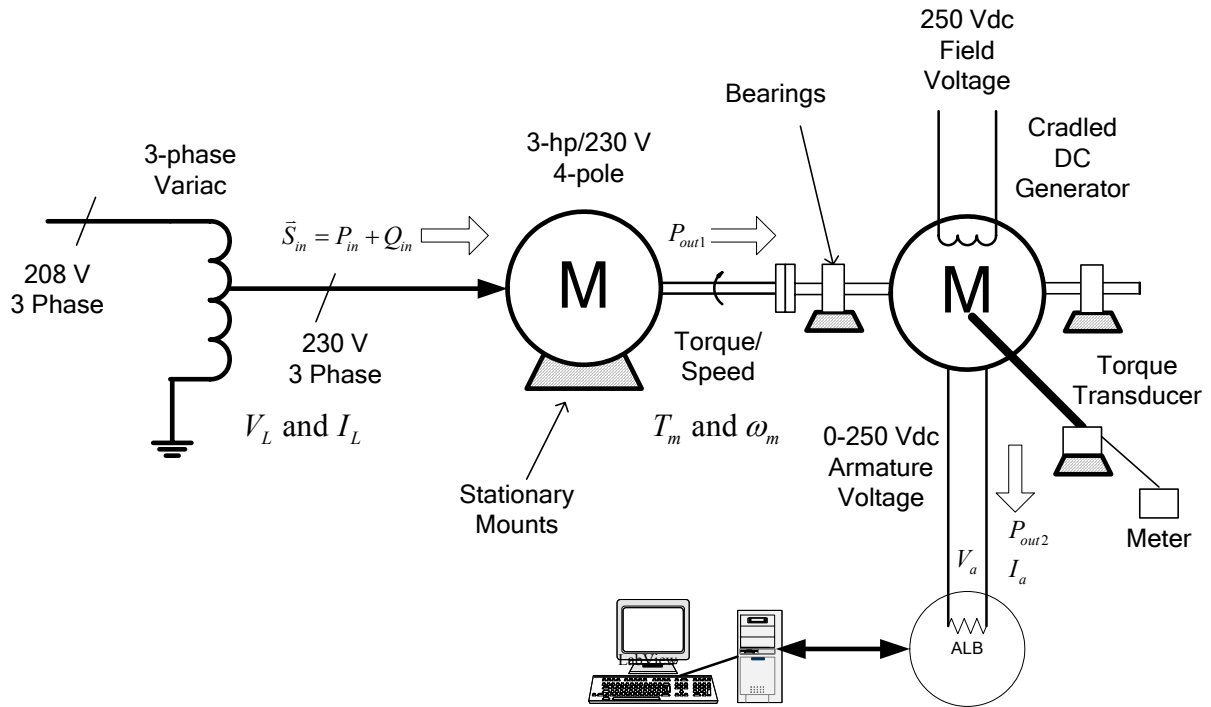


Figure 1: System diagram of motor/generator set

III. LAB 2: 3Φ Induction Motor Tests for a 1Φ Equivalent Circuit Model

The objectives of this lab are to perform standard DC, Blocked Rotor, and No-Load tests to arrive at a single phase equivalent circuit model for a 3-phase induction motor of Fig. 1. The circuit of Fig. 2 is the single phase equivalent model for the 3-phase induction motor⁶.

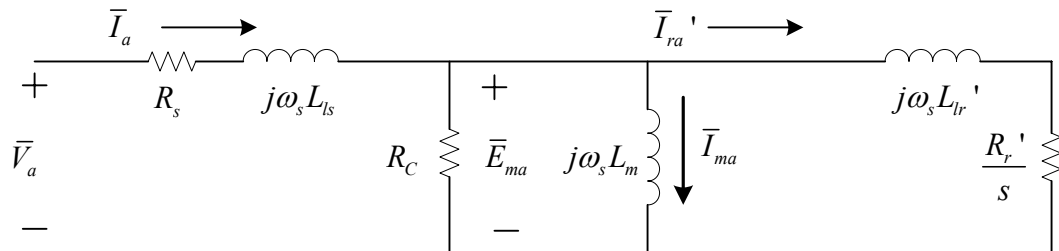


Figure 2: Single phase equivalent circuit model of a 3-phase induction motor.

Each of the variables is defined as follows:

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|--|--|
| <ul style="list-style-type: none"> • $\bar{V}_a \triangleq$ Line-to-neutral voltage • $\bar{I}_a \triangleq$ Line current • $\bar{E}_a \triangleq$ Magnetizing voltage • $\bar{I}_{ma} \triangleq$ Magnetizing current • $\bar{I}_{ra}' \triangleq$ Reflected rotor current to stator • $\omega_s \triangleq$ supply frequency (rad/s) | <ul style="list-style-type: none"> • $R_s \triangleq$ stator resistance • $L_{ls} \triangleq$ stator leakage inductance • $R_C \triangleq$ magnetic core resistance • $L_m \triangleq$ magnetizing inductance • $L_{lr}' \triangleq$ rotor leakage inductance • $R_r' \triangleq$ reflected rotor resistance |
|--|--|

A brief outline of each test follows, however, for a more detailed discussion; the reader is referred to course notes⁷.

DC-Resistance Test

The simplest of all the tests is the DC-Resistance test. Students apply a low dc voltage across two phases of the ac motor. Using Ohm's Law, and accounting for skin effect, a value for the stator resistance R_s is obtained.

Blocked-Rotor Test

Under the blocked-rotor test, the speed of the motor is constrained to be zero, and hence, the slip is $s = 1$, which results in the simplified (approximate) equivalent circuit of Fig. 3. A series of relatively straight forward measurements, employing the two-watt meter approach, results in values for R_r' and L_l . The MUT for this lab is a NEMA B (National Electrical Manufacturers Association) and using empirical methods based on IEEE Standard 112, the total leakage inductance is split such that $L_{ls} = 0.4L_l$ and $L_{lr}' = 0.6L_l$.

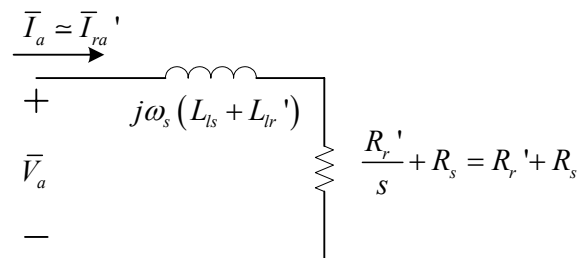


Figure 3: Single phase equivalent model under block-rotor condition

No-load Test

Under the no-load test, the speed of the motor is near synchronous speed, and hence, the slip is $s \approx 0$, which can be used to arrive at a simplified circuit model. Employing the two-watt meter approach again results in values for R_c and L_m . Students are made aware that the power factor under the no-load condition is very small, which results in one of the two watt meters to measure a negative real power.

PSpice model

To complete this lab, the students are required to construct a PSpice circuit model of Fig. 2. To account for varying load, the students are required to use the PARAM (parameter) function within PSpice to define the slip variable s . The students produce a mapping of slip to actual load value. Thus, a parametric sweep of slip establishes a sweep in output power, P_{out1} , as well as a sweep in motor speed, ω_m , based on the synchronous speed of the 4-pole motor. This modeling approach allows students to compare actual results from the first lab with predicted results from their PSpice simulation.

MATLAB model

A method for arriving at a torque equation based on the circuit model is provided in course notes⁸⁻⁹. Students employ the method of a Thévenin equivalent circuit and a relatively short Matlab program to produce torque vs. speed plots to compare with actual results from the previous lab.

IV. LAB 3: Microcontroller PWM coding for a V/Hz 3-hp 3-Phase Induction Motor Drive

The objective of the third lab in this sequence is for the students to gain an understanding into the actual workings of a motor controller. This requires the students to combine their knowledge of the induction motor model and the corresponding course development of the V/Hz motor drive equations to write and implement a portion of the pulse-width-modulation and frequency control algorithm that produces the required drive signals to the power stage of the electric drive. This laboratory exercise ensures that the students have a level of understanding that is much greater than that required to control a motor using a commercial off-the-shelf motor controller.

To simplify the procedure, it is assumed that the motor drive system is connected to a squared-power load, such as a compressors or roller. A significant feature of the 3-phase induction motor is that if a motor drive is used in such a way as to maintain peak magnetizing flux density, the efficiency of the motor drive system is maximized, as well as the performance over a wide range of speed and loads. Furthermore, the AC motor control performance can approach that of a DC motor drive system, taking advantage of the linear region of torque vs. speed operation by maintaining a low slip value.

The flux density is directly proportional to the magnetizing current I_{ma} , and using the fundamental relationship $\bar{E}_{ma} = j\omega_s L_m \bar{I}_{ma}$, the principle of V/Hz motor control is embedded in

the formula $\hat{I}_{ma} = \frac{1}{2\pi L_m} \frac{\hat{E}_{ma}}{f_s}$, where $\omega_s = 2\pi f_s$. Thus, to maintain peak magnetizing current

\hat{I}_{ma} , and hence peak flux density, for any supply frequency, the ratio $\frac{\hat{E}_{ma}}{f_s}$ must remain constant, such that $\hat{I}_{ma} = \hat{I}_{ma,rated}$.

Additional simplifying assumptions¹⁰ results in $\hat{V}_{an} \cong [2\pi(L_m + L_{ls})\hat{I}_{ma}]f_s + \hat{I}_{ra}'R_s$, which has the affine linear form of $y = mx + b$, where $m \triangleq k_m = 2\pi(L_m + L_{ls})\hat{I}_{ma}$ in V/Hz, and the offset given by $b = \hat{I}_{ra}'R_s$.

It can further be shown that the V/Hz slope (k_m) can be found by computing it with rated values

$$k_m = \frac{\hat{V}_{an,rated} - R_s \hat{I}_{ra,rated}'}{f_{rated}} \quad (1)$$

The torque and reflected rotor current (when operating in the linear region of the torque vs. speed curve) are linearly related as

$$\hat{I}_{ra}' = \left(\frac{T_{em}}{T_{em,rated}} \right) \hat{I}_{ra,rated}' \quad (2)$$

Assuming a squared-power load, a linear relationship exists between torque and speed, such that

$$\frac{T_{em}}{T_{em,rated}} = \frac{n_m}{n_{m,rated}} \quad (3)$$

Using (1-3), the supply voltage equations becomes

$$\hat{V}_{an} \cong k_m f_s + R_s \left(\frac{\hat{I}_{ra,rated}'}{n_{m,rated}} \right) n_m \quad (4)$$

Equation (4) computes the necessary supply voltage and frequency for a desired motor speed n_m .

Solving (1) for $\hat{I}_{ra,rated}'$, the supply voltage equation of (4) becomes

$$\hat{V}_{an} = k_m f_s + \left(\frac{V_{an,rated} - k_m f_{s,rated}}{n_{m,rated}} \right) n_m. \quad (5)$$

Taking into account the MUT and its nameplate ratings, (5) simplifies to (6)

$$\hat{V}_{an} = k_m f_s + \left(\frac{188 - 60k_m}{1750} \right) n_m. \quad (6)$$

For a given load setting, which corresponds to a particular value of slip s , the speed is calculated by $n_m = 30f_s(1-s)$. The result is (7), which is programmed into the man machine interface (MMI) of Fig. 4.

$$\hat{V}_{an} = k_m f_s + \left(\frac{188 - 60k_m}{1750} \right) 30f_s(1-s). \quad (7)$$

Using results from the previous lab, the V/Hz constant a student might enter is $k_m \approx 3.6$. Since the modeling of the motor is based on numerous assumptions and approximations, the value might be adjusted in order to obtain better motor drive performance.

Using an in-house keypad/LCD interface, the student is able to input values for k_m , f_s , and s . The MMI computes (7), which is then used to establish a duty-cycle parameter (d_{max}) needed by the microcontroller. The microcontroller is tasked with computing for and setting the pulse-width-modulated drive signals $d_a(t)$, $d_b(t)$ and $d_c(t)$ sent to the IGBTs (insulated gate bipolar transistors) in the inverter power stage.

For the motor studied in these labs, the bus voltage $V_d = 300$ Vdc and the switching frequency f_{switch} of the PWM pulse train ($d_a(t)$, $d_b(t)$ and $d_c(t)$) is set to a constant and sufficiently high value above the highest fundamental frequency of f_s . The microcontroller (Intel 80C196KC) used for this motor drive is capable of producing three separate PWM signals whose duty cycle $d_\phi(t)$ for $\phi = a, b, \text{ and } c$, is varied sinusoidally, each phase shifted 120° from each other in time. The controller has a register that can be 8-bits, 10-bits, or 12-bits wide. To simplify the coding, the register was selected to be 8-bits wide.

The duty cycle $d_\phi(t)$ is adjusted between a value of 0 to $d_{max} \leq 1$, where d_{max} is determined according to the required maximum value of $\hat{V}_{\phi n}$ for a particular set (k_m, f_s, s).

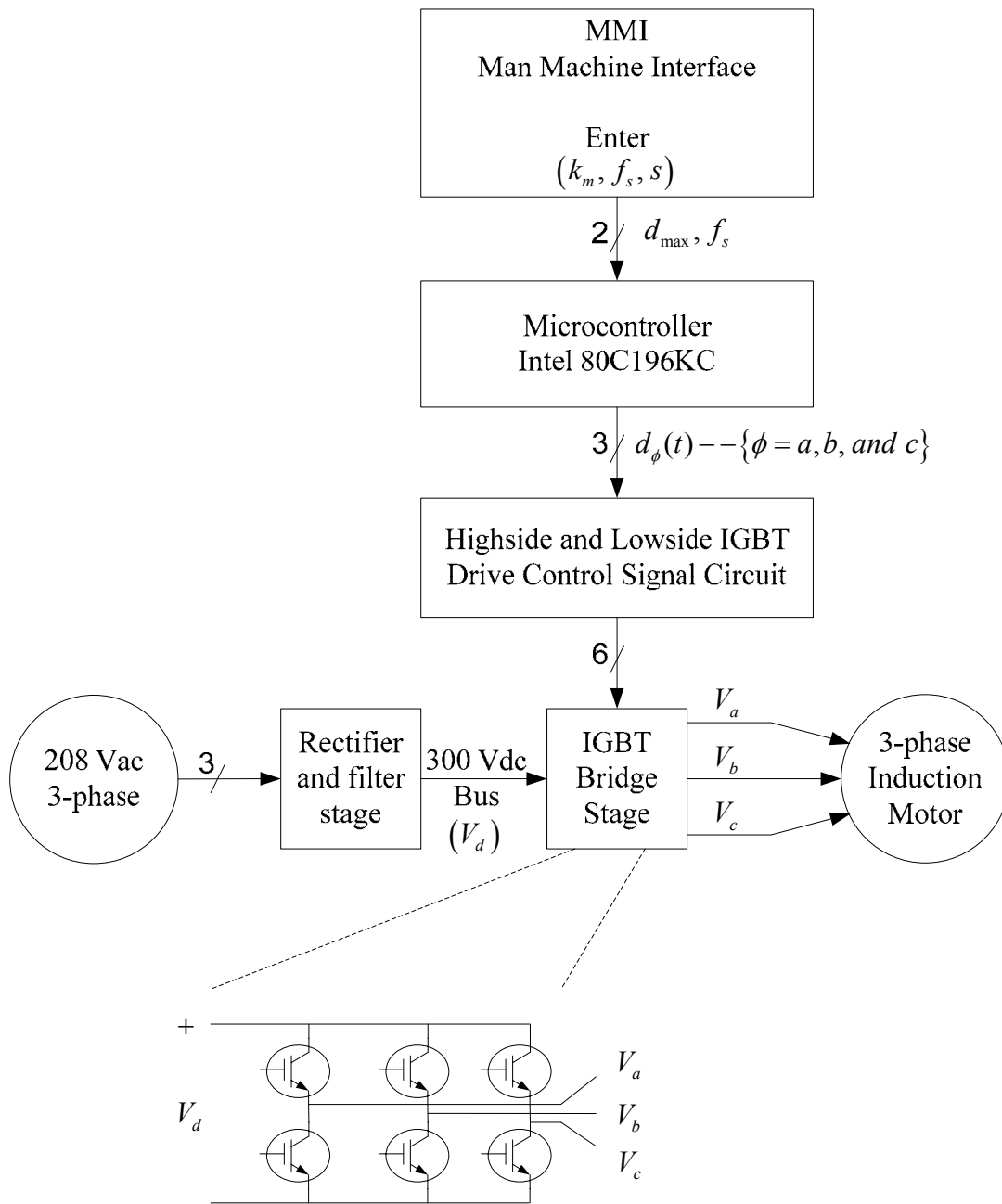


Figure 4: Functional block diagram for a sine wave motor drive

To remain balanced, it is required to maintain $d_{a,\max}(t) = d_{b,\max}(t) = d_{c,\max}(t)$ over a sufficient number of cycles given by $T_s = 1/f_s$. If the 8-bit register is loaded to a value of 255 decimal or

\$FF hex, then the average value of $d_\phi(t)$ will be 1. If 128 decimal (\$80 hex) is loaded into the register, the duty cycle of $d_\phi(t)$ will be 50%, i.e., a square wave, with an average value of 0.5. The quantization of the duty cycle $d_\phi(t)$ is therefore 1/256 divisions or 0.39%/div.

Lookup tables are used to reduce the computation time needed to shape the drive signal $d_\phi(t)$ into a sine wave with 0.5 bias. The construction of these tables is based on the equation $d_{\max} [0.5(1 + \sin \theta_k)]$, where $\theta_k = \frac{2\pi k}{N-1}$ for $k = 0, 1, \dots, N-1$. The quality of the wave (less distortion) increases with greater values of N , which also necessitates larger look up tables. The fact that 8-bit registers are used, the formula for the lookup table, in decimal values, is given by

$$PWM_{regval} = d_{\max} (128 + 127 \sin \theta_k), \text{ for } k = 0, 1, \dots, N-1,$$

and in hex the equation becomes $PWM_{regval} = d_{\max} (\$80 + \$7F \sin \theta_k)$. An example of a lookup table for $N = 256$ and $d_{\max} = 1$ is provided in¹¹. To further reduce computational overhead, rather than multiplying the table¹¹ by d_{\max} , 64 tables, corresponding to uniformly distributed values of d_{\max} between 0 and 1, were used.

The discretization using the microcontroller replaces the continuous time variable t with the discrete time variable k . To produce $d_a(k)$, $d_b(k)$ and $d_c(k)$ at 120° separation, phase a starts reading at location $k = 0$, phase b at location $k = 85$, and phase c , at location $k = 170$. Phase quantization error, given by $(360^\circ)/(N-1)$, results in 1.4° error in phase between each line voltage. The tables constructed thus far are referred to as the *magnitude* tables. To control the source frequency, f_s , the rate of reading from the table is changed. The period of the sine wave is given by $N\Delta t$, where Δt is the delay in seconds from reading consecutive values within the table. The frequency of the voltage source to the motor is give by $f_s = \frac{1}{N\Delta t}$.

Microcontroller programming approaches

The magnitude lookup table is comprised of 256 values, each representing the magnitude of the desired sine wave at a different point in time. These values represent samples taken at uniform times throughout the period of the sine wave, and repeats after 256 samples. To create a sine wave at a frequency of 60 Hz, this entire table (all 256 values, in order) must be sent to the output pins of the microcontroller 60 times per second. This requires writing to the control register 15,360 times per second. These control register writes must be timed precisely in order to achieve the desired result without damaging the motor.

A student, who is intimately familiar with the particular microcontroller being used, and able to compensate for all potential code latency, can implement a simple delay loop. The delay value can be determined empirically by measuring the frequency of several different sine waves and tabulating the relationship between frequency and delay value. A theoretical approach, which also relies on eliminating latency, would be to determine the number of (microcontroller) clock cycles in the delay loop and the associated overhead and calculate the number of times the loop must be executed in order to achieve the desired motor speed. By knowing the clock frequency of the microcontroller and performing an analysis similar to that shown above, the appropriate delay value can then be calculated. If the code latency is not eliminated, a better solution would be to set up a timer interrupt to give an interrupt every time a new value needs to be sent.

In the above example, 15,360 writes per second equates to one write every 11.51 microseconds. The microcontroller must be of sufficient speed, including an allowance for overhead, to meet this requirement. Since the motor will be driven at various frequencies, a *delay* lookup table is constructed. The lookup table is absolutely required in the empirical approach, and allows a more rapid response to a change in input parameters in all cases since the overhead associated with calculating these delays each time the frequency is changed is avoided.

VI. Conclusion

Three tightly-integrated lab exercises for an Electromechanical Systems Lab have been presented. The first lab (Steady-State Performance Characterization of a 3- Φ Induction Motor) provides students a means to become familiar with the operation and the performance of an induction motor. Students follow a traditional approach; however, the performance data gathered is required by the second and third labs. The second lab (3 Φ Induction Motor Tests for a 1 Φ Equivalent Circuit Model) builds on a standard procedure for the modeling of an induction motor. The students are then required to use PSpice and MATLAB to verify the accuracy of the circuit model by comparing simulation results with actual lab results from LAB 1. LAB 3 (Microcontroller PWM coding for a V/Hz 3-hp 3-Phase Induction Motor Drive) is, in some ways, the most challenging lab. It pushes beyond traditional machines labs and requires students to incorporate their microcontroller and programming language skills in the development of algorithms that implement the sinusoidal PMW drive signals for a V/Hz motor drive. Student feedback is still in progress before their assessment can be summarized.

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Biography

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